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MULTI-AGENCY RADIATION SURVEY AND SITE INVESTIGATION MANUAL (MARSSIM)

DRAFT FOR PUBLIC COMMENT

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ABSTRACT

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides information on planning, conducting, evaluating, and documenting building surface and surface soil radiological surveys for demonstrating compliance with requirements, often as part of a dose- or risk-based regulation or standard.[1] MARSSIM is a multi-agency consensus document that was developed collaboratively by four Federal agencies having authority and control over radioactive materials: Department of Defense (DOD), Department of Energy (DOE), Environmental Protection Agency (EPA), and Nuclear Regulatory Commission (NRC). MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil radiological surveys to meet established dose or risk-based release criteria, while concurrently encouraging an effective use of resources.

[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

DISCLAIMER

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DEDICATION

The MARSSIM Workgroup notes, with much sadness, the sudden loss of Dr. George Edward Powers of the U.S. Nuclear Regulatory Commission staff. Dr. Powers passed away in late 2011, as the effort to revise the MARSSIM manual was getting underway. As a member of the MARSSIM Workgroup, he made significant contributions on MARSSIM, both on the original document, on its revision in 2001, and on this latest revision. Dr. Powers also contributed in an important way to the development of the MARSAME and MARLAP manuals; his participation in the development of all three documents (MARSSIM, MARSAME, and MARLAP) is well recognized. The MARSSIM Workgroup members also are aware of the many contributions he made as an NRC employee, including his involvement in several USNRC NUREG publications over the years. Dr. Powers was truly a visionary in encouraging development of multi-agency documents in this collaborative and collegial manner for use by many people. Dr. Powers' sense of humor enhanced his ability to work so well in a positive manner with many of his colleagues in multi-agency settings. He was a technically accomplished, kind, and courteous man who contributed much to the Workgroup's efforts.

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TABLES

FIGURES

ABBREVIATIONS

1st Lt.	First Lieutenant
AARST	American Association of Radon Scientists and Technologists
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AFI	Air Force Instructions
AGL	above ground level
AL	action level
ALARA	as low as reasonably achievable
AMC	Army Materiel Command
AMS	accelerator mass spectrometry
ANSI	American National Standards Institute
AR	Army Regulations
ARA	Army Radiation Authorization
ASQ	American Society for Quality
ASTM	American Society of Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
CAA	Clean Air Act
Capt.	Captain (Air Force)
CAPT	Captain (Navy)
CDR	Commander
CED	committed effective dose
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CFR	Code of Federal Regulations
CHP	Certified Health Physicist
COC	chain of custody
Col.	Colonel
CV	coefficient of variation
DCF	dose conversion factor
DCGL	derived concentration guideline level
$DCGL_{EMC}$	DCGL for small areas of elevated activity, used with the EMC
$DCGL_W$	DCGL for average concentrations over a wide area, used with statistical tests
DEFT	Decision Error Feasibility Trials
DGPS	differential global positioning system
DHS	Department of Homeland Security
DL	discrimination limit
DLC	Data Life Cycle
DOD	U.S. Department of Defense

DOE	U.S. Department of Energy
DOT	Department of Transportation
DQA	Data Quality Assessment
DQIs	Data Quality Indicators
DQO	Data Quality Objectives
ED	electronic dosimeter
EERF	Eastern Environmental Radiation Facility
Ehf	human factors efficiency
EIC	electret ion chamber
EMC	elevated measurement comparison
EML	Environmental Measurements Laboratory
EMMI	Environmental Monitoring Methods Index
EPA	U.S. Environmental Protection Agency
EPIC	Environmental Photographic Interpretation Center
ERAMS	Environmental Radiation Ambient Monitoring System
FA-MS	flowing afterglow mass spectrometer
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Maps
FRDS	Federal Reporting Data System
FSP	Field Sampling Plan
FSS	Final Status Survey
FUSRAP	Formerly Utilized Sites Remedial Action Program
FWPCA	Federal Water Pollution Control Act
GCS	geographic coordinate system
GEMS	Geographical Exposure Modeling System
GIS	geographic information system
GM	Geiger-Mueller
GPR	ground-penetrating radar
GPS	global positioning system
GRIDS	Geographic Resources Information Data System
GWSI	Ground Water Site Inventory
HASP	Health and Safety Plan
HPS	Health Physics Society
HSA	Historical Site Assessment
HSWA	Hazardous and Solid Waste Amendments
HRS	Hazard Ranking System
HTD	hard-to-detect
HWP	hazard work permit
IAEA	International Atomic Energy Agency
ICP	inductively coupled plasma
ICP-AES/MS	inductively coupled plasma-atomic emission spectrometry/mass spectrometry
ICP-MS	inductively coupled plasma mass spectrometer
IEEE	Institute of Electrical and Electronics Engineers

IR-MS	isotope ratio mass spectrometer
ISGS	*in situ* gamma spectroscopy
ISI	Information System Inventory
ISO	International Organization for Standardization
IV	independent verification
JSA	job safety analysis
KPA	kinetic phosphorescence analysis
LA-ICP-AES	laser ablation-inductively coupled plasma-atomic emission spectrometry
LA-ICP-MS	laser ablation-inductively coupled plasma-mass spectrometry
LANL	Los Alamos National Laboratory
LBGR	lower bound of the gray region
LCD	liquid crystal display
LCDR	Lieutenant Commander
LLD	lower limit of detection
LLNL	Lawrence Livermore National Laboratory
LLRWPA	Low-Level Radioactive Waste Policy Act, as Amended
LSC	liquid scintillation counter
Lt.	Lieutenant (Air Force)
LT	Lieutenant (Navy)
Lt. Col.	Lieutenant Colonel
MARLAP	Multi-Agency Radiation Laboratory Analytical Protocols (Manual)
MARSAME	Multi-Agency Radiation Survey and Assessment of Materials and Equipment (Manual)
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCA	multichannel analyzer
MDA	minimum detectable activity
MDC	minimum detectable concentration
MDCR	minimum detectable count rate
MDER	minimum detectable exposure rate
MDLEST	Mobile Demonstration Laboratory for Environmental Screening Technologies
MED	Manhattan Engineering District
MeV	megaelectron volt
MQC	minimal quantifiable concentration
MQO	Measurement Quality Objectives
MS	mass spectrometry
MS/MD	matrix spike/matrix duplicate
NAREL	National Air and Radiation Environmental Laboratory
NARM	naturally occurring and accelerator produced radioactive material
NCAPS	National Corrective Action Prioritization System
NCP	National Contingency Plan
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology

NORM	naturally occurring radioactive material
NPDC	National Planning Data Corporation
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWWA	National Water Well Association
ODES	Ocean Data Evaluation System
ORISE	Oak Ridge Institute for Science and Education
ORNL	Oak Ridge National Laboratory
OSHA	U.S. Occupational Safety and Health Administration
OSL	optically stimulated luminescence
OSLNs	optically stimulated luminescence devices sensitive to neutrons
PAEC	potential alpha energy concentration
PCi	picocurie
PE	performance evaluation
PERALS	photon electron rejecting alpha liquid scintillator
PIC	pressurized ionization chamber
PMT	photomultiplier tube
PPE	personal protective equipment
QA	quality assurance
QAM	Quality Assurance Manual
QAPP	Quality Assurance Project Plan
QC	quality control
QMP	Quality Management Plan
RAGS/HHEM	Risk Assessment Guidance for Superfund/Human Health Evaluation Manual
RAS	Remedial Action Support
RASP	Radiological Affairs Support Program
RCRA	Resource Conservation and Recovery Act
RCRIS	Resource Conservation and Recovery Information System
RFI/CMS	RCRA Facility Investigation/Corrective Measures Study
RFP	Request for Proposal
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
RODS	Records of Decision System
RSS	Ranked Set Sampling
RSSI	Radiation Survey and Site Investigation
RWP	radiation work permit
SADA	Visual Sample Plan and Spatial Analysis and Decision Assistance
SAP	Sampling and Analysis Plan
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SFMP	Surplus Facilities Management Program

SOPs	Standard Operating Procedures
SOR	sum of the ratios
SOW	statement of work
SPP	systematic planning process
SRS	simple random sampling
STORET	Storage and Retrieval for Water Quality Data
TED	total effective dose
TEDE	total effective dose equivalent
TENORM	technologically enhanced naturally occurring radioactive material
TIMS	thermal ionizing mass spectrometry
TLD	thermoluminescent dosimeter
TOF-MS	time-of-flight mass spectrometry
TRU	transuranic
TSCA	Toxic Substances Control Act
TVA	Tennessee Valley Authority
UBGR	upper boundary of the gray region
UCL	upper confidence limit
UFP	Uniform Federal Policy
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plans
UFP-QS	Uniform Federal Policy for Implementing Environmental Quality Systems
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	United States Geological Survey
USPHS	United States Public Health Service
USRADS	Ultrasonic Ranging and Data System
UXO	unexploded ordnance
VOCs	volatile organic compounds
WATSTORE	National Water Data Storage and Retrieval System
WL	working level
WQX	Water Quality Exchange
WRS	Wilcoxon Rank Sum
WSR	Wilcoxon signed rank
WT	Wilcoxon test

Symbols, Nomenclature, and Notations

$<$	less than
$>$	greater than
$\leq$	less than or equal to
$\geq$	greater than or equal to
°	degrees (angle or temperature)
%	percent
$1-\beta$	statistical power of a hypothesis test
α	Type I decision-error rate
α_Q	alpha used for the quantile test
αS	alpha scintillation survey meter
a	half-width of a rectangular or triangular probability distribution
A	area
A	overall sensitivity of a measurement
Ac	actinium (isotope listed: ^{228}Ac)
A_{EA}	area of elevated activity
AL_i	action level value an individual radionuclide (i = 1, 2, …, n)
$AL_{meas,mod}$	modified action level for the radionuclide being measured when it is used as a surrogate for other radionuclide(s)
AL_{meas}	action level for the radionuclide being measured
AL_{infer}	action level for the inferred radionuclide (in surrogate measurements)
A_m	area factor
Am	americium (isotope listed: ^{241}Am)
A_S	surface activity
β	Type II decision-error rate
b	background count rate
b_i	the average number of counts in the background interval (scanning)
B	mean background counts
Be	beryllium (isotope listed: ^{7}Be)
Bi	bismuth (isotopes listed: ^{210}Bi, ^{212}Bi, ^{214}Bi)
Bq	becquerel
γS	gamma scintillation (gross)
C	carbon (isotope listed: ^{14}C)
C	radionuclide concentration or activity
C	constant
C_b	number of background counts
C_{S+b}	number of gross counts
Ci	curie
C_i	concentration value an individual radionuclide (i = 1, 2, …, n)

c_i	sensitivity coefficient
$c_i \mu(x_i)$	component of the uncertainty in y due to x_i
C_{infer}/C_{meas}	ratio of amount of the inferred radionuclide to that of the measured surrogate radionuclide
C_S	concentration for the surrogate radionuclide
°C	degrees Celsius
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
Cd	cadmium (isotope listed: ^{109}Cd)
Co	cobalt (isotopes listed: ^{57}Co, ^{60}Co)
cpm	counts per minute
Cr	chromium (isotope listed: ^{51}Cr)
Cs	cesium (isotope listed: ^{137}Cs)
CsI(Tl)	cesium iodide (thallium activated)
CZT	cadmium-zinc telluride
δ	estimate of the mean concentration of residual radioactive material in the survey unit
Δ	shift (width of the gray region, UBGR–LBGR)
Δ/σ	relative shift
Δt_i	the observation interval
d	parameter in the Stapleton Equation for the critical net signal
d	width of the detector in the direction of the scan
d'	detectability index (scanning)
$DCGL_{gross}$	derived concentration guideline level for a gross measurement
$DCGL_i$	derived concentration guideline level of the *i*th component leading to dose or risk
$DCGL_{min}$	lowest of the derived concentration guideline levels
$DCGL_{S\text{-}mod}$	modified derived concentration guideline level of the surrogate radionuclide
$DCGL_{S\text{-}unmod}$	derived concentration guideline level of the surrogate radionuclide before modification
dpm	disintegrations per minute
ε_i	instrument efficiency
ε_s	surface (or source) efficiency
ε_t	total efficiency of the instrument
eV	electron-volt
E_γ	energy of a gamma photon of concern in kiloelectron-volts (keV)
E_i	energy of a photon of interest
°F	degrees Fahrenheit
f_i	relative fraction of activity contributed by radionuclide *i* to the total
ft	foot (feet)

ft^3	cubic foot (feet)
Fe	iron (isotopes listed: ^{55}Fe, ^{59}Fe)
g	gram
G	activity
GBq	gigabecquerel (1×10^9 becquerels)
GG_{AL}	gross gamma action level
GM	Geiger-Mueller survey meter
GPα	gas-flow proportional counter (α mode)
GPβ	gas-flow proportional counter (β mode)
h	hour
H	hydrogen (isotope listed: ^3H [tritium])
H_0	null hypothesis
H_1	alternative hypothesis
Hz	hertz
i	ith sample or measurement in a set
i	observation time interval length (scanning)
I	iodine (isotopes listed: ^{123}I, ^{125}I, ^{131}I)
in.	inch
Ir	iridium (isotope listed: ^{192}Ir)
ISγ	in situ gamma spectrometry
k	k-statistic for the quantile test
k	coverage factor for the expanded uncertainty, *U*
k	Poisson probability sum for α and β (assuming α and β are equal)
k	critical value of the sign test
K	potassium (isotope listed: ^{40}K)
K_d	distribution coefficient
kBq	kilobecquerel (1×10^3 becquerels)
keV	kiloelectron-volt (1×10^3 electron-volts)
kg	kilogram
km	kilometer
k_Q	multiple of the standard deviation defining y_Q, usually chosen to be 10
L	length
L	liter
L	grid size spacing
L_C	critical level
L_D	detection limit
L_{EA}	revised spacing of the systematic pattern
LaBr	lanthanum bromide
lb	pound
μ	micro (10^{-6})
μ	true mean

μ	theoretical mean of a population distribution
$(\mu_{en}/\rho)_{\mathrm{air}}$	mass energy absorption coefficient in air centimeters squared per gram (cm^2/g)
μBq	microbecquerel
μCi	microcuries
μR	microroentgen (1×10^{-6} roentgen)
μSv	microsievert
m	number of reference measurements (WRS test or Quantile test)
m	number of ranking categories
m	adjusted reference sample measurements
m	meter
m^2	square meter
M_i	total amount of [dose counts, activity, etc.]
mBq	millibecquerels
$MDCR_{\mathrm{surveyor}}$	required number of net source counts
MeV	megaelectron-volt (1×10^6 electron-volt)
mg	milligram(s)
mGy	milligray
mm	millimeter(s)
Mn	manganese (isotope listed: ^{54}Mn)
M/R	mass-to-charge ratio
mR	milliroentgen
mrad	millirad
mrem	millirem (1×10^{-3} rem)
mSv	milliseivert (1×10^{-3} Sv)
n	number of survey unit measurements (WRS test or Quantile test)
n	nth sample or measurement in a set
n	number of laboratory samples (for the Ranked Set Sampling test)
N	sample size (i.e., number of data points [or samples]) for the Sign test
N	number of field screening measurements (for the Ranked Set Sampling test)
n_{EA}	survey unit area divided by the maximum area corresponding to the area factor, which yields the number of measurements needed so the scan MDC is adequate
Na	sodium (isotope listed: ^{22}Na)
NaI	sodium iodide
NaI(Tl)	sodium iodide (thallium activated)
nBq	nanobecquerels
n_{EA}	required number of data points for assessing small areas of elevated activity
ng	nanogram
Ni	nickel (isotope listed: ^{57}Ni, ^{63}Ni)
Np	neptunium (isotope listed: ^{237}Np)
ξB	non-Poisson variance component of the background count rate correction

p	coverage probability for expanded uncertainty
p	efficiency of a less than ideal surveyor (scanning)
P	probabilityr
Pa	protactinium (isotopes listed: ^{234}Pa, ^{234m}Pa)
PA	probe area
Pb	lead (isotopes listed: ^{212}Pb, ^{214}Pb)
PC	personal computer
pCi	picocurie (1×10^{-12} curies)
PIC	pressurized ionization chamber
Pm	promethium (isotope listed: ^{147}Pm)
Po	polonium (isotopes listed: ^{210}Po, ^{212}Po, ^{214}Po, ^{216}Po)
ppt	parts per trillion
Pu	plutonium (isotopes listed: ^{238}P, ^{239}Pu, ^{240}Pu, ^{241}Pu)
q	critical value for statistical tests
ρ	density
$\rho(X_i,X_j)$	correlation coefficient for two input quantities, X_i and X_j
r	number of cycles
r	random number from a data set
r	r-statistic for the quantile test
R	ratio
R	roentgen (exposure rate)
Ra	radium (isotopes listed: ^{224}Ra, ^{226}Ra, ^{228}Ra)
R_B	mean background count rate
R_i	established ratio of the concentration of the *i*th radionuclinde to the concentration of the surrogate radionuclide for $I = 2,\ldots n$
R_I	mean interference count rate
Rh	rhodium
Rn	radon (isotopes listed: ^{220}Rn, ^{222}Rn)
R_{net}	net counting rate
Ru	ruthenium (isotope listed: ^{106}Ru)
$r(x_i,x_j)$	correlation coefficient for two input estimates, x_i and x_j
σ	theoretical total standard deviation of the population distribution being sampled
σ^2	theoretical total variance of the population distribution being sampled
σ_M	theoretical measurement standard deviation of the population distribution being sampled, estimated by the combined standard uncertainty of the measurement
σ_M^2	theoretical measurement variance of the population distribution being sampled
σ_{MR}	required measurement method standard deviation (upper limit)
σ_n	standard deviation of the net count rate result
σ_r	estimate of the measurement variability in the reference area

σ_s	estimate of the measurement variability in the survey unit
σ_S^2	theoretical sampling variance of the population distribution being sampled
$\sigma(X_i, X_j)$	covariance for two input quantities, X_i and X_j
σ_y	total uncertainty
s	standard deviation of the survey unit
$S+$	Sign test statistic
$s(x)$	sample standard deviation of the input estimate, xi
s_b^2	mean square between reference areas
S_C	critical value of the net instrument signal
S_D	mean value of the net signal that gives a specified probability, 1−β, of yielding an observed signal greater than its critical value S_C
s_i	minimum detectable number of net source counts in the observation interval (scanning)
$s_{i,surveyor}$	minimum detectable number of net source counts in the observation interval by a less than ideal surveyor (scanning)
Sr	strontium (isotope listed: ^{90}Sr)
Sv	seivert
s_w^2	mean square within reference areas
t	t-test statistic
t	number of “less than” values
T	weighted sum
$t_{1/2}$	half-life
Tc	techicium (isotopes listed: ^{99}Tc, ^{99m}Tc)
Th	thorium (isotopes listed: ^{228}Th: ^{230}Th, ^{232}Th, ^{234}Th)
Th nat	natural thorium
Tl	thalium (isotopes listed: ^{201}Tl, ^{204}Tl, ^{208}Tl)
t_b	count time for the background
t_i	time interval
t_S	count time for the source
t_{S+b}	gross count time
U	expanded uncertainty
U	uranium (isotopes listed: ^{234}U, ^{235}U, ^{238}U)
U nat	natural uranium
$u(x_i)$	standard uncertainty of the input estimate, x_i
$u(x_i)/\mid x_i \mid$	relative standard uncertainty of x_i
$u(x_i,x_j)$	covariance of two input estimates, x_i and x_j
$u_c(y)$	combined standard uncertainty of y
$u_c(y)/y$	relative combined standard uncertainty of the output quantity for a particular measurement
$u_c^2(y)$	combined variance of y
$u_i(y)$	component of the combined standard uncertainty, $u_c(y)$, generated by the standard uncertainty of the input estimate x_i, $u(x_i)$, multiplied by the sensitivity coefficient, c_i

u_M	measurement method uncertainty
u_{MR}	required measurement method uncertainty
φ_{MR}	required relative measurement method uncertainty
$\varphi(x_i)$	relative standard uncertainty of a nonzero input estimate, x_i, for a particular measurement. $\varphi(x_i) = u(x_i)/x_i$
$\Phi(z)$	cumulative normal distribution function
V	volt(s)
v	scan speed
$\widehat{\omega}^2$	variance
W	physical probe area
W_r	sum of the ranks of the (adjusted) reference measurements (WRS test)
W_s	sum of the ranks of the (adjusted) sample measurements (WRS test)
WS	weighted instrument sensitivity
x	estimate of the input quantity, X
x	reference area measurement
$\bar{x}$	sample mean
X	maximum length
$X_{[k]l}$	survey unit measurements
x_i	results of the individual samples
X_i	an input quantity
x_C	the critical value of the response variable, x
x_Q	minimum quantifiable value of the response variable, x
y	year
y	estimate of the output quantity for a particular measurement, Y
Y	maximum width
Y	yttrium
Y	output quantity, measurand
y_C	critical value of the concentration
y_D	minimum detectable concentration (MDC)
y_Q	minimum quantifiable concentration (MQC)
yd	yard
yd^3	cubic yard
z	adjusted reference area measurements
Z	atomic number
$z_{1-\alpha}$	(1 − α)-quantile of the standard normal distribution
$z_{1-\beta}$	(1 − β)-quantile of the standard normal distribution
ZnS(Ag)	zinc sulfide (silver activated)

CONVERSION FACTORS

To Convert From	To	Multiply By	To Convert From	To	Multiply By
acre	hectare	0.405	meter (m)	inch	39.4
	m^2	4,050		mile	0.000621
	ft^2	43,600	m^2	acre	0.000247
Bq	Ci	$2.7x10^{-11}$		hectare	0.0001
	dps	1		ft^2	10.8
	pCi	27		square mile	$3.86x10^{-7}$
Bq/kg	pCi/g	0.027	m^3	liter	1,000
Bq/m^2	dpm/100 cm^2	0.60	mrem	mSv	0.01
Bq/m^3	Bq/L	0.001	mrem/y	mSv/y	0.01
	pCi/L	0.027	mSv	mrem	100
centimeter (cm)	inch	0.394	mSv/y	mrem/y	100
Ci	Bq	$3.70x10^{10}$	ounce (oz)	L	0.0296
	pCi	$1x10^{12}$	pCi	Bq	0.037
dps	dpm	60		dpm	2.22
	pCi	27	pCi/g	Bq/kg	37
dpm	dps	0.0167	pCi/L	Bq/m^3	37
	pCi	0.451	rad	Gy	0.01
gray (Gy)	rad	100	rem	mrem	1,000
hectare	acre	2.47		mSv	10
liter (L)	cm^3	1000		Sv	0.01
	m^3	0.001	seivert (Sv)	mrem	100,000
	ounce oz (fluid)	33.8		mSv	1,000
				rem	100

Abbreviations: m = meter; ft = foot; Bq = becquerel; Ci = curie; dps = decays per second; pCi = picocurie; kg = kilogram; g = gram; L = liter; cm = centimeter; in. = inch; dpm = decays per minute; oz = ounce; mrem = millirem; mSv = millisievert; y = year; Gy = gray; Sv = sievert.

1 INTRODUCTION

1.1 Purpose and Scope of MARSSIM

Radioactive materials have been produced, processed, used, and stored at thousands of sites throughout the United States. Many of them at one time had or now have residual radioactive material in excess of natural background. The sites range in size from Federal weapons-production facilities covering hundreds of square kilometers to the nuclear medicine departments of small hospitals. Owners and managers would like to find and remove any excess residual radioactive material and release these sites for restricted use or for unrestricted public use.

The U.S. Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DoD) are responsible for the release of federally controlled sites after cleanup. Such sites include DOE and DoD sites, sites licensed by the NRC and its Agreement States, and former unlicensed industrial facilities that handled ores containing radioactive materials that are addressed under Federal or State regulatory programs.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides a nationally consistent consensus approach to conducting radiation surveys and investigations at sites with the potential for residual radioactive material. This approach is both scientifically rigorous and flexible enough to be applied to a diversity of site cleanup conditions.

To release a site after remediation, it is normally necessary to demonstrate to the responsible Federal or State agency that the cleanup effort was successful and that the release criteria (specific regulatory limits) were met. In MARSSIM, the “Final Status Survey” (FSS) provides this demonstration. This manual assists site personnel or others in performing or assessing such a demonstration. (MARSSIM may also serve to guide or monitor other types of remediation efforts.)

As illustrated in **Figure 1.1,** the demonstration of compliance with respect to conducting surveys is comprised of three interrelated parts:

I. *Translate:* Translating the cleanup/release criteria (e.g., mSv/y, mrem/y, specific risk) into corresponding derived concentration guideline levels (e.g., Bq/kg or pCi/g in soil) through the use of environmental pathway modeling.

II. *Measure:* Acquiring scientifically sound and defensible site-specific data on the levels and distribution of residual radioactive material, as well as levels and distribution of radionuclides present in the background, by employing suitable field and/or laboratory measurement techniques.[1]

III. *Decide:* Determining that the data obtained from sampling support the conclusion that the site meets the release criteria, within an acceptable degree of uncertainty, through application of a statistically based decision rule.

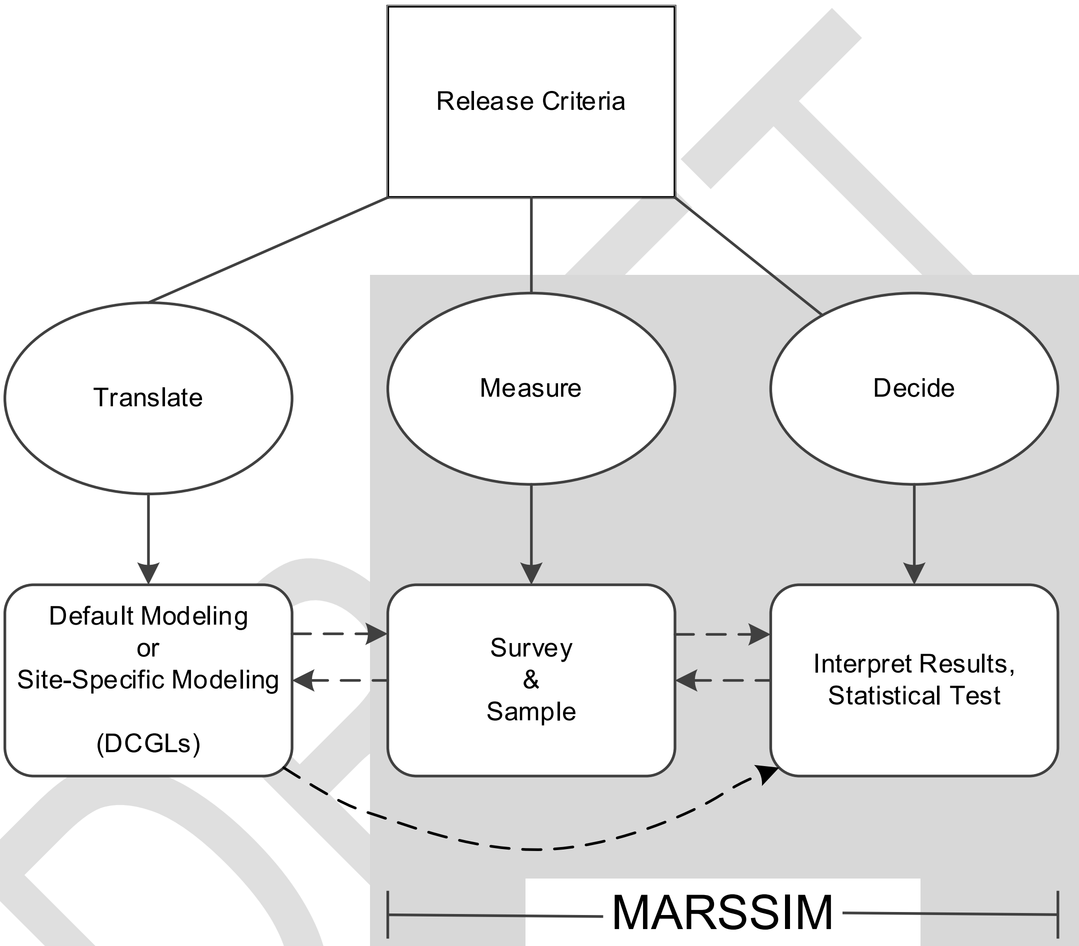

Figure 1.1: Compliance Demonstration

MARSSIM provides standardized and consistent approaches for planning, conducting, evaluating, and documenting environmental radiological surveys, with a specific focus on the FSSs that are carried out to demonstrate compliance with cleanup regulations. The MARSSIM

[1] Measurements include field and laboratory analyses; however, MARSSIM leaves detailed discussions of laboratory sample analyses to another manual (i.e., a companion document, the Multi-Agency Radiation Laboratory Analytical Protocols [MARLAP] manual).

process gathers comprehensive technical information—specifically for II and III above—on residual radioactive material in surface soils and on building surfaces. This information is used in a performance-based approach for demonstrating compliance with a dose- or risk-based regulation. This approach includes processes that identify data quality needs and may reveal limitations on the data that can be collected from a survey. MARSSIM's approach supports decision-making at sites with residual radioactive material in surface soil and on building surfaces. In particular, MARSSIM describes generally acceptable approaches for the following:

- planning and designing scoping, characterization, remediation-support, and FSSs for sites with residual radioactive material in surface soil and on building surfaces
- Historical Site Assessment (HSA)
- quality assurance/quality control (QA/QC) in data acquisition and analysis
- conducting surveys
- field and laboratory methods and instrumentation, and interfacing with radiation laboratories
- statistical hypothesis testing, and the interpretation of statistical data
- documentation

Table 1.1 summarizes the scope of MARSSIM. Several issues related to releasing sites are beyond the scope of MARSSIM. These include the translation of dose or risk standards into radionuclide-specific concentrations or demonstrating compliance with ground water or surface water regulations. MARSSIM can be applied to surveys performed at vicinity properties—those not under Government or licensee control—but the decision to apply MARSSIM at vicinity properties is a regulatory decision outside the scope of MARSSIM. Information on designing, implementing, and assessing radiological surveys of materials and equipment is presented in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) supplement to MARSSIM. The potential presence of residual radioactive material in other media (e.g., subsurface soil, ground water) is not addressed by MARSSIM. MARSSIM's main focus is on FSSs, so the processes in this manual may follow remediation activities that remove below-surface residual radioactive material. Therefore, some of the reasons for limiting the scope of the document to surface soils and building surfaces include—

- Residual radioactive material is limited to these media for many sites following remediation.
- Because many sites have surface soil and building surface residual radioactive material as the leading source of exposure to radiation, existing computer models used for calculating the concentrations based on dose or risk generally consider only surface soils or building surfaces as a source term.

Table 1.1: Scope of MARSSIM

Within Scope of MARSSIM		Beyond Scope of MARSSIM	
Technical Information	MARSSIM provides technical, performance-based guidance on conducting radiation surveys and site investigations, remediation and restoration activities, and demonstration of compliance with dose- or risk-based regulations. MARSSIM includes a framework for developing a phased approach to site investigations that include stakeholder involvement, and which emphasizes the development of the final status survey (FSS) for site release.	*Regulation*	MARSSIM does not set new regulations or requirements, or address non-technical issues (e.g., legal or policy) for site cleanup. Release criteria will be provided rather than calculated using MARSSIM.
Tool Box	MARSSIM can be thought of as an extensive tool box with many components—some within the text of MARSSIM, others by reference.	*Tool Box*	Many topics are beyond the scope of MARSSIM. For example— • a public participation program • staging, classification, packaging, and transportation of wastes for disposal • remediation and stabilization techniques • training
Stakeholder Involvement	MARSSIM encourages stakeholder involvement but does not provide specific guidance.	*Stakeholder Involvement*	Specific guidance is determined by the individual Federal and State agencies.
Measurement	The information given in MARSSIM is performance-based and directed toward acquiring site-specific data and goals.	*Procedure*	The approaches suggested in MARSSIM vary depending on the various site data needs—there are no set procedures for sample collection, measurement techniques, storage, or disposal established in MARSSIM.
Modeling	The interface between environmental pathway modeling and MARSSIM is an important survey design consideration addressed in MARSSIM.	*Modeling*	Environmental pathway modeling and ecological endpoints in modeling are beyond the scope of MARSSIM.

Within Scope of MARSSIM		Beyond Scope of MARSSIM	
Soil and Buildings	The two main media of interest in MARSSIM are surface soil and building surfaces affected by residual radioactive material.	*Other Media*	MARSSIM does not cover other media, including construction materials, equipment, subsurface soil, surface or subsurface water, biota, air, sewers, or sediments.
Final Status Survey	The focus of MARSSIM is on the FSS, as this is the deciding factor in judging whether the site meets the restricted or unrestricted release criteria.	*Instruments and Radiation Detection Equipment*	MARSSIM does not recommend the use of any specific radiation detection equipment—there is too much variability in the types of radiation sites.
Radiation	MARSSIM considers only radiation-derived hazards.	*Chemicals*	MARSSIM does not consider any hazards posed by chemicals.
Remediation Method	MARSSIM assists users in determining when sites are ready for an FSS and provides information on how to determine if remediation was successful.	*Remediation Method*	MARSSIM does not discuss selection and evaluation of remediation alternatives, public involvement, legal considerations, and policy decisions related to planning.
Data Quality Objectives (DQO) Process	MARSSIM presents a systemized approach for designing surveys to collect data needed for making decisions, such as whether to release a site.	*DQO Process*	MARSSIM does not provide prescriptive or default DQOs.
Data Quality Assessment (DQA)	MARSSIM provides a set of statistical tests for evaluating data and lists alternate tests that may be applicable at specific sites.	*DQA*	MARSSIM does not prescribe a statistical test for use at all sites.
Radon Assessment	MARSSIM does address measurements of radon (concentration or flux) at sites with the immediate radon parents present because of previous site operations.	*Radon Assessment*	MARSSIM does not include measurements of radon in ambient air, air emissions, effluents, water, or indoor air at sites with none of the immediate radon parents present because of previous site operations.

MARSSIM also recognizes that there may be other factors that have an impact on designing surveys, such as cost or stakeholder concerns. Guidance on how to address these specific concerns is outside the scope of MARSSIM. Unique site-specific cases may arise that require a modified approach beyond what is presently described in MARSSIM. This includes examples such as—

- sites affected by naturally occurring radioactive material (NORM) or technically enhanced naturally occurring radioactive material (TENORM) in which the concentrations corresponding to the release criteria are close to the variability of the background
- sites where a reference background cannot be established

However, the process of planning, implementing, assessing, and making decisions about a site described in MARSSIM is applicable to all sites, even if the examples in this manual do not meet a site's specific objectives.

Of MARSSIM's many topics, the Data Quality Objective (DQO) approach to data acquisition and analysis and the Data Quality Assessment (DQA) for determining that data meet stated objectives are a consistent theme throughout the manual. The DQO process and DQA approach, described in **Chapter 2,** present a scientific, common-sense method for designing and conducting surveys and making best use of the obtainable information. A formal framework for systematizing the planning of data acquisition surveys can ensure that the information can support important decisions, such as whether to release a particular site following remediation.

DQOs must be developed on a site-specific basis. The approaches presented in MARSSIM may not meet the DQOs at every site, so other methods may be used to meet site-specific DQOs, as long as an equivalent level of performance can be demonstrated.

1.2 Structure of the Manual

Chapter 2 provides an overview of the Radiation Survey and Site Investigation (RSSI) process. **Figures 2.4 through 2.8** are flowcharts that summarize the steps taken and decisions made in the process. **Chapter 3** provides instructions for performing an HSA—a detailed investigation to collect existing information on the site or facility and to develop a conceptual site model. The results of the HSA are used to plan surveys, perform measurements, and collect additional information at the site. **Chapter 4** covers issues that arise in all types of surveys. Detailed information on performing specific types of surveys is included in **Chapter 5.** Information on selecting the appropriate measurement method combining instruments and measurement techniques is included in **Chapters 6 and 7. Chapter 6** discusses direct measurements and scanning surveys, and **Chapter 7** discusses sampling and sample preparation for laboratory measurements. The interpretation of survey results is described in **Chapter 8.**

MARSSIM also contains several appendices to provide additional information on specific topics. **Appendix A** presents an example of how to apply the MARSSIM process to a specific site through an FSS. **Appendix B** describes a simplified procedure for compliance demonstration that may be applicable at certain types of sites. **Appendix C** summarizes the regulations and requirements associated with radiation surveys and site investigations for each of the agencies involved in the development of MARSSIM. Detailed information on the EPA Quality System is in **Appendix D.** The ranked set sampling approach, a form of double sampling that can be useful for hard-to-detect radionuclides, is in **Appendix E. Appendix F** describes the relationships among MARSSIM; the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); and the Resource Conservation and Recovery Act (RCRA). Sources of information used during site assessment are listed in **Appendix G. Appendix H** describes field survey and laboratory analysis equipment that may be used for radiation surveys and site investigations. **Appendix I** offers tables of statistical data and supporting information for interpreting survey results described in Chapter 8. The derivation of the alpha scanning detection limit calculations used in **Chapter 6** is described in **Appendix J.** Comparison tables for QA documents are in **Appendix K. Appendix L** includes guidance for the use of stem and leaf displays and quantile plots. Instructions for the calculation of power curves are included in **Appendix M. Appendix N** includes three illustrative examples demonstrating the potential consequences of using methods with different levels of precision for planning and designing an FSS and for actually performing the FSS. **Appendix O** provides additional information about the Wilcoxon Rank Sum test (WRS) and Sign test and illustrates examples of the derived concentration guideline level (DCGL) determinations.

MARSSIM is presented in a modular format, with each module containing information on conducting specific aspects of, or activities related to, the survey process. Followed in order, each module leads to the generation and implementation of a complete survey plan. Although this approach may involve some overlap and redundancy in information, it also allows many users to concentrate only on those portions of the manual that apply to their own particular needs or responsibilities. The procedures within each module are listed in order, and options are provided to let the user skip portions of the manual that may not be applicable to a specific site. Where appropriate, checklists condense and summarize major points in the process. The checklists may be used to verify that every suggested step is followed or explain why a step was not needed.

MARSSIM contains a simplified procedure (see **Appendix B**) that many users of radioactive materials may be able to employ to demonstrate compliance with the release criteria—with the approval of the responsible regulatory agency. Sites that may qualify for simplified release procedures are those in which the radioactive materials used were—

- of relatively short half-life (e.g., $t_{1/2} \leq 120$ days) and have since decayed to insignificant quantities
- kept only in small enough quantities so as to be exempted or not requiring a specific license from a regulatory authority
- used or stored only in the form of non-leaking sealed sources
- combinations of the above

1.3 Use of the Manual

Potential users of this manual are Federal, State, and local government agencies with regulatory authority and control of residual radioactive material in the environment; their contractors; and other parties, such as organizations with licensed authority to possess and use radioactive materials. The manual is intended for a technical audience having knowledge of radiation health physics and statistics, as well as experience with the practical applications of radiation protection. An understanding of instrumentation and methodologies and expertise in planning, approving, and implementing surveys of environmental levels of radioactive material is assumed. This manual has been written so that individuals responsible for planning, approving, and implementing radiological surveys will be able to understand and apply the information provided here. Certain situations and sites may require consultation with personnel with specific types of expertise and experience.

MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

As previously stated, MARSSIM supports compliance with dose- or risk-based regulations. The translation of the regulatory dose limit to a corresponding concentration level is not addressed in MARSSIM, so the information in this manual is applicable to a broad range of regulations, including concentration-based regulations. The terms dose, risk, and dose-based and risk-based regulation are used throughout the manual, but these terms are not intended to limit the use of the manual.

> Note that Federal or State agencies that can approve a demonstration of compliance may support requirements that differ from what is presented in this version of MARSSIM. It is essential, therefore, that the persons carrying out the surveys remain in close communication with the proper Federal or State regulatory authorities throughout the compliance demonstration process.

1.4 Missions of the Federal Agencies Producing MARSSIM

MARSSIM is the product of a multi-agency workgroup with representatives from EPA, NRC, DOE, and DoD. This section briefly describes the missions of the participating agencies. Regulations and requirements governing site investigations for each of the agencies associated with radiation surveys and site investigations are presented in **Appendix C.**

1.4.1 U.S. Environmental Protection Agency

The mission of the EPA is to improve and preserve the quality of the environment, on both national and global levels. The EPA's scope of responsibility includes implementing and enforcing environmental laws, setting guidelines, monitoring pollution, performing research, and promoting pollution prevention. EPA Headquarters maintains overall planning, coordination, and control of EPA programs, and EPA's 10 regional offices are responsible for executing EPA's programs within the boundaries of each region. EPA also coordinates with State and local governments' pollution control activities and supports further research and development.

1.4.2 U.S. Nuclear Regulatory Commission

The mission of the NRC is to ensure adequate protection of public health and safety, the common defense and security, and the environment in the use of certain radioactive materials in the United States. The NRC's scope of responsibility includes regulation of commercial nuclear power reactors; nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste. The Energy Reorganization Act of 1974 and the Atomic Energy Act of 1954, as amended, provide the foundation for regulation of the Nation's commercial use of radioactive materials.

1.4.3 U.S. Department of Energy

The mission of the DOE is to develop and implement a coordinated national energy policy to ensure the availability of adequate energy supplies and to develop new energy sources for domestic and commercial use. In addition, DOE is responsible for the development, construction, and testing of nuclear weapons for the U.S. Military. DOE is also responsible for managing the low- and high-level radioactive wastes generated by past nuclear weapons and research programs and for constructing and maintaining a repository for civilian radioactive wastes generated by commercial nuclear reactors. DOE has the lead in remediating facilities and sites previously used in atomic energy programs.

1.4.4 U.S. Department of Defense

The global mission of the DoD is to provide for the defense of the United States. In doing this, DoD is committed to protecting the environment. Each military service has specific regulations addressing the use of radioactive sources and the development of occupational health programs and radiation protection programs. The documents describing these regulations are used as guidance in developing environmental radiological surveys within DoD and are discussed in **Appendix C.**

In accordance with section 91b of the Atomic Energy Act of 1954, as amended, DoD (including separate military services) has authority to acquire nuclear reactor systems and special nuclear materials. Additionally, DoD (including separate military services) is the lead federal agency for environmental remediation under several federal regulatory programs.

2 OVERVIEW OF THE RADIATION SURVEY AND SITE INVESTIGATION PROCESS

2.1 Introduction

The purpose of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) is to provide a standardized approach to demonstrating compliance with release criteria.[1] This chapter provides a brief overview of the Radiation Survey and Site Investigation (RSSI) process, several important aspects of this process, and its underlying principles. The purpose of this chapter is to provide the overview information required to understand the rest of this manual. The concepts introduced here are discussed in detail throughout the manual.

- **Section 2.2** introduces and defines key terms used throughout the manual. Some of these terms may be familiar to the MARSSIM user, while others are new terms developed specifically for this manual.
- **Section 2.3** describes the flow of information used to decide whether a site or facility complies with release criteria. The section describes the framework that is used to demonstrate compliance with the release criteria and is the basis for all information presented in this manual. The decision-making process is broken down into four phases: (1) planning, (2) implementation, (3) assessment, and (4) decision-making.
- **Section 2.4** introduces the RSSI process, which can be used for compliance demonstration at many sites. The section describes a series of surveys that form the core of this process. Each survey has specified goals and objectives to support a final decision on whether a site or facility complies with the appropriate criteria. Flow diagrams are provided showing how the different surveys support the overall process, along with descriptions of the information obtained through each type of survey.
- **Section 2.5** presents major considerations that relate to the decision-making and survey-design processes. This section, in addition to the examples discussed in detail throughout the manual, focuses on residual radioactive material in surface soils and on building surfaces. Recommended survey designs for demonstrating compliance are presented, along with the rationale for selecting these designs.
- **Section 2.6** recognizes that the methods presented in MARSSIM may not represent the most appropriate survey design at all sites. Some alternate methods for applying the RSSI process are discussed. Different methods for demonstrating compliance that are technically defensible may be developed with the approval of the responsible regulatory agency.

MARSSIM provides an approach that is technically defensible and flexible enough to be applied to a variety of site-specific conditions. Applying this approach to dose- or risk-based criteria

[1] MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

provides a consistent approach to protecting human health and the environment. The manual's performance-based approach to decision-making provides the flexibility needed to address compliance demonstration at individual sites.

2.2 Understanding Key MARSSIM Terminology and Survey Unit Classification

2.2.1 Key MARSSIM Terminology

The first step in understanding the RSSI process is accomplished by understanding this manual's scope, the terminology, and the concepts. Some terms were developed specifically for MARSSIM, for the purposes of this manual, while other commonly used terms were adopted. This section explains some of the terms roughly in the order of their presentation in the manual. The italicized terms in this section are all defined in the Glossary of this document.

The process described in MARSSIM begins with the premise that release criteria have already been provided in terms of a measurement quantity. The methods presented in MARSSIM are generally applicable and are not dependent on the value of the release criteria.

Release criteria are regulatory limits expressed in terms of dose (millisieverts/year or millirem/year) or risk (cancer morbidity or cancer mortality) or concentrations of radioactive material specified in regulations or standards. The terms "release limit" and "cleanup standard" are also used to describe this term. Release criteria that are typically based on dose (e.g., total effective dose [TED], committed effective dose [CED], total effective dose equivalent [TEDE], or committed effective dose equivalent [CEDE]) or risk (e.g., risk of cancer incidence [morbidity] or risk of cancer death [mortality]) generally cannot be measured directly.

Exposure pathway modeling is an analysis of various *exposure pathways* and scenarios used to convert dose or risk into concentration. Exposure pathway modeling is used to calculate a radionuclide-specific predicted concentration of radioactive material or surface area concentration of radioactive material of specific nuclides that could result in a dose or risk equal to the release criteria within the required performance period. In this manual, such a concentration is termed the *derived concentration guideline level (DCGL)*. In many cases, DCGLs can be derived from applicable requirements or regulatory agency guidance based on default modeling input parameters (e.g., screening-level analyses) if site conditions are consistent with the underlying assumptions in the default modeling or screening analyses; in other cases, it may be necessary to develop site-specific parameters. In general, the units for the DCGL are the same as the units for measurements performed to demonstrate compliance (e.g., becquerel/kilogram [Bq/kg] or picocurie/gram [pCi/g], becquerel/square meter [Bq/m^2] or decays per minute [dpm]/100 cm^2). This allows direct comparisons between the survey results and the DCGL. A discussion of the uncertainty associated with using DCGLs to demonstrate compliance is included in **Appendix D, Section D.1.6.**

An *investigation level* is a derived media-specific, radionuclide-specific concentration that, if exceeded, triggers some response, such as further investigation or remediation. An investigation level may be used early in the process to identify areas requiring further investigation; it may also be used as a screening tool during compliance demonstration to identify potential problem areas. A DCGL is an example of a specific investigation level that is based on the release criteria.

While the derivation of DCGLs is outside the scope of MARSSIM, it is important to understand the assumptions that underlie this derivation of DCGLs to ensure consistency with the statistical approach used to demonstrate compliance with regulatory criteria. For example, the estimated dose, and consequently the cleanup level or DCGL, may be sensitive to assumptions regarding the lateral extent (i.e., area) of residual radioactive material for relatively small exposure areas (e.g., areas that do not approximate an infinite source for external radiation exposure, or areas that would not support crop cultivation in quantities consistent with the assumed annual consumption rates of contaminated produce for the resident farmer scenario). Other important factors may include depth of residual radioactive material, chemical and physical form of the source, hydrogeological considerations, and potential exposure scenarios. For more information on environmental pathway modeling, check with your regulator’s guidance on the topic.

MARSSIM defines two potential DCGLs based on the area of residual radioactive material:

- Evenly distributed activity—If the residual radioactive material is evenly distributed over a large area, MARSSIM looks at the average or median concentration of radioactive material over the entire area. The $DCGL_W$[2] (the DCGL used when applying the Wilcoxon Rank Sum [WRS] or Sign tests; see **Section 2.5.1.2**) is derived based on assuming an average concentration over a wide area in the exposure pathway modeling.
- Small areas of elevated concentrations of radioactive material—If the residual radioactive material appears as small areas of elevated concentrations of radioactive material[3] within a larger area, MARSSIM also considers the results of individual measurements. The $DCGL_{EMC}$ (the DCGL used for the elevated measurement comparison [EMC], see **Section 2.5.1.1**) is derived separately for these small areas and generally from different exposure assumptions than those used for larger areas.

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, resuspension of particles for inhalation, and mixing from human disturbances. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Historically, this layer has often been represented as the top 15 cm (6 inches) of soil (40 CFR 192), but it will vary depending on radionuclide, surface characteristics, measurement method, and pathway modeling assumptions. For the purposes of MARSSIM, surface soil may be considered to include gravel fill, waste piles, concrete, or asphalt paving. Similarly, a *building surface* is defined as the thickness of building surface material that can be measured using direct measurement or scanning techniques and will also

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[2] The “W” in $DCGL_W$ historically stood for Wilcoxon Rank Sum test, which is the statistical test recommended in MARSSIM for demonstrating compliance when the radionuclide is present in background. However, as the Sign test is also a recommended test in MARSSIM for demonstrating compliance when the radionuclide is not present in background, the term now colloquially refers to “wide-area” or “average.”

[3] A small area of elevated concentration of radioactive material, or maximum point estimate of residual radioactive material, might also be referred to as a “hot spot.” This term has been purposefully omitted from MARSSIM because the term often has different meanings based on operational or local program concerns. As a result, there may be problems associated with defining the term and reeducating MARSSIM users in the proper use of the term.

vary depending on radionuclide, surface characteristics, measurement technique, and pathway modeling assumptions.

A *site* is any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof that is being considered for survey and investigation. *Area* is a very general term that refers to any portion of a site, up to and including the entire site.

Remediation includes those actions that are consistent with a permanent remedy taken instead of, or in addition to, removal action in the event of a release or threatened release of a hazardous substance into the environment, to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment.

Decommissioning is a term for the process of safely removing a site from service, reducing the concentration of residual radioactive material through remediation to a level that permits release of the property, and termination of the license or other authorization for site operation.

A *survey unit* is a physical area consisting of structures or land areas of specified size and shape at a site for which a separate decision will be made as to whether the unit meets the release criteria. (This decision is made as a result of the *final status survey [FSS]*—the survey in the RSSI process used to demonstrate compliance with release criteria.) Survey units are established to facilitate the survey process and the statistical analysis of survey data. The size and shape of the survey unit are based on such factors as the potential for residual radioactive material, the expected distribution of residual radioactive material, and any physical boundaries (e.g., buildings, fences, roads, soil type, and surface water body) at the site. Survey units are generally formed by grouping contiguous site areas with a similar use history and the same classification of potential for residual radioactive material.

Measurement in MARSSIM is used interchangeably to mean (1) the act of using a detector to determine the level or quantity of radioactive material on a surface or in a sample of material removed from a media being evaluated, or (2) the quantity obtained by the act of measuring.

Direct measurements are obtained by placing a detector near the surface or media being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly.

Scanning is a measurement technique performed by moving a portable radiation detector at a specified speed and distance next to a surface to detect radiation.

Sampling is the process of collecting a portion of an environmental medium as being representative of the locally remaining medium. The collected portion, or aliquot, of the medium is then analyzed to identify the radionuclide and determine the concentration. The word sample may also refer to a set of individual measurements drawn from a population whose properties are studied to gain information about the entire population. The latter is primarily used for statistical discussions.

The *graded approach* is defined as the process where the level of application of managerial controls for an item or work is determined according to the intended use of the results and the degree of confidence needed in the quality of the results. To make the best use of resources for decommissioning, MARSSIM places greater survey efforts on areas that have, or had, the highest potential for residual radioactive material. The FSS uses statistical tests to support decision-making. These statistical tests are performed using survey data from areas with common characteristics, such as potential for residual radioactive material, which are distinguishable from other areas with different characteristics.

Categorization is the act or result of separating an area or survey unit into one of two categories: impacted or non-impacted. Areas that have no reasonable potential for residual radioactive material are categorized as non-impacted areas. These areas have no radiological impact from site operations and are typically identified early in the cleanup process. Areas with some reasonable potential for residual radioactive material are categorized as impacted areas.

Classification is the process by which impacted areas or survey units are separated into *Class 1, Class 2, or Class 3 areas* according to radiological characteristics. Survey unit classification determines the FSS design and the procedures used to develop this design. Preliminary area classifications, made earlier in the MARSSIM process, are useful for planning subsequent surveys.

The *background reference area* is a geographical area from which representative reference measurements are performed for comparison with measurements performed in specific survey units. If the radionuclide of concern is present in the background, or if the measurement system used to determine concentration in the survey unit is not radionuclide-specific, background measurements are compared to the survey unit measurements to determine the concentration of residual radioactive material. The site radiological reference area is defined as an area that has similar physical, chemical, radiological, and biological characteristics as the survey unit(s) being investigated but has not been affected by site activities (i.e., non-impacted).

The *Data Life Cycle* is the process of planning the survey, implementing the survey plan, and assessing the survey results before making a decision. Survey planning uses the *Data Quality Objectives (DQO) Process,* which is a series of logical steps to create a plan for the resource-effective acquisition of environmental data, to ensure that the survey results are of sufficient quality and quantity to support the final decision. *Measurement Quality Objectives (MQOs)* are the specific analytical data requirements of the DQOs. *Quality assurance (QA)* is an integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer. *Quality control (QC)* is the overall system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer, operational techniques, and activities that are used to fulfill requirements for quality. QA/QC procedures are performed during implementation of the survey plan to collect information necessary to evaluate the survey results. *Data Quality Assessment (DQA)* is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use.

A systematic process and structure for quality should be established to provide confidence in the quality and quantity of data collected to support decision-making. The data used in decision-making should be supported by a planning document that records how quality assurance and quality control are applied to obtain the types and quality of results that are needed and expected. There are several terms used to describe a variety of planning documents, some of which document only a small part of the survey design process. MARSSIM uses the term *Quality Assurance Project Plan (QAPP)* to describe a written document outlining the procedures a monitoring project will use to ensure the data it collects and analyzes meets project requirements. This term conforms to consensus guidance ANSI/ASQC E4-1994 (ASQC 1995) and U.S. Environmental Protection Agency (EPA) guidance (EPA 2001b; EPA 2002a), and its use is recommended to promote consistency. The use of the term QAPP in MARSSIM does not exclude the use of other terms (e.g., Decommissioning Plan, Sampling and Analysis Plan, Field Sampling Plan) to describe survey documentation, provided that the information included in the documentation supports the objectives of the survey. The QAPP is a plan for obtaining data of sufficient quality and quantity to satisfy data needs; it describes policy, organization, and functional activities and includes DQOs and MQOs.

2.2.2 Classification Assessment

Impacted areas are divided into three classifications:

- *Class 1 Areas*: Areas that have, or had before remediation, a potential for residual radioactive material (based on site operating history) or known residual radioactive material (based on previous radiation surveys) above the $DCGL_W$. Examples of Class 1 areas include—
    - site areas previously subjected to remedial actions[4]
    - locations where leaks or spills are known to have occurred
    - former burial or disposal sites
    - waste storage sites
    - areas with residual radioactive material in discrete solid pieces of material and high specific activity
- *Class 2 Areas*: Areas that have, or had before remediation, a potential for residual radioactive material or known residual radioactive material but are not expected to exceed the $DCGL_W$. To justify changing an area's classification from Class 1 to Class 2, the existing data (from the Historical Site Assessment [HSA], scoping surveys, or characterization surveys) should provide a high degree of confidence that no individual measurement would exceed the $DCGL_W$. Other justifications for this change in an area's classification may be

[4] Remediated areas are identified as Class 1 areas because the remediation process often results in less than 100 percent removal of the radioactive material. The residual radioactive material that remains on the site after remediation is often associated with relatively small areas with elevated levels of radioactive material. This results in a non-uniform distribution of the radionuclide and a Class 1 classification. If an area is expected to have no potential to exceed the $DCGL_W$ and was remediated to demonstrate the residual radioactive material is as low as reasonably achievable, the remediated area might be classified as Class 2 for the final status survey.

appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 2 for the FSS include—

- locations where radioactive materials were present in an unsealed form (e.g., process facilities)
- residual radioactive material potentially along transport routes
- areas downwind from stack release points
- upper walls, roof support frameworks, and ceilings of some buildings or rooms subjected to airborne radioactive material
- areas where low concentrations of radioactive materials were handled
- areas on the perimeter of former buffer or radiological control areas

- *Class 3 Areas*: Any impacted areas that are not expected to contain any residual radioactive material or are expected to contain levels of residual radioactive material at a small fraction of the $DCGL_W$, based on site operating history and previous radiation surveys. To justify changing an area's classification from Class 1 or Class 2 to Class 3, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that there is either no residual radioactive material, or that any levels of residual radioactive material are a small fraction of the $DCGL_W$. Other justifications for this change in an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 3 include buffer zones around Class 1 or Class 2 areas, and areas with very low potential for residual radioactive material but insufficient information to justify a non-impacted classification.

Class 1 areas have the greatest potential for residual radioactive material and, therefore, receive the highest degree of survey effort for the FSS using a graded approach, followed by Class 2, and then by Class 3.

Survey units should be classified as Class 1 unless there is sufficient justification for classifying the survey as Class 2 or Class 3. Likewise, the classification of a survey unit should not be reduced without sufficient justification.

Non-impacted areas do not receive any level of survey coverage, because they have no reasonable potential for residual radioactive material. Non-impacted areas are determined on a site-specific basis from information collected during site identification, the HSA, and scoping and characterization surveys. Examples of areas that would be non-impacted rather than impacted usually include administrative, residential, or other buildings that have not contained radioactive materials except such devices as smoke detectors or exit signs with sealed radioactive sources.

2.3 Making Decisions Based on Survey Results

Compliance demonstration is simply a decision as to whether a survey unit meets the release criteria. For most sites, this decision is based on the results of one or more surveys. When survey results are used to support a decision, the decision maker[5] needs to ensure that the data will support that decision with satisfactory confidence. Uncertainty in the survey results is unavoidable, so the possibility of errors in decisions supported by the survey results is unavoidable. For this reason, actions must be taken to manage the uncertainty in the survey results so that sound and defensible decisions can be made. These actions include proper survey planning to control known causes of uncertainty, proper application of QC procedures during implementation of the survey plan to detect and control significant sources of error, and careful analysis of uncertainty before the data are used to support decision-making. These actions describe the flow of data throughout each type of survey and are combined in the Data Life Cycle, as shown in **Figure 2.1.**

There are four phases of the Data Life Cycle:

- *Planning Phase*: The survey design is developed and documented using the DQO process. QA/QC procedures are developed and documented in the QAPP. The QAPP is the principal product of the planning process, which incorporates the DQOs as it integrates all technical and quality aspects for the life cycle of the project, including planning, implementation, and assessment. The QAPP contains plans for survey operations and provides a specific format for obtaining the type and quality of data needed for decision-making. The QAPP elements are presented in the order of the Data Life Cycle and are grouped into two types of elements: (1) project management and (2) collection and evaluation of environmental data (ASQC 1995). The DQO process is described in **Appendix D** and applied in **Chapters 3, 4, and 5** of this manual. Development of the QAPP is described in **Appendix D** and applied throughout the RSSI process.

- *Implementation Phase*: The survey is carried out in accordance with the standard operating procedures (SOPs) and QAPP, and it generates raw data. **Chapters 6–7** and **Appendix H** provide information on the selection of data collection techniques. The QA and QC measurements, discussed in **Chapters 6–7,** also generate data and other important information that will be used during the Assessment Phase.

- *Assessment Phase:* The data generated during the Implementation Phase first are verified to ensure that the SOPs specified in the QAPP were followed and that the measurement systems performed in accordance with the criteria specified in the QAPP. Then the data are validated to ensure that the results of data collection activities support the objectives of the survey as documented in the QAPP or permit a determination that these objectives should be modified. The DQA process is then applied using the validated data to determine if the quantity and quality of the data satisfy their intended use. The DQA process is described in **Appendix D** and is applied in **Chapter 8.**

- *Decision-making Phase*: A decision is made, in coordination with the regulatory agency, based on the conclusions drawn from the assessment process. The ultimate objective is to make technically defensible decisions with a specified level of confidence (**Chapter 8**).

[5] The term decision maker is used throughout this section to describe the person, team, board, or committee responsible for the final decision regarding release of the survey unit.

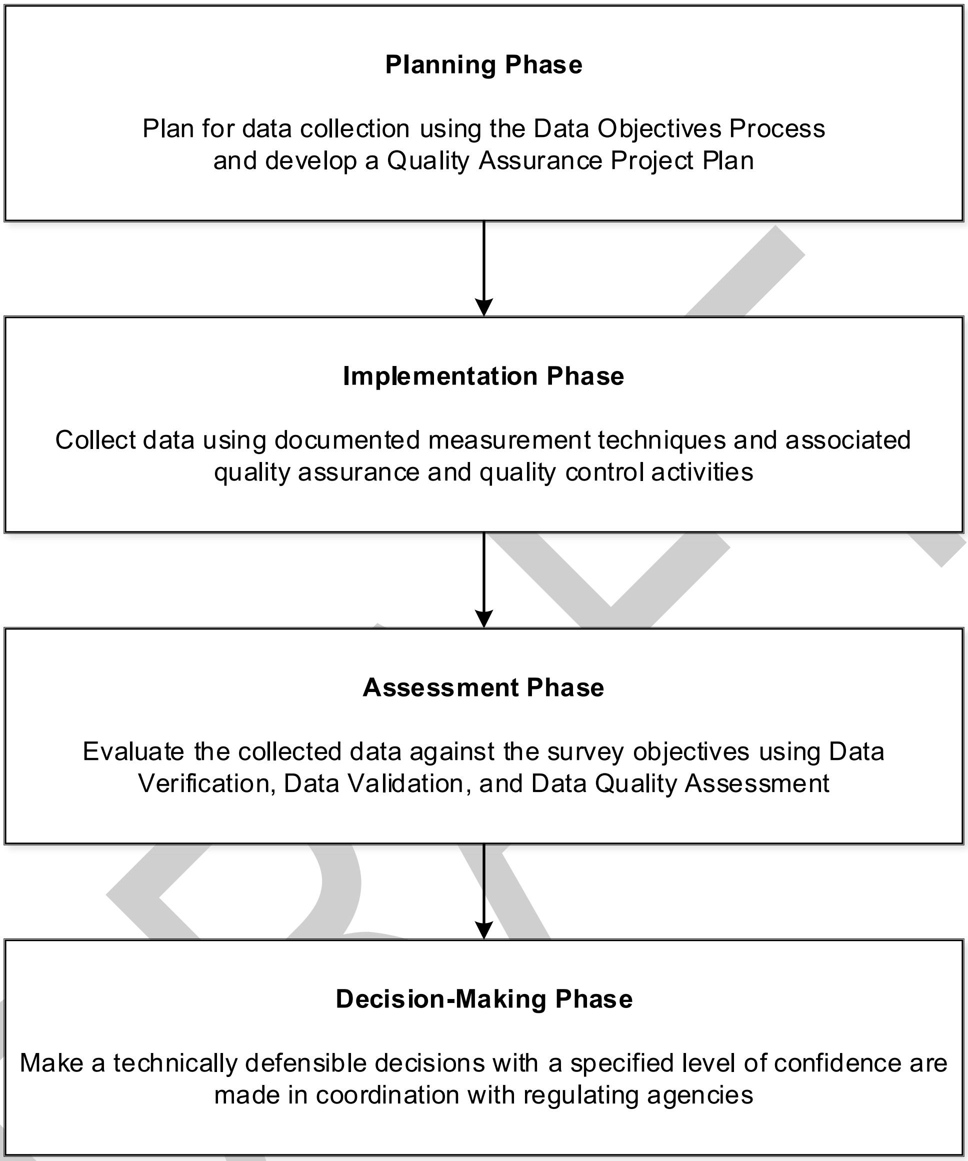


Figure 2.1: The Data Life Cycle

2.3.1 Planning Effective Surveys—Planning Phase

The first step in designing effective surveys is planning. The DQO process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (ASQC 1995, EPA 2006a, EPA 1987a, EPA 1987b). Planning radiation surveys using the DQO process improves the survey effectiveness and efficiency, and thereby the defensibility of decisions. Proper data collection planning minimizes expenditures by eliminating unnecessary, duplicative, or overly precise data. Using the DQO process ensures that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. MARSSIM supports the use of the DQO process to design surveys for input to both evaluation techniques (elevated measurement comparison and the statistical test). The DQO process provides systematic procedures for defining the criteria that the survey design should satisfy, including whether to perform scan-only surveys or scan surveys in conjunction with direct measurements/sampling, what type of measurements to perform, when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The level of effort associated with planning a survey is based on the complexity of the site. Large and complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning. In addition, the complexity of the survey depends not only on the size of the site or survey unit, but also on the physical and chemical characteristics of the site and the radioactive materials on the site. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

DQOs are qualitative and quantitative statements derived from the outputs of the DQO process that—

- clarify the study objective
- define the most appropriate type of data to collect
- determine the most appropriate conditions (e.g., environmental, legal, safety) for collecting the data
- specify limits on decision errors, which will be used as the basis for establishing the quantity and quality of data needed to support the decision

The DQO process consists of seven steps, as shown in **Figure 2.2.** Each step is discussed in detail in **Appendix D.** Although all of the outputs of the DQO process are important for designing efficient surveys, there are some that are referred to throughout the manual. These DQOs are mentioned briefly here and are discussed in detail throughout MARSSIM and in **Appendix D.**

The minimum information (outputs) required from the DQO process to proceed with the methods described in MARSSIM are—

- Classify and specify boundaries of survey units. This can be accomplished at any time but must be finalized during FSS planning (**Section 4.6, Section 4.9**).

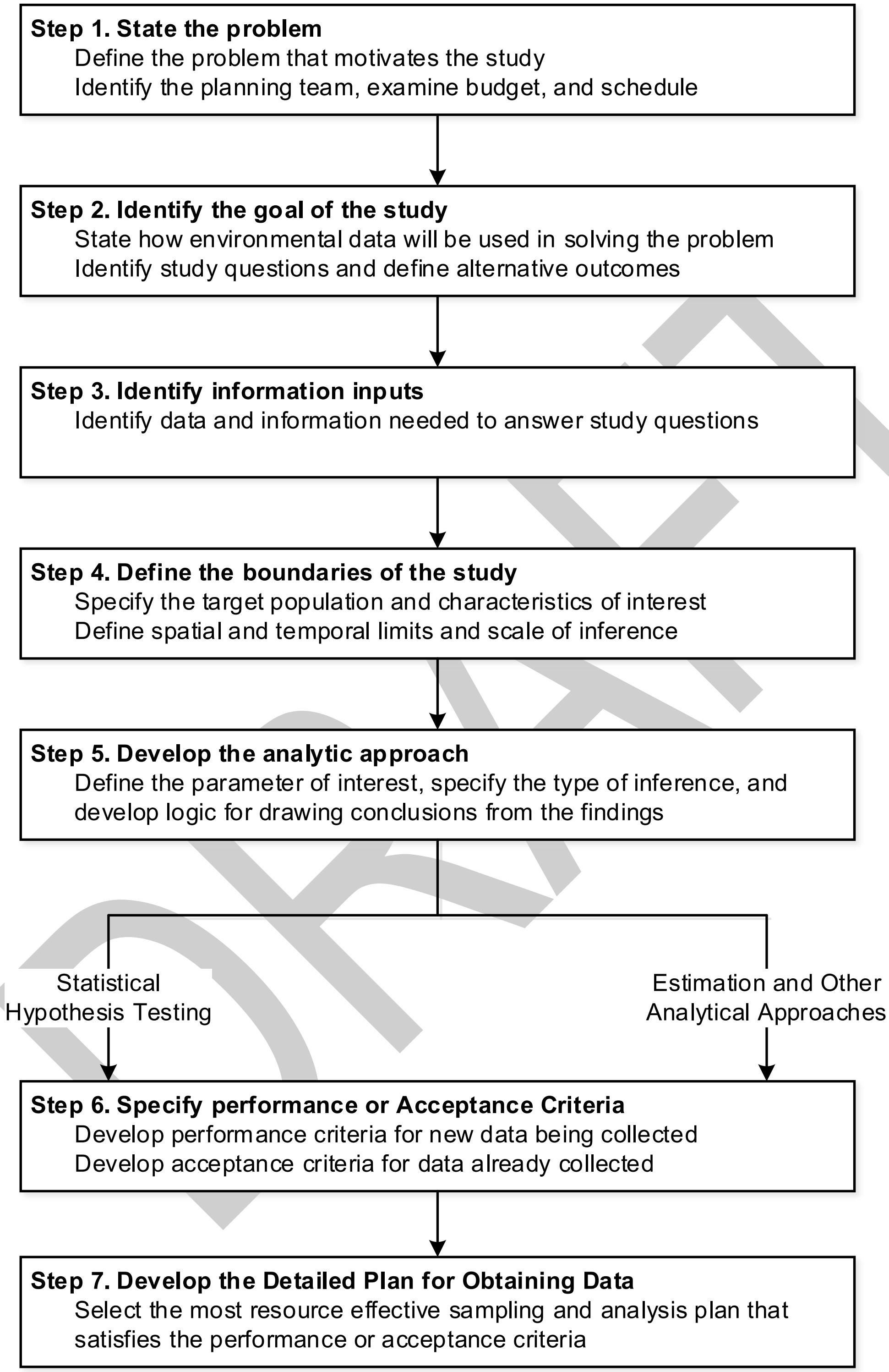


Figure 2.2: The Data Quality Objectives Process

- Determine if Scenario A or Scenario B will be used to evaluate the survey unit. Scenario A uses a null hypothesis that assumes the concentration of radioactive material in the survey unit exceeds the $DCGL_W$. Scenario A is sometimes referred to as “presumed not to comply” or “presumed not clean.” Scenario B uses a null hypothesis that assumes the level of concentration of radioactive material in the survey unit is less than or equal to the discrimination level. Scenario B is sometimes referred to as “indistinguishable from background” or “presumed clean” (**Section 5.3.1**).

- State the null hypothesis (H_0). For Scenario A, the concentration of residual radioactive material in the survey unit exceeds the release criteria (**Section 2.5, Appendix D, Section D.1.6**). For Scenario B, the residual radioactive material in the survey unit does not exceed the release criteria (**Section 2.5, Appendix D, Section D.1.6**).

- Specify a gray region where the consequences of decision errors are considered relatively minor. For Scenario A the upper bound of the gray region is defined as the $DCGL_W$, and the lower bound of the gray region (LBGR) is a site-specific variable generally chosen to be a conservative (slightly higher) estimate of the concentration of residual radioactive material remaining in the survey unit and adjusted to provide an acceptable value for the relative shift. For Scenario B the LBGR is the action level (AL), and the upper bound is defined by a discrimination limit (DL) that can be reliably distinguished from the AL (**Section 5.3.3.1, Section 5.3.4.1, Appendix D, Section D.1.7.3**).

- Define decision errors and assign their probability limits for the chosen Scenario (A or B). The probability of making a Type I decision error (α) or a Type II decision error (β) is a site-specific variable (**Section 5.3.2, Appendix D, Section D.1.6**).

- Estimate the standard deviation of the measurements in the survey unit. The standard deviation (σ) is a site-specific variable, typically estimated from preliminary survey data.

- Specify the relative shift (Δ/σ). The relative shift is equal to the width of the gray region (Δ)—which in Scenario A is equal to ($DCGL_W$ - LBGR) and for Scenario B is equal to (DL - AL)—divided by an estimate of the uncertainty (σ). The relative shift is generally designed to have a value greater than one (**Section 5.3.3.2, Section 5.3.4.2**).

- Select a survey strategy based on the measurement requirements and site classifications to include one of the following:

    - a combination of scanning and direct measurements or sample collection and analysis

    - scanning only, provided that the scanning measurement system meets the detection capability and uncertainty requirements of a scan-only survey design (**Section 5.3.6.1, Section 5.3.9**)

- For surveys utilizing the Sign or WRS test, calculate the estimated number of measurements (N) and specify the measurement locations required to demonstrate compliance. The number of measurements depends on the relative shift, Type I and Type II decision error rates, and the potential for small areas of elevated activity (**Sections 5.3.3 and 5.3.4**).

- Determine the percentage of scanning coverage for survey units based on the assigned classification of the survey unit and relative shift. Class 1 areas and survey units will have scan coverage of 100 percent, while the scan coverage of Class 2 and Class 3 areas and survey units will vary between 10 percent and 100 percent as a function of the relative shift (**Section 5.3.6**).

- Specify the documentation requirements for the survey, including survey planning documentation. Documentation supporting the decision on whether or not the site complies with the release criteria is determined on a site-specific basis (**Appendix D, Section D.2**).

- Specify the required MQOs for all measurement techniques (scanning, direct measurement, and sample analysis) specified in the QAPP. The MQOs are unique for each measurement system (**Sections 6.2–6.4**).

MQOs are an important subset of inputs into the DQO process that define performance requirements and objectives for the measurement system. MQOs that should be considered include the following:

- *Method uncertainty:* Method uncertainty is the sum of the random and systematic uncertainties in the measurement system. MARSSIM uses the term “measurement method uncertainty” to refer to the predicted uncertainty of a measured value that would be calculated if the method were applied to a hypothetical sample with a specified concentration, typically the release limit. Reasonable values for measurement method uncertainty can be predicted for a particular measurement technique based on typical values for specific parameters (e.g., count time, efficiency) and previous surveys of the areas being investigated. The MQO for the required measurement method uncertainty is calculated based on the width of the gray region and is related to the minimum detectable concentration (MDC).

- *Detection capability:* The MDC is recommended as the MQO for defining the detection capability of the measurement system, which is the net response level that can be expected to be seen using a detector with a fixed level of confidence. To account for cases where decisions are being made based on multiple measurements, the MDC should be less than 50 percent of the DCGL in Scenario A and the DL in Scenario B.

- *Range:* The method range is the lowest and highest concentration of an analyte that a method can accurately detect. The expected concentration range for a radionuclide of concern may be an important MQO. Most radiation measurement techniques are capable of measuring over a wide range of radionuclide concentrations. However, if the expected concentration range is large, the range should be identified as an important measurement method performance characteristic, and an MQO should be developed. The MQO for the acceptable range should be a conservative estimate. This will help prevent the selection of measurement techniques that cannot accommodate the actual concentration range.

- *Specificity:* Specificity is the ability of the measurement method to measure the radionuclide of concern in the presence of interferences. To determine if specificity is an important MQO, the planning team needs information on expected concentration ranges for the radionuclides of concern and other chemical and radionuclide constituents, along with chemical and physical attributes of the residual radioactive material being investigated.

- *Ruggedness:* For a project that involves field measurements that are performed in difficult or variable environments, or laboratory measurements that are complex in terms of chemical and physical characteristics, the measurement method's ruggedness may be an important MQO. Ruggedness refers to the relative stability of the measurement technique's performance when small variations in method parameter values are made. For field measurements, the changes may include temperature, humidity, or atmospheric pressure. For laboratory measurements, variability in sample conditions (e.g., pH) or laboratory conditions may be important. To determine if ruggedness is an important measurement method performance characteristic, the planning team needs detailed information on the chemical and physical characteristics of the soil or surfaces being investigated and operating parameters for the radiation instruments used by the measurement technique.

Precision, bias, representativeness and sensitivity, comparability, and completeness are the Data Quality Indicators (DQIs) recommended for quantifying the amount of error for survey data (EPA 2002a). These DQIs are discussed in detail in **Appendix D, Section D.1.6.**

2.3.2 Evaluating Sources of Variability in Survey Results—Implementation Phase

To encourage flexibility and the use of appropriate measurement techniques for a specific site, MARSSIM does not provide detailed recommendations on specific techniques to be used. Instead, MARSSIM encourages the decision maker to evaluate available techniques based on the survey DQOs and MQOs. Information on evaluating whether these objectives have been met, such as the required measurement method uncertainty and minimum detectable concentration, is provided.

QC programs can both lower the chances of making an incorrect decision and help the data user understand the level of uncertainty that surrounds the decision (EPA 2002a). As discussed previously, QC data are collected and analyzed during implementation to provide an estimate of the uncertainty associated with the survey results. QC measurements (scans, direct measurements, and samples) are technical activities performed to measure the attributes and performance of the survey. During any survey, a certain number of measurements should be taken for QC purposes.

2.3.3 Evaluating Survey Results—Assessment Phase

Assessments of environmental data are used to evaluate whether the data meet the objectives of the survey and are sufficient to determine compliance with the DCGL (EPA 1992a, EPA 1992b, EPA 2006a). The assessment phase of the Data Life Cycle consists of three phases: data verification, data validation, and DQA.

- Data verification is used to ensure that the requirements stated in the planning documents are implemented as prescribed (see **Appendix D.4.1**).

- Data validation is used to ensure that the results of the data collection activities support the objectives of the survey as documented in the QAPP or to permit a determination that these objectives should be modified (see **Appendix D.4.2**).

- DQA is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use (EPA 2006a). DQA helps complete the Data Life Cycle by providing the assessment needed to determine that the planning objectives are achieved (see **Section 8.2**). **Figure 2.3** illustrates where data verification, data validation, and DQA fit into the Assessment Phase of the Data Life Cycle.

There are five steps in the DQA process:

- review the DQOs and survey design
- conduct a preliminary data review
- select the statistical test(s)
- verify the assumptions of the statistical test(s)
- draw conclusions from the data

The strength of DQA is its design that progresses in a logical and efficient manner to promote an understanding of how well the data meet the intended use. The Assessment Phase is described in more detail in **Appendix D. Section 2.6** discusses the flexibility of the Data Life Cycle and describes the use of survey designs other than those described later in MARSSIM.

2.3.4 Uncertainty in Survey Results

Uncertainty in survey results arises primarily from two sources—survey design errors and measurement errors:

- Survey design errors occur when the survey design is unable to capture the complete extent of variability that exists for the radionuclide distribution in a survey unit. Because it is impossible in every situation to measure the concentration of residual radioactive material at every point in space and time, the survey results will be incomplete to some degree. It is also impossible to know with complete certainty the concentration of residual radioactive material at locations that were not measured, so the incomplete survey results give rise to uncertainty. The greater the natural or inherent variation in residual radioactive material, the greater the uncertainty associated with a decision based on the survey results. The unanswered question is, “How well do the survey results represent the true level of residual radioactive material in the survey unit?”

- Measurement errors create uncertainty by masking the true level of residual radioactive material and may be classified as random or systematic errors. Random errors affect the precision of the measurement system and show up as variations among repeated measurements. Systematic errors show up as measurements that are biased to give results that are consistently higher or lower than the true value. Measurement uncertainty is discussed in **Section 6.4.**

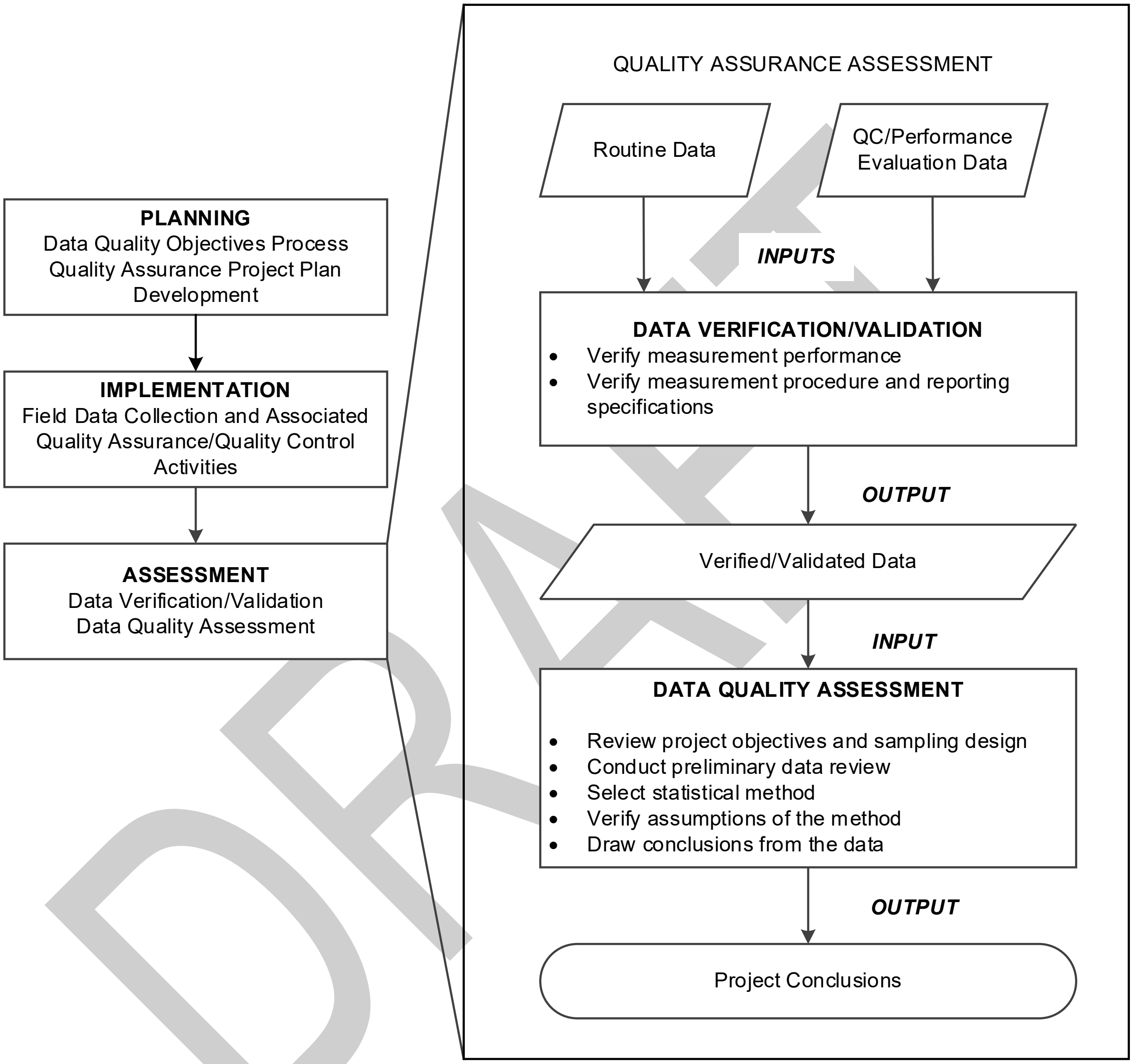


Figure 2.3: The Assessment Phase of the Data Life Cycle (EPA 2006a)

MARSSIM uses the Data Life Cycle to control and estimate the uncertainty in the survey results on which decisions are made. Adequate planning should minimize known sources of uncertainty. QC data collected during implementation of the survey plan provide an estimate of the uncertainty. Statistical hypothesis testing or comparison to an upper confidence limit during the assessment phase provides a level of confidence for the final decision. There are several levels of decisions included within each survey type. Some decisions are quantitative, based on the numerical results of measurements performed during the survey. Other decisions are qualitative based on the available evidence and best professional judgment. The Data Life Cycle can and should be applied consistently to both types of decisions.

2.3.5 Reporting Survey Results

The process of reporting survey results is an important consideration in planning the survey. Again, the level of effort for reporting should be based on the complexity of the survey. A simple survey with relatively few results may require a single report, while a more complicated survey may require several reports to meet the objectives of the survey. Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP. These requirements should be developed with cooperation from the people performing the analyses (e.g., the analytical laboratory should be consulted on reporting results for samples). The Health Physics Society and Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP) have provided several suggestions for reporting survey results (EPA 1980a, NRC 2004):

- Report the actual result of the analysis. Do not report data as "less than the detection limit." Even negative results and results with large uncertainties can be used in the statistical tests to demonstrate compliance. Results reported only as "< MDC" cannot be fully used and, for example, complicate even such simple analyses as an average. Although the nonparametric tests described in **Sections 8.3–8.4** and the upper confidence limit comparison described in **Section 8.5** can accommodate situations where up to 40 percent of the results as non-detects, it is better to report the actual results.

- Report results using the correct units and the correct number of significant digits. The choice of reporting results using International System units (e.g., Bq/kg, Bq/m^2) or conventional units (e.g., pCi/g, dpm/100 cm^2) is made on a site-specific basis. Generally, MARSSIM recommends that all results be reported in the same units as the DCGLs. Sometimes the results may be more convenient to work with as counts directly from the detector. In these cases, the user should decide what the appropriate units are for a specific survey based on the survey objectives. MARLAP suggests that the uncertainty and MDC should be reported to two significant figures, while environmental radiation measurements seldom warrant more than two or three significant figures.

- Report the measurement uncertainty for every analytical result or series of results, such as for a measurement system. This uncertainty, while not directly used for demonstrating compliance with the release criteria, is used for survey planning and data assessment throughout the RSSI process. In addition, the uncertainty is used for evaluating the performance of measurement systems using QC measurement results (as described in **Section 6.2** for scans and direct measurements, and in **Section 7.2** for laboratory analysis of samples). The uncertainty is also used for comparing individual measurements to the action level, which is especially important in the early stages of the RSSI process (scoping, characterization, and remedial action support surveys described in **Section 2.4**) when decisions are made based on a limited number of measurements. **Section 6.4** discusses methods for calculating the measurement uncertainty.

- Report the MDC for the measurement system as well as the method used to calculate the MDC. The MDC is an a priori estimate of the capability for detecting an activity concentration with a specific measurement system (EPA 1980a). As such, this estimate is valuable for planning and designing radiation surveys. Optimistic estimates of the MDC (calculated using ideal conditions that may not apply to actual measurements) overestimate the ability of a technique to detect residual radioactive material, especially when scanning for alpha or low-energy beta radiations. This can invalidate survey results, especially for scanning surveys. Using a more realistic MDC during scoping and characterization surveys, as described in **Section 6.3,** helps in the proper classification of survey units for FSSs and minimizes the possibility of designing and performing subsequent surveys because of errors in classification. Estimates of the MDC that minimize potential decision errors should be used for planning surveys.

Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP.

2.4 Radiation Survey and Site Investigation Process

The Data Life Cycle discussed in **Section 2.3** is the basis for the performance-based approach in MARSSIM. The RSSI process is a series of surveys designed to demonstrate compliance with dose- or risk-based criteria for sites with residual radioactive material. The size, complexity, and amount of existing information on the site will determine how many of the surveys in the series will be necessary.

There are six principal steps in the RSSI process:

- site identification
- HSA
- scoping survey
- characterization survey
- remedial action support survey
- FSS

Table 2.1 provides a simplified overview of the principal steps in the RSSI process and how the Data Life Cycle can be used in an iterative fashion within the process. Each of these steps is briefly described in the **Sections 2.4.1–2.4.6** and described in more detail in **Chapter 5.** In addition, there is a brief description of regulatory agency confirmation and verification (**Section 2.4.7**). Because MARSSIM focuses on demonstrating compliance with release criteria, specifically by using an FSS, some of these surveys have additional objectives that are not fully discussed in MARSSIM (e.g., health and safety of workers, supporting selection of values for exposure pathway model parameters).

Figure 2.4 illustrates the RSSI process in terms of area classification and lists the major decision to be made for each type of survey. The flowchart demonstrates one method for quickly estimating the survey unit classification early in the MARSSIM process based on limited information. This figure is a useful tool for visualizing the classification process, but there are site-specific characteristics that may cause variation from this scheme. This illustration is not designed to comprehensively consider every possibility that may occur at individual survey units.

The flowcharts in **Figures 2.5–2.8** present the principal steps and decisions in the site investigation process and shows the relationship of the survey types to the overall assessment process. As shown in these figures, there are several sequential steps in the site investigation process and each step builds on information provided by its predecessor. Properly applying each sequential step in the RSSI process should provide a high degree of assurance that the release criteria have not been exceeded.

2.4.1 Site Identification

Often, sites where radioactive material is known or suspected to have been used or stored are readily identified before decommissioning or cleanup. Any facility preparing to terminate an NRC or agreement state license would be identified as a site. Formerly terminated NRC licenses may also become sites for the EPA Superfund Program. Portions of military bases or U.S. Department of Energy facilities may be identified as sites based on records of authorization to possess or handle radioactive materials. Where records are incomplete, site identification can be more difficult. In addition, information obtained during the performance of survey activities may identify additional potential radiation sites related to the site being investigated. More detailed information on site identification is provided in **Section 3.4.**

2.4.2 Historical Site Assessment

The primary purpose of the HSA is to collect existing information concerning the site and its surroundings.

The primary objectives of the HSA are to—

- Identify potential sources of residual radioactive material.
- Determine whether sites pose an imminent threat to human health and the environment.
- Differentiate impacted from non-impacted areas.
- Provide input to scoping and characterization survey designs.
- Provide an assessment of the likelihood of migration of radioactive material.
- Identify additional potential sites containing radioactive material related to the site being investigated.

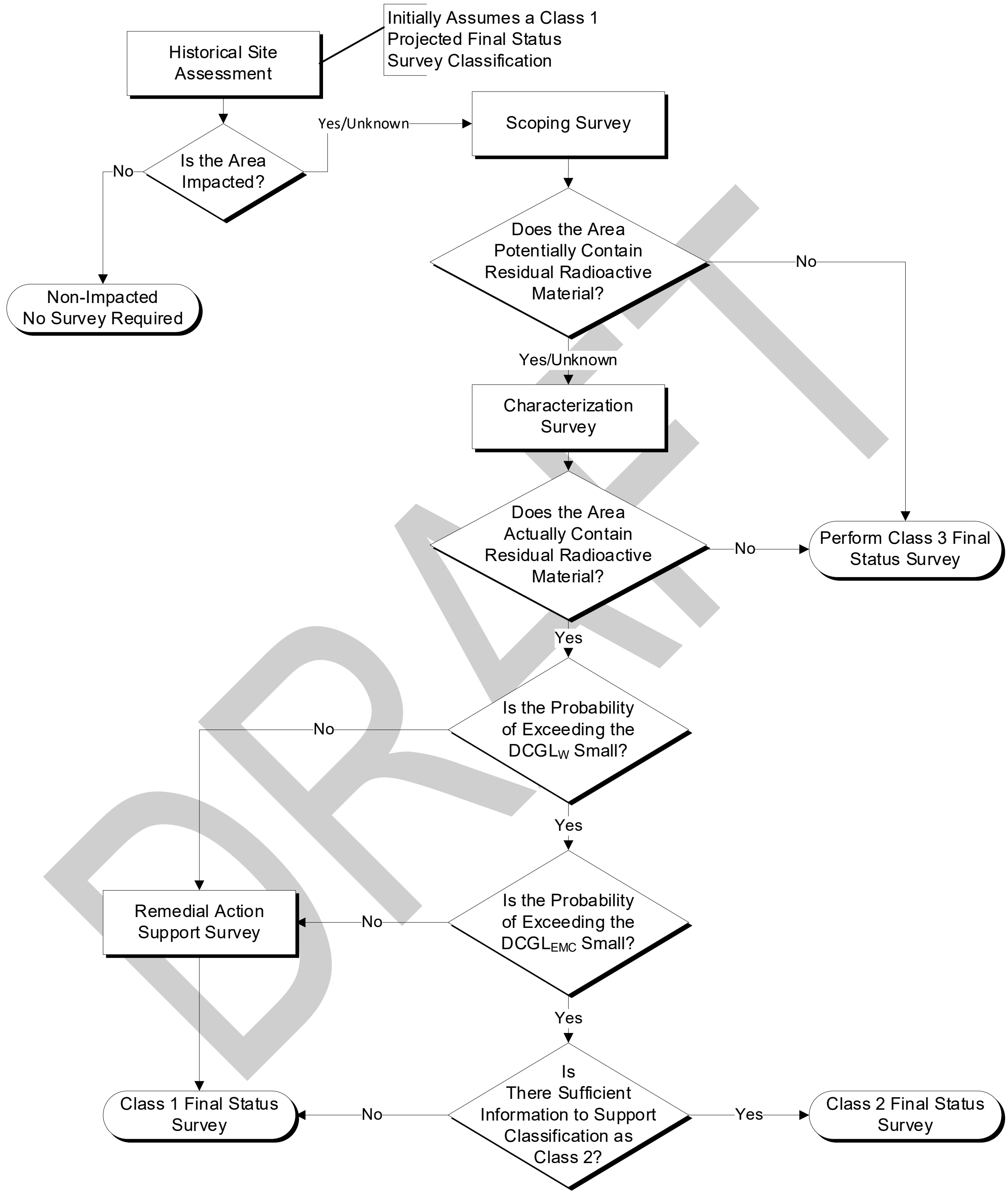
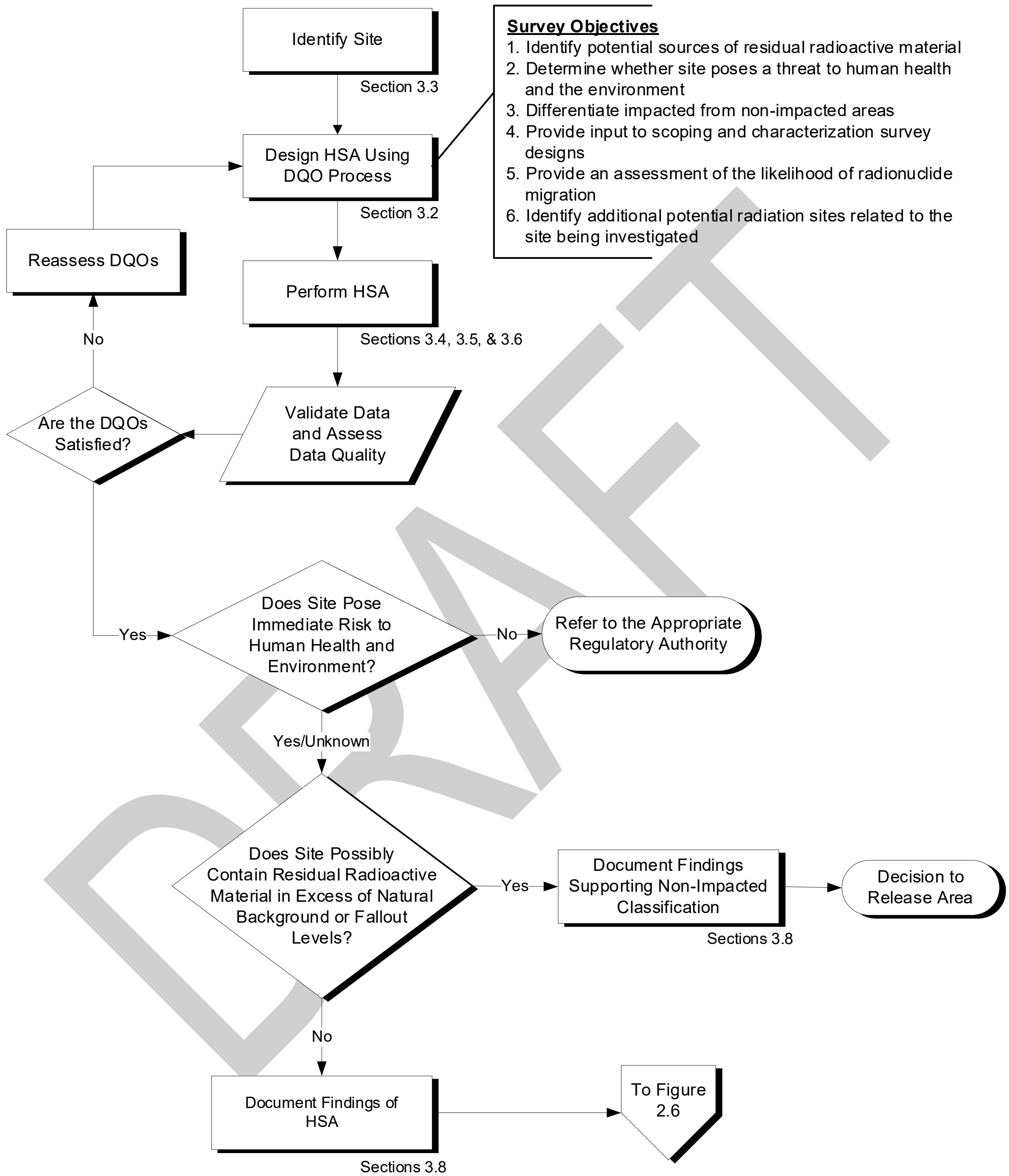


Figure 2.4: Radiation Survey and Site Investigation Process in Terms of Area Classification



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2 **Figure 2.5: The Historical Site Assessment Portion of the Radiation Survey and Site**
3 **Investigation Process**

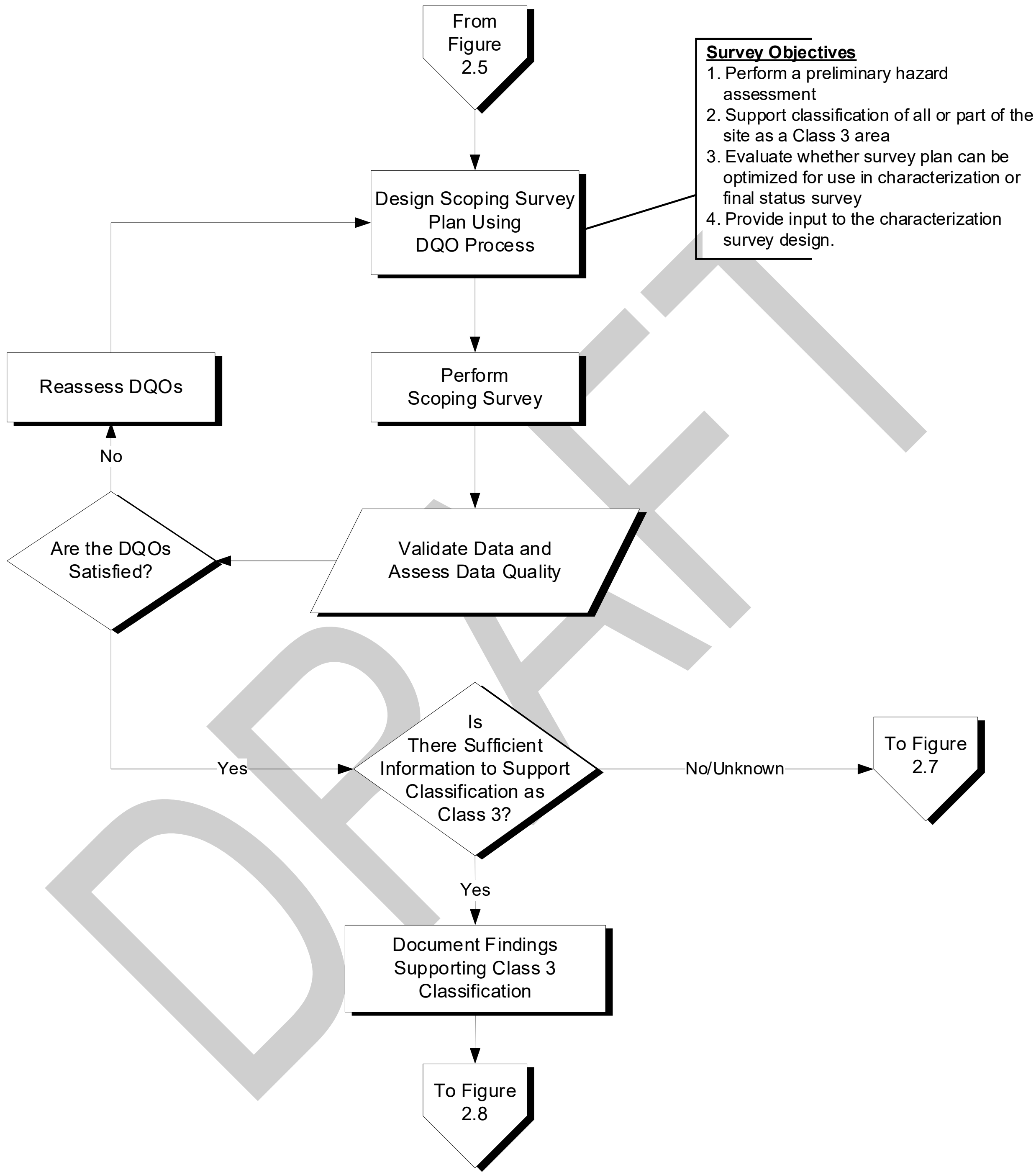
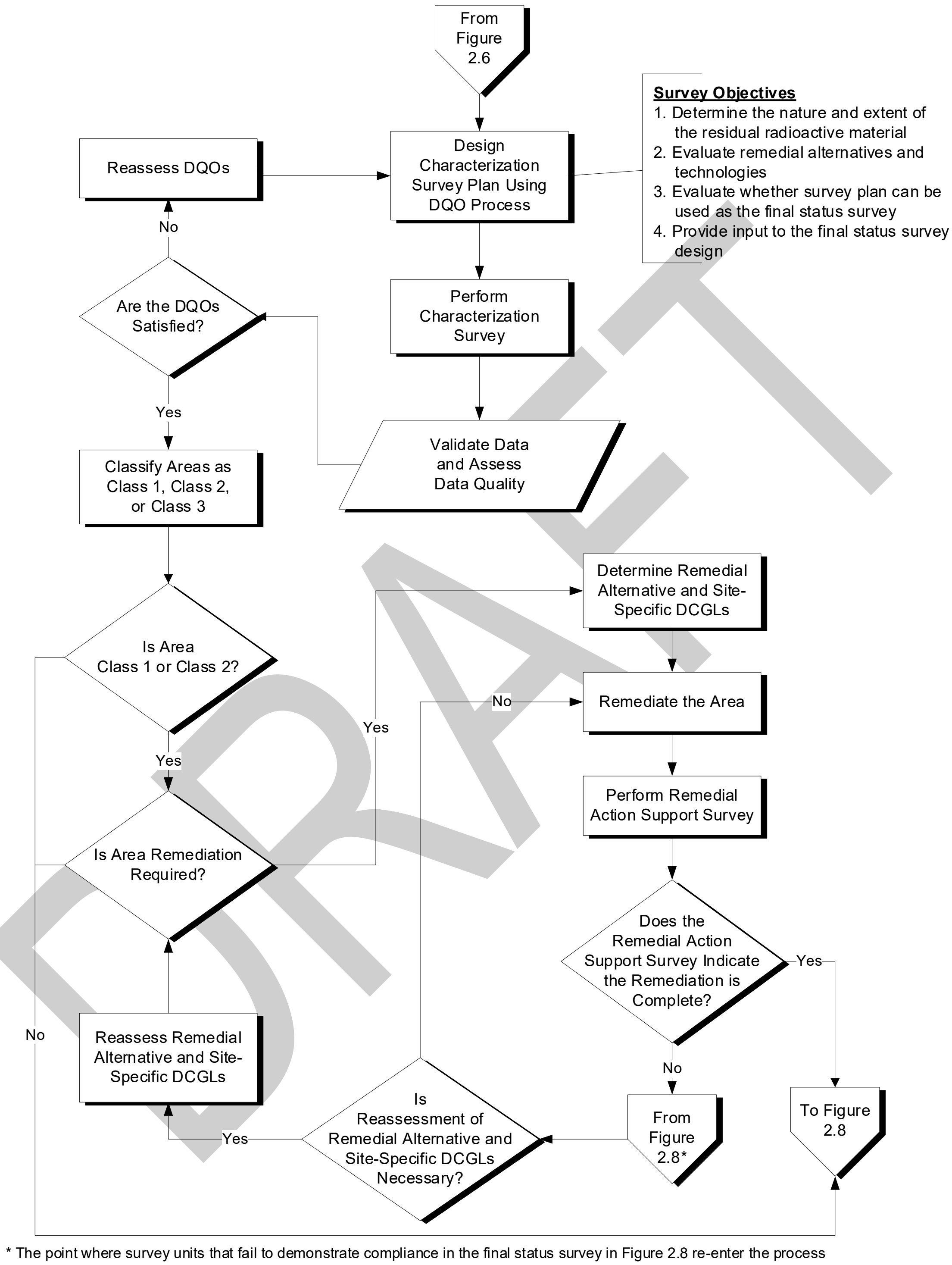


Figure 2.6: The Scoping Survey Portion of the Radiation Survey and Site Investigation Process



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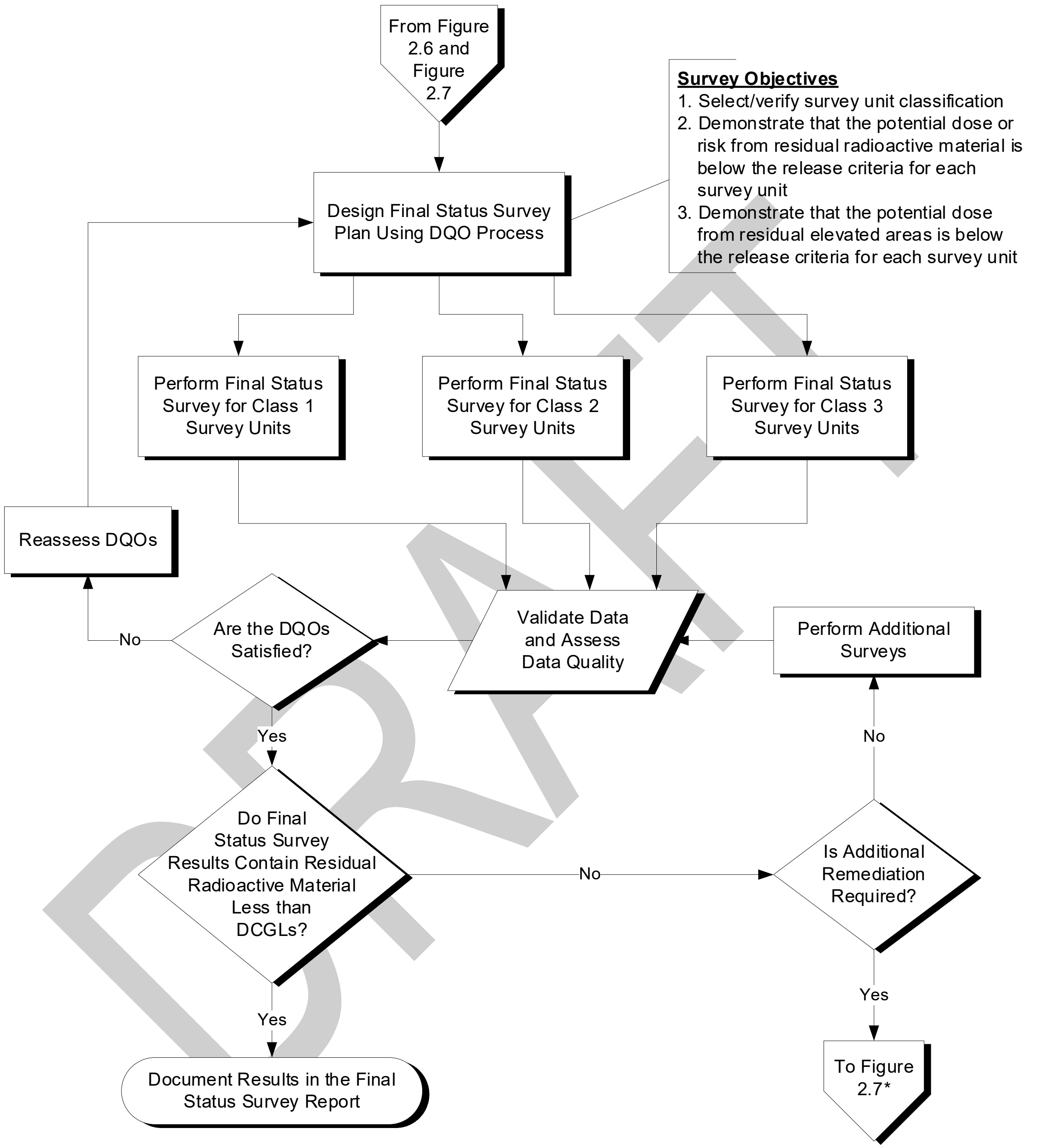
2 **Figure 2.7: The Characterization and Remedial Action Support Survey Portion of the**
3 **Radiation Survey and Site Investigation Process**



* Connects with the Remedial Action Support Survey portion of the process in Figure 2.7

Figure 2.8: The Final Status Survey Portion of the Radiation Survey and Site Investigation Process

The HSA typically consists of three phases: identification of a candidate site, preliminary investigation of the facility or site, and site visits or inspections. Information collected during the HSA is then used to evaluate the site.

2.4.3 Scoping Survey

If the data collected during the HSA indicate that an area is impacted, a scoping survey may be performed. Scoping surveys provide site-specific information based on limited measurements.

The primary objectives of a scoping survey are to—

- Perform a preliminary hazard assessment.
- Support classification of all or part of the site as a Class 3 area, if appropriate.
- Evaluate whether the survey plan can be optimized for use in the characterization survey or FSS.
- Provide data to complete the site prioritization scoring process (Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA] and Resource Conservation and Recovery Act [RCRA] sites only).
- Provide input to the characterization survey design, if necessary.

Table 2.1 provides an overview of how the Data Life Cycle (Plan, Implement, Assess, and Decide) can be used to support each of the steps in the RSSI process up through the FSS.

Table 2.1: The Data Life Cycle[6] used to Support the Radiation Survey and Site Investigation Process

RSSI Process	Data Life Cycle	MARSSIM Methodology
Site Identification	—	Provides information on identifying potential radiation sites (**Section 3.3**)
Historical Site Assessment	Historical Site Assessment Data Life Cycle	Provides information on collecting and assessing existing site data (**Sections 3.4–3.9**) and potential sources of information (**Appendix F**)
Scoping Survey	Scoping Data Life Cycle	Discusses the purpose and general approach for performing scoping surveys, especially as sources of information when planning final status surveys (**Section 5.2.1**)

[6] The steps of the Data Life Cycle can be found in **Figure 2.1.** The DQO process for each of the steps can be found in **Figure 2.2.**

RSSI Process	Data Life Cycle	MARSSIM Methodology
Characterization Survey	Characterization Data Life Cycle	Discusses the purpose and general approach for performing characterization surveys, especially as sources of information when planning final status surveys (**Section 5.2.2**)
Remedial Action Support Survey	Remedial Action Data Life Cycle	Discusses the purpose and general approach for performing remedial action support surveys, especially as sources of information when planning final status surveys (**Section 5.2.3**)
Final Status Survey	Final Status Data Life Cycle	Provides detailed information for planning final status surveys (**Chapter 4, Section 5.3**), selecting measurement techniques (**Chapter 6, Chapter 7, Appendix H**), and assessing the data collected during final status surveys (**Chapter 8, Appendix D**)

Scoping surveys can be conducted after the HSA is completed and typically consist of judgment measurements based on the HSA data. If the results of the HSA indicate that an area is Class 3 and no residual radioactive material is found during a scoping survey, the area may be classified as Class 3, and a Class 3 FSS is performed. If the scoping survey locates residual radioactive material, the area may be considered as Class 1 (or Class 2) for the FSS, and a characterization survey is typically performed. Sufficient information should be collected to identify situations that require immediate radiological attention. For sites where the CERCLA requirements are applicable, the scoping survey should collect sufficient data to complete the Hazard Ranking System (HRS) scoring process. For sites where the RCRA requirements are applicable, the scoping survey should collect sufficient data to complete the National Corrective Action Prioritization System (NCAPS) scoring process. Sites that meet the National Contingency Plan (NCP) criteria for a removal should be referred to the Superfund removal program (EPA 1996c). A comparison of the MARSSIM approach to CERCLA and RCRA requirements is provided in **Appendix F.**

2.4.4 Characterization Survey

If the results of the HSA and scoping survey indicate that an area could be classified as Class 1 or Class 2 for the FSS, a characterization survey may be warranted. The characterization survey is planned based on the HSA and scoping survey results. This type of survey typically is a detailed radiological environmental characterization of the area.

The primary objectives of a characterization survey are as follow:

- Determine the nature and extent of the residual radioactive material.
- Collect data to support evaluation of remedial alternatives and technologies.

- Support a hazard assessment of the potential dose and risk to workers or the public during remediation.
- Evaluate whether the survey plan can be optimized for use in the FSS.
- Support remedial investigation/feasibility study requirements (CERCLA sites only) or facility investigation/corrective measures study requirements (RCRA sites only).
- Provide input to the FSS design.

The characterization survey can be the most comprehensive of all the survey types and typically generates the most data. This can include preparing a reference grid, taking systematic or judgment measurements, and performing surveys of different media (e.g., surface soils, interior and exterior surfaces of buildings). The decision as to which media will be surveyed is site-specific and will be addressed throughout the RSSI process.

2.4.5 Remedial Action Support Survey

If an area is adequately characterized and has concentrations of residual radioactive material above the DCGLs, a remediation plan should be prepared. A remedial action support survey is performed while remediation is being conducted and guides the remediation in a real-time mode.

Remedial action support surveys are conducted to—

- support remediation activities
- determine when a site or survey unit is ready for the FSS
- provide updated estimates of site-specific parameters used for planning the FSS

This manual does not provide information on the routine operational surveys used to support remediation activities. The determination that a survey unit is ready for an FSS following remediation is an important step in the RSSI process. In addition, remedial activities result in changes to the distribution of residual radioactive material within the survey unit. For most survey units, the site-specific parameters used during FSS planning (e.g., variability in the radionuclide concentration, probability of small areas of elevated activity) will need to be re-established following remediation. Obtaining updated values for these critical parameters should be considered when planning a remedial action support survey.

2.4.6 Final Status Survey

The FSS is used to demonstrate compliance with release criteria. This type of survey is the major focus of this manual.

The primary objectives of the FSS are as follow:

- Verify that survey unit classification is correct.

- Demonstrate that the total potential dose or risk from all residual radioactive material in each survey unit is below the release criteria.

- Demonstrate that the potential dose or risk from any small areas of elevated concentration of radioactive material is below the release criteria for each survey unit, if necessary.

The FSS provides data to demonstrate that all radiological parameters satisfy the established guideline values and conditions. Data from other surveys conducted during the RSSI process—such as scoping, characterization, and remedial action support surveys—can provide valuable information for planning an FSS, provided they are of sufficient quality.

Professional judgment in sampling is often used for locating and characterizing the extent of residual radioactive material at a site. However, the MARSSIM focus is on planning the FSS, which utilizes a more systematic approach to sampling. Systematic sampling is based on rules that endeavor to achieve the representativeness in sampling consistent with the application of statistical tests.

2.4.7 Regulatory Agency Confirmation and Verification Survey

The regulatory agency responsible for the site often confirms whether the site may be released. Terms for this process can include confirmatory surveys or independent verification. This confirmation may be accomplished by the agency or an impartial party either as an ongoing activity during site remediation or after remediation and the FSS has been completed. Although some actual measurements may be performed, much of the work required for confirmation and verification will involve evaluation and review of documentation and data from survey activities, though the evaluation may include site visits to observe survey and measurement procedures or split-sample analyses by the regulatory agency's laboratory. Therefore, accounting for confirmation and verification activities during the planning stages is important to each type of survey. In some cases, post-remedial sampling and analysis may be performed by an impartial party. The review of survey results should include verifying that the DQOs and MQOs are met, reviewing the analytical data used to demonstrate compliance, and verifying that the statistical test results support the decision to release the site.

2.5 Demonstrating Compliance with Dose- or Risk-Based Criteria

MARSSIM presents a process for demonstrating compliance with dose- or risk-based criteria. The RSSI process provides flexibility in planning and performing surveys based on site-specific considerations. Dose- or risk-based criteria usually allow one to account for radionuclide and site-specific differences.

The FSS is designed to demonstrate compliance with the release criteria. The earlier surveys in the RSSI process are performed to support decisions and assumptions used in the design of the FSS. These preliminary surveys (e.g., scoping, characterization) may have other objectives in addition to compliance demonstration that need to be considered during survey planning that are not fully discussed in this manual. For this reason, MARSSIM focuses on FSS design. To allow maximum flexibility in the survey design, MARSSIM provides information on designing a survey using the RSSI process. This allows users with few resources available for planning to develop an acceptable survey design. The rationale for the development of the information in

MARSSIM is presented in the following sections. Users with available planning resources are encouraged to investigate alternate survey designs for site-specific applications using the information provided in **Section 2.6.**

2.5.1 The Decision to Use Statistical Tests

The objective of compliance demonstration is to provide an acceptable level of confidence that the release criteria are not exceeded. As previously stated, 100 percent confidence in a decision cannot be proven because the data always contain some uncertainty. The use of statistical methods is necessary to provide a quantitative estimate of the probability that average concentration of radioactive material at a particular site results in a dose or risk above the release criteria. Statistical methods provide for specifying (controlling) the probability of making decision errors and for extrapolating from a set of measurements to the entire site in a scientifically valid fashion (EPA 1994a).

Clearly stating the null hypothesis is necessary before statistical hypothesis testing can be performed. MARSSIM provides the option to establish the null hypothesis under either Scenario A or Scenario B. The Scenario A null hypothesis in MARSSIM is the concentration of residual radioactive material in the survey unit exceeds the release criteria. This statement directly addresses the issue of compliance demonstration for the regulator and places the burden of proof for demonstrating compliance on the site owner or responsible party. The Scenario B null hypothesis in MARSSIM is the concentration of residual radioactive material in the survey unit does not exceed the release criteria. This statement also addresses the issue of compliance demonstration for the regulator; however, it places the burden of proof for demonstrating a lack of compliance on the regulator.

In Scenario B, the burden of proof is no longer on the individuals designing the survey and thus should be used with caution and only in those situations where Scenario A is not an effective alternative and regulators have agreed on the use of Scenario B. Regardless of the scenario selected, the probability of rejecting the null hypothesis (i.e., the statistical power) will depend on the variability in the survey unit and the tolerable Type II error probability (i.e., β). Under Scenario A, this type of decision error can result in deciding that a survey unit does not meet the release criteria when it actually does. However, under Scenario B, this type of decision error can result in deciding that a survey unit does meet the release criteria when it actually does not. For this reason, the value of β under Scenario B should be chosen carefully and in consultation with regulatory authorities.

Because inadequate statistical power under Scenario B can result in a decision error that a survey meets release criteria when it does not, individuals designing a MARSSIM Survey using Scenario B should make conservative assumptions for σ so that, even if the variability in the survey unit is higher than expected, the power of the resulting survey (1-β) will still be sufficient to ensure that survey units with residual radioactive material in excess of the DCGL will be discovered at least 1-β percent of the time. To ensure adequate statistical power, a retrospective power analysis that indicates that regulatory agency requirements on β were met needs to be completed following the completion of Scenario B MARSSIM Surveys. See **Chapter 8** and **Appendix I** for more information on performing retrospective power analyses.

The information needed to perform a statistical test is determined by the assumptions used to develop the test. MARSSIM recommends the use of nonparametric statistical tests because these tests use fewer assumptions and, consequently, require less information to verify these assumptions. If a large number of measurements will be made (scan-only surveys), then MARSSIM recommends comparison to an upper confidence limit. If the radionuclide is not part of the natural background and radionuclide-specific measurements will be made, MARSSIM recommends the Sign test. If the radionuclide is part of the natural background, or radionuclide-specific measurements will not be made, MARSSIM recommends the WRS test. For Scenario B, MARSSIM also recommends the quantile test and a retrospective power analysis. These additional tests provide assurance that when the null hypothesis is not rejected, it is not because there is insufficient power in the statistical tests. The retrospective power analysis can also be useful for Scenario A in identifying the reasons why the null hypothesis was not rejected. The tests described in MARSSIM (see **Chapter 8**) are relatively easy to understand and implement. Ranked set sampling (see **Appendix E**) is another method for performing statistical testing of samples and can be useful for hard-to-detect radionuclides. For the reasons described above, Scenario A is preferred to Scenario B. Scenario B should be used instead of Scenario A only when there is sufficient justification for its use.

Site conditions can potentially affect the validity of statistical tests. The distribution of residual radioactive material is particularly of concern. Is the residual radioactive material distributed uniformly, or is it located in small areas? Is the residual radioactive material present in the surface soil or on building surfaces, or does it extend into the subsurface? MARSSIM addresses only surface soil and building surfaces for the FSS to demonstrate compliance. This represents a situation that is expected to commonly occur at sites with residual radioactive material, and it allows the survey design to account for the ability to directly measure surface radioactivity using scanning techniques. Radioactive material in other media may be identified during the HSA or preliminary surveys (i.e., scoping, characterization, remedial action support). If radioactive material in other media (e.g., subsurface soils or building materials) is identified, methodologies for demonstrating compliance other than those described in this manual may need to be developed or evaluated. Situations where scanning techniques may not be effective (e.g., volumetric or subsurface radioactive material) are discussed in existing guidance (EPA 1989a, EPA 1994a, EPA 2001a).

2.5.1.1 Small Areas of Elevated Activity

While the development of DCGLs is outside the scope of MARSSIM, this manual assumes that DCGLs will be developed using exposure pathway models that assume a relatively uniform distribution of radioactive material. While this represents an ideal situation, small areas of elevated activity are a concern at many sites.

MARSSIM addresses the concern for small areas of elevated activity by using a simple comparison to an investigation level as an alternative to statistical methods. Using the EMC is a conservative approach, because additional investigation is required unless every measurement is below the investigation level. For Class 1 survey units, the investigation level for this comparison is called the $DCGL_{EMC}$. The $DCGL_{EMC}$ can be higher than the $DCGL_{W}$ due to the lower dose or risk resulting from a smaller area of radioactive material. In the case of multiple areas of elevated activity in a survey unit, a posting plot (discussed in **Section 8.2.2.2**) or similar representation of the distribution of activity in the survey unit can be used to determine any pattern in the location of these areas.

If elevated levels of residual radioactive material are found in an isolated area in addition to residual radioactive material distributed relatively uniformly across the survey unit, the unity rule (**Section 4.4**) can be used to ensure that the total dose or risk meets the release criteria. If there is more than one of these areas, a separate term should be included in the calculation for each area of elevated activity. As an alternative to the unity rule, the dose or risk from the actual distribution of residual radioactive material can be calculated if there is an appropriate exposure pathway model available. Note that these considerations generally only apply to Class 1 survey units, since areas of elevated activity should not be present in Class 2 or Class 3 survey units.

2.5.1.2 Relatively Uniform Distribution of Residual Radioactive Material

As discussed previously, the development of a DCGL starts with the assumption of a relatively uniform distribution of residual radioactive material. Some variability in the measurements is expected. This is primarily due to a random spatial distribution of residual radioactive material and uncertainties in the measurement process.

With a scan-only survey, the upper confidence limit (UCL) for the mean derived from the arithmetic mean, the variance, and the number of the measurements would represent the parameter of interest for demonstrating compliance. Survey units where a large number of measurements are taken (scan-only surveys) can utilize this technique. Instructions on generating a UCL from scan-only survey data are provided in **Section 8.5.**

When statistical sampling is performed, whether the radionuclide of concern is present in background helps determine the form of the statistical test. The WRS test is recommended for comparisons of survey unit radionuclide concentrations with background. When the radionuclide of concern is not present in background, the Sign test is recommended. Instructions on performing these tests are provided in **Section 8.3** and **Section 8.4.**

The WRS and Sign tests are designed to determine whether the level of residual activity uniformly distributed throughout the survey unit exceeds the $DCGL_W$. Because these methods are based on ranks or number of measurements below the DCGL, the statistical tests are tests of the median. When the underlying measurement distribution is symmetric, the mean is equal to the median. When the underlying distribution is asymmetric, these tests are still true tests of the median but only approximate tests of the mean. However, numerous studies show that this is a fair approximation (Hardin and Gilbert, 1993). The assumption of symmetry is less restrictive than that of normality, because the normal distribution is itself symmetric. If, however, the measurement distribution is skewed to the right, the mean will generally be greater than the median. In severe cases, the mean may exceed the $DCGL_W$ while the median does not. For this reason, MARSSIM recommends comparing the arithmetic mean of the survey unit data to the $DCGL_W$ as a first step in the interpretation of the data (see **Section 8.2.2.1**). A mean survey unit concentration less than the $DCGL_W$ is a necessary, but not sufficient, condition for a survey unit to meet the release criteria.

The WRS test compares the distribution of a set of measurements in a survey unit to that of a set of measurements in a reference area. In scenario A, the test is performed by first adding the value of the $DCGL_W$ to each measurement in the reference area. The combined set of survey unit data and adjusted reference area data are listed, or ranked, in increasing numerical order. If the ranks of the adjusted reference site measurements are significantly higher than the ranks of the survey unit measurements, the survey unit demonstrates compliance with the release criteria.

The quantile test is a statistical test to account for non-uniform distributions of radioactive material. The quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey unit. The quantile test is only performed when Scenario B is used, and only if the null hypothesis is not rejected for the WRS test. Using the quantile test and the WRS test in tandem results in higher statistical power to identify survey units that do not meet the release criteria than either test by itself.

The Sign test compares the distribution of a set of measurements in a survey unit to a fixed value, namely the $DCGL_W$. First, the value for each measurement in the survey unit is subtracted from the $DCGL_W$. The resulting distribution is tested to determine if the center of the distribution is greater than zero. If the adjusted distribution is significantly greater than zero, the survey unit demonstrates compliance with the release criteria.

Information on performing the statistical tests and presenting graphical representations of the data are provided in **Chapter 8** and **Appendix I.**

2.5.2 Categorization and Classification

Categorizing and classifying a survey unit determine the level of survey effort based on the potential for residual radioactive material. Areas are initially categorized as impacted or non-impacted based on the results of the HSA. Non-impacted areas have no reasonable potential for residual radioactive material and require no further evidence to demonstrate compliance with the release criteria, although documentation of the decision to categorize an area as non-impacted would still be needed. When planning the FSS, impacted areas may be further classified into survey units. If a survey unit is given a less restrictive classification than is warranted, the potential for making decision errors increases. For this reason, all impacted areas are initially assumed to be Class 1. Class 1 areas require the highest level of survey effort because they are known to have concentrations of residual radioactive material above the $DCGL_W$, or the residual radioactive material concentrations are unknown.

Information indicating the potential or known residual radioactive material concentration is less than the $DCGL_W$ can be used to support re-classification of an area or survey unit as Class 2 or Class 3.

There is a certain amount of information necessary to demonstrate compliance with the release criteria. The amount of this information that is available and the level of confidence in this information are reflected in the area classification. The initial assumption for affected areas is that none of the necessary information is available. This results in a default Class 1 classification.

Not all of the information available for an area will have been collected for purposes of compliance demonstration. For example, data are collected during characterization surveys to determine the extent, and not necessarily the amount, of residual radioactive material. This does not mean that the data do not meet the objectives of compliance demonstration, but it may mean that statistical tests would be of little or no value because the data have not been collected using appropriate protocols or design. Rather than discard potentially valuable information, MARSSIM allows for a qualitative assessment of existing data (**Chapter 3**). Non-impacted areas represent areas where all of the information necessary to demonstrate compliance is available from existing sources. For these areas, no statistical tests are considered necessary. A classification as Class 2 or Class 3 indicates that some information on describing the potential for residual radioactive material is available for that survey unit. The data collection recommendations are modified to account for the information already available, and the statistical tests are performed on the data collected during the FSS. The HSA (described in **Chapter 3**) is used to provide an initial categorization for the area of impacted or non-impacted based on existing data and professional judgment.

2.5.3 Design Considerations for Small Areas of Elevated Activity

Scanning surveys are typically used to identify small areas of elevated activity. The size of the area of elevated activity that the survey is designed to detect affects the $DCGL_{EMC}$, which in turn determines the ability of a scanning technique to detect these areas. Larger areas have a lower $DCGL_{EMC}$ and are more difficult to detect than smaller areas. Ranked set sampling (RSS), as described in **Appendix E,** provides an alternative approach for identifying small areas of hard-to-detect radionuclides through a combination of field measurements and samples to identify small areas.

The percentage of the survey unit to be covered by scans is also an important consideration. One-hundred percent coverage means that the entire surface area of the survey unit has been covered by the field of view of the scanning instrument. One-hundred percent scanning coverage provides a high level of confidence that all areas with elevated concentrations of radioactive material have been identified. One-hundred percent coverage is recommended for all Class 1 survey units. If the available information concerning the survey unit provides information demonstrating that areas of elevated concentrations of radioactive material may not be present, the survey unit may be classified as Class 2 or Class 3. Because there is already some level of confidence that areas of elevated activity are not present, 100 percent coverage may not be necessary to demonstrate compliance. **Section 5.3.6** provides information on determining the scan area for Class 2 and 3 areas. For Class 2 areas, the scan area will be based on the width of the gray region and the uncertainty, typically somewhere between 10–100 percent of the area, with a combination of systematic scanning and scanning in areas judged to have the highest potential for residual radioactive material. For Class 3 areas, the scan area is the same as Class 2 survey units, except for surveys where samples and/or direct measurements are collected, in which case the scan area can be less than 10 percent and is typically only in areas judged to have the highest potential for residual radioactive material. A general recommendation when deciding which areas to scan is to always err in the direction that minimizes the decision error. In general, scanning the entire survey unit is less expensive than finding areas of elevated concentrations of radioactive material later in the survey process.

Finding such areas will lead to performing additional surveys due to survey unit misclassification.

Another consideration for scanning surveys is the selection of scanning locations. This is not an issue when 100 percent of the survey unit is scanned. Whenever less than 100 percent of the survey unit is scanned, a decision must be made on what areas should be scanned. The general recommendation is that when large amounts of the survey unit are scanned (e.g., less than 50%), the scans should be systematically performed along transects of the survey unit. When smaller amounts of the survey unit are scanned, selecting areas based on professional judgment may be more appropriate and efficient for locating areas of elevated activity (e.g., drains, ducts, piping, ditches, floor joints, sumps). A combination of 100 percent scanning in portions of the survey unit based on professional judgment and less coverage (e.g., 20–50 percent) for all remaining areas may result in an efficient scanning survey design for some survey units.

2.5.4 Design Considerations for Relatively Uniform Distributions of Residual Radioactive Material

The survey design for areas with relatively uniform distributions of residual radioactive material is primarily controlled by classification and the requirements of the statistical test. Again, the recommendations provided for Class 1 survey units are designed to minimize the decision error. Recommendations for Class 2 or Class 3 surveys may be based on existing information if the level of confidence associated with this information is sufficient.

The first consideration is the identification of survey units. The identification of survey units may be accomplished early (e.g., scoping) or late (e.g., final status) in the survey process but must be accomplished before performing an FSS. Early identification of survey units can help in planning and performing surveys throughout the RSSI process. Late identification of survey units can prevent misconceptions and problems associated with reclassification of areas based on results of subsequent surveys. The area of an individual survey unit is determined based on the area classification and modeling assumptions used to develop the $DCGL_W$. Identification of survey units is discussed in **Section 4.6.**

When performing surveys for which the Sign or WRS test is used, another consideration is the estimated number of measurements to demonstrate compliance using the statistical tests. **Sections 5.3.3–5.3.4** describe the calculations used to estimate the number of measurements. These calculations use information that is usually available from planning or from preliminary surveys (i.e., scoping, characterization, remedial action support).

The information needed to perform these calculations is—

- acceptable values for the probabilities of making Type I or Type II decision errors
- the estimates of the measurement variability in the survey unit (σ_s) and the reference area (σ_r) if necessary
- Δ, or the shift

MARSSIM recommends that site-specific values be determined for each of these parameters. When selecting site-specific values for decision error rates and Δ, MARSSIM recommends that an initial value be selected and adjusted to develop a survey design that is appropriate for a specific site. For Scenario A, the $DCGL_W$ is chosen as the upper bound of the gray region, and the lower bound of the gray region is typically chosen to represent a conservative (slightly higher) estimate of the concentration of residual radioactive material remaining in the survey unit at the beginning of the FSS. For Scenario B, the AL is chosen as the lower bound of the gray region and the upper bound is the DL, a value that represents how much effort will be taken to determine there is no residual radioactive material. For decision error rates, a value that minimizes the risk of making a decision error is recommended for the initial calculations. The number of measurements can be recalculated using different values for the LBGR, DL, or decision error rates until an appropriate survey design is obtained.[7] A prospective power curve (see **Appendix M**) that considers the effects of these parameters can be very helpful in designing a survey and considering alternative values for these parameters and is highly recommended.

To ensure that the desired power is achieved with the statistical test and to account for underestimated values of the measurement variability, MARSSIM recommends that the estimated number of measurements calculated using the formulas in **Sections 5.3.3–5.3.4** be increased by 20 percent to account for a reasonable amount of uncertainty in the parameters used to calculate and still allow flexibility to account or some lost or unusable data. Insufficient numbers of measurements may result in failure to achieve the DQO for power and result in increased Type II decision errors, where survey units below the release criteria fail to demonstrate compliance in Scenario A. Of more concern to the regulator, Type II decision errors for Scenario B lead to the incorrect release of survey units with average or median concentrations above the release criteria.

Once survey units are identified and the number of measurements is determined, measurement locations should be selected. The statistical tests assume that the measurements are taken from random locations within the survey unit. A systematic grid with a random starting point is used for Class 1 and Class 2 survey units. A systematic grid with a random starting point or a random survey design is used for Class 3 survey units.

2.5.5 Developing an Integrated Survey Design

To account for assumptions used to develop the $DCGL_W$ and the realistic possibility of small areas of elevated activity, if required, an integrated survey design should be developed to include all the design considerations. An integrated survey design combines a scanning survey for areas of elevated activity with random measurements for relatively uniform distributions of radioactive material. **Table 2.2** presents the recommended conditions for demonstrating compliance for an FSS based on classification.

[7] Note that for some areas, an appropriate survey design may not be possible within initial survey design constraints, such as the requirements on α and survey power ($1-\beta$), available funds, and estimated values for the average and variability of the concentration of residual radioactive material remaining at the site. In these cases, the planning team will have to reconsider the survey design constraints or their decision to conduct a final status survey, in consultation with their regulator.

Table 2.2: Recommended Conditions for Demonstrating Compliance Based on Survey Unit Classification for a Final Status Survey

Survey Unit Classification		Statistical Test(s)[a]	Elevated Measurement Comparison	Sampling and Direct Measurements[b]	Scanning
Impacted	Class 1	Yes	Yes	Systematic	100% Coverage
	Class 2	Yes	Yes	Systematic	10–100% Systematic/ Judgmental
	Class 3	Yes	Yes	Random or Systematic	10–100%[c] Systematic/ Judgmental
Non-Impacted		No	No	No	None

[a] Statistical tests may consist of the Sign test, Wilcoxon Rank Sum test, quantile test, or comparison to an upper confidence limit, depending on the survey design chosen.
[b] For scan-only surveys, omit the sampling and direct measurements.
[c] For surveys utilizing sampling and/or direct measurements, this percentage can be lower than 10% judgmental.

Random-start systematic grids are used for Class 1 and Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision maker to draw conclusions about the size of any potential areas of elevated activity based on the area between measurement locations, while the random starting point of the grid provides an unbiased method for determining measurement locations for the statistical tests. The random start numbers should be furnished by an unbiased source to ensure that the survey results are similarly unbiased.

Random measurement patterns are used for Class 3 survey units to ensure that the measurements are independent and meet the requirements of the statistical tests.

Scan-only surveys can be used in place of direct measurements and/or sampling and analysis if the scanning measurement system has an MDC that is less than 50 percent of the $DCGL_W$ and meets requirements for measurement method uncertainty. When scanning is used alongside sampling and/or direct measurements, it is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and receive additional investigations to determine the concentration, area, and extent of the residual radioactive material. For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity that are not detected by the measurements using the systematic grids. For this reason, the measurement locations and the number of measurements may need to be adjusted based on the sensitivity of the scanning technique (see **Section 5.3.5**). This is also the reason for recommending 100 percent coverage for the scanning survey.

Scanning surveys in Class 2 areas are also performed primarily to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the measurement locations are not adjusted based on sensitivity of the scanning technique, and scanning is only performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity. In Class 2 survey units that have concentrations of residual radioactive material closer to the release criteria or a higher variability across the survey unit, a larger portion of the survey unit would be scanned; for survey units that are closer to background or have a lower variability, scanning a smaller portion of the survey unit may be appropriate. Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgmental scanning surveys would focus on the portions of the survey unit with the highest probability for areas of elevated activity. If the entire survey unit has an equal probability for areas of elevated activity, or the judgmental scans do not cover at least 10 percent of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 areas have the lowest potential for areas of elevated activity. For scan-only surveys, the scan area and methodology are the same as for Class 2, but for surveys that contain both statistical sampling and scanning, scanning surveys should be performed in areas of highest potential (e.g., corners, ditches, and drains) based on professional judgment. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area.

2.6 Flexibility in Applying MARSSIM Approach

Section 2.5 describes an example that applies the performance-based approach presented in **Sections 2.3–2.4** to design a survey for a site with residual radioactive material in surface soils and/or building surfaces. Obviously, this design cannot be uniformly applied at every site with residual radioactive material, so flexibility has been provided in the form of a performance-based approach. This approach encourages the user to develop a site-specific survey design to account for site-specific characteristics. It is expected that most users will adopt the portions of the MARSSIM methodology that apply to their site. In addition, changes to the overall survey design that account for site-specific differences would be presented as part of the survey plan. The plan should also demonstrate that the extrapolation from measurements performed at specific locations to the entire site or survey unit is performed in a technically defensible manner.

Where **Section 2.5** describes the development of a generic survey design that will be applicable at most radiation sites, this section describes the flexibility available within the MARSSIM for designing a site-specific survey design. Alternate methods for accomplishing the demonstration of compliance are briefly described, and references for obtaining additional information on these alternate methods are provided.

2.6.1 Alternate Statistical Methods

MARSSIM encourages the use of statistics to provide a quantitative estimate of the probability that the release criteria are not exceeded at a site. While it is unlikely that any site will be able to demonstrate compliance with dose- or risk-based criteria without at least considering the use of statistics, MARSSIM recognizes that the use of statistical tests may not always provide the most effective method for demonstrating compliance. For example, MARSSIM recommends a simple comparison to an investigation level to evaluate the presence of small areas of elevated activity in place of complicated statistical tests.

MARSSIM recommends the use of nonparametric statistical tests for evaluating environmental data. There are two reasons for this recommendation: (1) Environmental data are usually not normally distributed, and (2) there are often a significant number of qualitative survey results (e.g., less than MDC). Either one of these conditions means that parametric statistical tests may not be appropriate. If one can demonstrate that the data are normally distributed and that there are sufficient results to support a decision concerning the survey unit, parametric tests will generally provide higher power (or require fewer measurements to support a decision concerning the survey unit). The tests to demonstrate that the data are normally distributed generally require more measurements than the nonparametric tests. EPA provides guidance on selecting and performing statistical tests to demonstrate that data are normally distributed (EPA 2006a). Guidance is also available for performing parametric statistical tests (NRC 1992a, EPA 1989a, EPA 1994a, EPA 2006a).

There are a wide variety of statistical tests designed for use in specific situations. These tests may be preferable to the generic statistical tests recommended in MARSSIM when the underlying assumptions for these tests can be verified. **Table 2.3** lists several examples of statistical tests that may be considered for use at individual sites or survey units. A brief description of the tests and references for obtaining additional information on these tests are also listed in the table. Applying these tests may require consultation with a statistician.

2.6.2 Integrating MARSSIM with Other Survey Designs

2.6.2.1 Accelerated Cleanup Models

There are a number of approaches designed to expedite site cleanups. These approaches can save time and resources by reducing sampling, preventing duplication of effort, and reducing inactive time periods between steps in a cleanup process. Although **Section 2.4** describes the RSSI process recommended in MARSSIM as one with seven principal steps, MARSSIM is not intended to be a serial process that would slow site cleanups. Rather, MARSSIM supports existing programs and encourages approaches to expedite site cleanups. Planning in MARSSIM promotes saving time and resources.

Table 2.3: Examples of Alternate Statistical Tests

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Alternate 1-Sample Tests (No Reference Area Measurements)					
Student's *t* Test	Normal	Parametric test for H_0: Mean < t	*Guidance for Data Quality Assessment,* EPA QA/G-9, p. 3.2-2.	Appropriate if data appear to be normally distributed and symmetric.	Relies on a non-robust estimator for μ and σ. Sensitive to outliers and departures from normality.
***t* Test Applied to Logarithms**	Lognormal	Parametric test for H_0: Median < t	*Guidance for Data Quality Assessment,* EPA QA/G-9, p. 3.2-2.	A well-known and easy-to-apply test. Useful for a quick summary of the situation if the data are skewed to right.	Relies on a non-robust estimator for σ. Sensitive to outliers and departures from lognormality.
Minimum Variance Unbiased Estimator for Lognormal Mean	Lognormal	Parametric estimates for mean and variance of lognormal distribution	Gilbert, *Statistical Methods for Environmental Pollution Monitoring,* p. 164, 1987.	A good parametric test to use if the data are lognormal.	Inappropriate if the data are not lognormal.
Chen Test	Skewed to right, including lognormal	Parametric test for H_0: Mean > 0	*Journal of the American Statistical Association (90),* p. 767, 1995.	A good parametric test to use if the data are lognormal.	Applicable only for testing H_0: "survey unit is clean." Survey unit must be significantly greater than 0 to fail. Inappropriate if the data are not skewed to higher values.

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric test for H_0: Mean < L	DeGroot, *Optimal Statistical Decisions*, 2005.	Permits use of subjective "expert judgment" in interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
Bootstrap	No restriction	Nonparametric; uses resampling methods to estimate sampling variance	Hall, *Annals of Statistics (22)*, p. 2011–2030, 1994.	Avoids assumptions concerning the type of distribution.	Computer-intensive analysis required. Accuracy of the results can be difficult to assess.
Lognormal Confidence Intervals Using Bootstrap	Lognormal	Uses resampling methods to estimate one-sided confidence interval for lognormal mean	Angus, *The Statistician (43)*, p. 395, 1994.	Nonparametric method applied within a parametric lognormal model.	Computer-intensive analysis required. Accuracy of the results can be difficult to assess.
Alternate 2-Sample Tests (Reference Area Measurements Are Required)					
Student's *t* Test	Symmetric, normal	Parametric test for difference in means H_0: $\mu_x < \mu_y$	*Guidance for Data Quality Assessment,* EPA QA/G-9, p. 3.3-2.	Easy to apply. Performance for non-normal data are acceptable.	Relies on a non-robust estimator for σ; therefore, test results are sensitive to outliers.

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Mann-Whitney Test	No restrictions	Nonparametric test difference in location H_0: $\mu_x < \mu_y$	Hollander, *Nonparametric Statistical Methods*, 2014.	Equivalent to the WRS test, but used less often. Similar to resampling, because test is based on set of all possible differences between the two data sets.	Assumes that the only difference between the test and reference areas is a shift in location.
Kolmogorov-Smirnov	No restrictions	Nonparametric test for any difference between the two distributions	Hollander, *Nonparametric Statistical Methods*, 2014.	A robust test for equality of two sample distributions against all alternatives.	May reject because variance is high, although mean is in compliance.
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric tests for difference in means or difference in variance	Box and Tiao, *Bayesian Inference in Statistical Analysis*, 2011.	Permits use of “expert judgment” in the interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
2-Sample Quantile Test	No restrictions	Nonparametric test for difference in shape and location	EPA, *Methods for Evaluating the Attainment of Cleanup Standards, Vol. 3*, p. 7.1, 1994.	Will detect if survey unit distribution exceeds reference distribution in the upper quantiles.	Applicable only for testing H_0: “survey unit is clean.” Survey unit must be significantly greater than 0 to fail.
Sign Test when Background is Present	No restrictions	Nonparametric test for difference in location assuming uniform background	Abelquist, *Decommissioning Health Physics: A Handbook for MARSSIM Users*, 2nd Edition, 2014.	Less computationally intensive. Consistent with pre-MARSSIM survey designs.	Less powerful than the Wilcoxon Rank Sum Test because of assumptions concerning background distributions.

Alternate Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Bootstrap and Other Resampling Methods	No restrictions	Nonparametric; uses resampling methods to estimate sampling variance	Hall, *Annals of Statistics (22)*, p. 2011, 1994.	Avoids assumptions concerning the type of distribution. Generates informative resampling distributions for graphing.	Computer-intensive analysis required.
Alternate to Statistical Tests					
Decision Theory	No restrictions	Incorporates loss function in the decision theory approach	DOE, *Statistical and Cost-Benefit Enhancements to the DQO Process for Characterization Decisions*, 1996.	Combines elements of cost-benefit analysis and risk assessment into the planning process.	Limited experience in applying the method to compliance demonstration and decommissioning. Computer-intensive analysis required.

Abbreviations: H_0 = null hypothesis; t: = t-test statistic, L = bayesian test statistic; μ = mean; σ = standard deviation.

Sandia National Laboratories in New Mexico used a combination of the observational approach, process knowledge, judgmental soil sampling, and Global Positioning System (GPS)/gamma survey techniques to identify and remediate potential residual radioactive material during execution of the Environmental Restoration Project there. Depleted uranium was almost exclusively the radionuclide of concern. There were 268 individual designated test locations on the site ranging from tens of square meters to hundreds of acres, necessitating the application of a flexible, graded approach, as appropriate. GPS/gamma in situ surveys were particularly valuable in cost-effectively screening large areas and identifying sub-areas that warranted more rigorous investigation than other, non-affected areas. As-completed survey maps and data files consisted of ArcGIS figures generated from the GPS/gamma surveys (before and after) supplemented by analytical laboratory results which were correlated to the GPS/gamma surveys, when both were used. Use of in situ GPS/gamma surveys complemented by ArcGIS analytical tools enabled convenient statistical treatment of thousands of data points, making demonstration of successful remediation much easier to present, as well as easier to understand by the stakeholders.

At the U.S. Department of Energy's Hanford Site, the parties to the Tri-Party Agreement negotiated a method to implement the CERCLA process in order to (1) accelerate the assessment phase, and (2) coordinate RCRA and CERCLA requirements whenever possible, thereby resulting in cost savings. The Hanford Past Practice Strategy was developed in 1991 to accelerate decision-making and initiation of remediation through activities that include maximizing the use of existing data consistent with DQOs (DOE 1991).

The Adaptive Sampling and Analysis Programs at the Environmental Science Division of Argonne National Laboratory quantitatively fuse soft data (e.g., historical records, aerial photos, nonintrusive geophysical data) with hard sampling results to estimate residual radioactive material extent, measure the uncertainty associated with these estimates, determine the benefits from collecting additional samples, and assist in siting new sample locations to maximize the information gained (DOE 2001).

2.6.2.2 Superfund Soil Screening Guidance

The Soil Screening Guidance for Radionuclides (EPA 1996a, EPA 1996b) is a tool developed by EPA to help standardize and accelerate the evaluation and cleanup of radioactively contaminated soils at sites on the National Priorities List (NPL) where future residential land use is anticipated. The guidance provides a methodology for calculating risk-based, site-specific soil screening levels for radionuclides in soil that may be used to identify areas needing further investigation at NPL sites. The Soil Screening Guidance assumes that there is a low probability of residual radioactive material and does not account for small areas of elevated activity. These assumptions correlate to a Class 3 area in MARSSIM. Because the Soil Screening Guidance is designed as a screening tool instead of a final demonstration of compliance, the specific values for decision error levels, the bounds of the gray region, and the number and location of measurements are developed to support these objectives. However, the MARSSIM approach can be integrated with the survey design in the Soil Screening Guidance using this guidance as an alternate MARSSIM survey design.

The Soil Screening Guidance survey design is based on collecting samples, so scan surveys and direct measurements are not considered. To reduce analytical costs, the survey design recommends compositing samples and provides a statistical test for demonstrating compliance. If utilizing the Soil Screening Guidance in conjunction with MARSSIM, factor in the effects of the compositing technique when calculating measurement method uncertainty and detection capability and in the determination of areas of elevated radioactive material.

3 HISTORICAL SITE ASSESSMENT

3.1 Introduction

The Radiation Survey and Site Investigation (RSSI) process uses a graded approach that starts with the Historical Site Assessment (HSA) and is later followed by other surveys that lead to the final status survey (FSS). The HSA is an investigation to collect existing information describing a site's complete history from the start of site activities to the present time. During the HSA process, additional information is collected to categorize the site or areas within the site as impacted or non-impacted and to make preliminary site classification assessments. In this chapter[1]—

- **Section 3.1** provides an overview of the HSA.
- **Section 3.2** describes the Data Quality Objectives (DQO) process, utilized to establish criteria for planning HSA data collection activities.
- **Section 3.3** describes how site identification is used to establish a site or an area within a site as having the potential to have residual radioactive material based on prior activities at the site.
- **Section 3.4** describes the preliminary investigation, utilized to obtain sufficient information to determine an initial categorization of a site or survey unit.
- **Section 3.5** explains how site reconnaissance is utilized to gather sufficient information to support decisions on further action.
- **Section 3.6** covers the evaluation of HSA data to differentiate sites that need further action from those that pose little to no threat from the environment.
- **Section 3.7** describes how to utilize the data gathered from the HSA to determine the next step in the RSSI process.
- **Section 3.8** covers the preparation of an HSA report to summarize what is known about a site, assumptions and inferences made about the site, activities conducted during the HSA, and all researched information.
- **Section 3.9** provides a review of the HSA process.
- **Figure 3.1** presents a flowchart of HSA activities and **Figure 3.2** provides initial categorization of the site or survey unit[2] as impacted or non-impacted.

[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

[2] Refer to **Section 4.6.2** for a discussion of survey units.

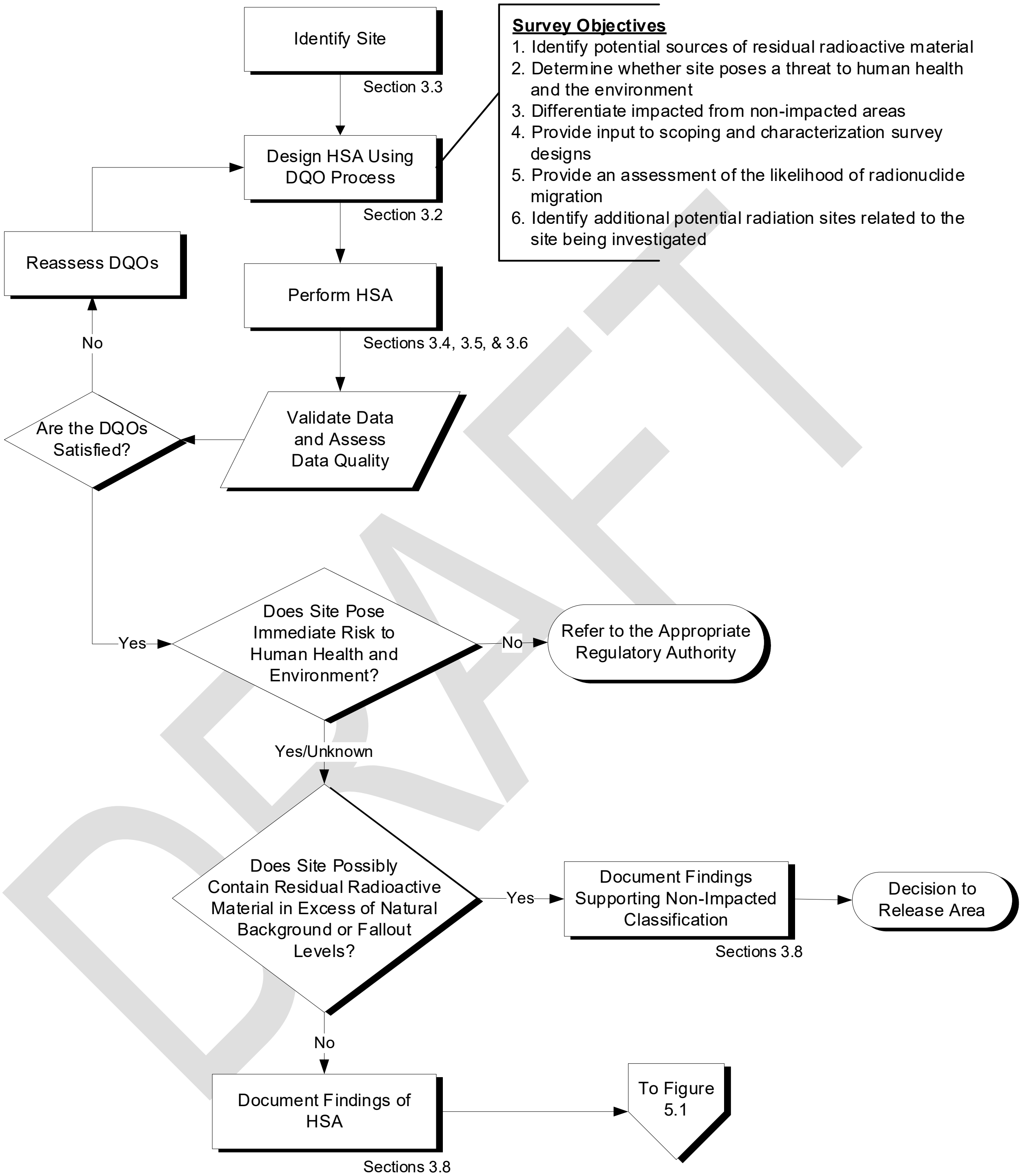


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Figure 3.1: Historical Site Assessment Process Flowchart

The HSA may provide information needed to calculate derived concentration guideline levels (DCGLs, initially described in **Section 2.2**), as well as information that reveals the magnitude of a site's DCGLs. This information is used for comparing historical data to potential DCGLs and determining the suitability of the existing data for assessment of the site. The HSA also supports emergency response and removal activities within the context of the the U.S. Environmental Protection Agency's (EPA) Superfund program, fulfills public information needs, and furnishes appropriate information about the site early in the RSSI process. For a large number of sites, such as currently licensed facilities, site identification and reconnaissance may not be needed. For certain response activities, such as reports concerning the possible presence of radioactive material, preliminary investigations may consist more of site reconnaissance and a scoping survey in conjunction with collection of historical information.

This chapter describes three sections of an HSA: (1) identification of a candidate site (**Section 3.3**), (2) preliminary investigation of the facility or site (**Section 3.4**), and (3) site reconnaissance (**Section 3.5**). The site reconnaissance is not a scoping survey, however, because the intent is to find physical conditions that may affect the investigative process and not to collect measurements. The HSA is followed by an evaluation of the site based on information collected during the HSA.

The amount of detailed information and effort needed to conduct an HSA depends on the type of site, associated historical events, regulatory framework, and availability of documented information. For example, information for an HSA is readily available at some facilities that routinely maintain records throughout their operations, such as licensees of the U.S. Nuclear Regulatory Commission (NRC) or Agreement States. At other facilities, such as Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, a comprehensive search may be necessary to gather information for an HSA (see **Appendix F**). In the former case, the HSA is essentially complete, and a review of the following sections will serve to ensure that the information justifies the recommendation. In the latter case, the HSA process has identified data gaps that will be addressed in subsequent scoping or characterization surveys. In still other cases, where sealed sources or small amounts of radionuclides are described by the HSA, the site may qualify for a simplified decommissioning procedure (see **Appendix B**).

3.2 Data Quality Objectives

The Data Quality Objectives (DQO) process assists in directing the planning of data collection activities performed during the HSA. Information gathered during the HSA can also support the DQOs of subsequent surveys.

Three inputs to the HSA/DQO process are expected:

- identifying an individual or a list of planning team members, including the decision maker (DQO Step 1, **Appendix D, Section D.1**)
- concisely describing the problem (DQO Step 1, **Appendix D, Section D.1**)
- initially classifying site and survey unit as impacted or non-impacted (DQO Step 4, **Appendix D, Section D.2.2**)

Other inputs may accompany these three, and this added information may be useful in supporting subsequent applications of the DQO process.

The planning team clarifies and defines the DQOs for a site-specific survey. This multidisciplinary team of technical experts offers the greatest potential to solve the problems encountered in designing a survey. Including a stakeholder group representative is an important consideration when assembling this team. Once formed, the team can also consider the role of public participation in this assessment and the possible surveys to follow. The number of team members is directly related to the scope and complexity of the problem. For a small site or simplified situations, planning may be performed by the site owner. For a large, complex facility, the team may include project managers, site managers, scientists, engineers, community and local government representatives, health physicists, statisticians, and regulatory agency representatives. A reasonable effort should be made to include other individuals—that is, specific decision makers or data users—who may use the study findings sometime in the future.

The role of the regulatory agency representatives is to facilitate survey planning—without direct participation in survey plan development—by offering comments and information based on past precedent, current guidance, and potential pitfalls. A regulatory agency representative may also be included at specific sites when needed (e.g., CERCLA).

The planning team is generally led by a member who is referred to as the decision maker. This individual is often the person with the most authority over the study and may be responsible for assigning the roles and responsibilities to planning team members. Overall, the decisionmaking process arrives at final decisions based on the planning team's recommendations. The problem or situation description provides background information on the fundamental issue to be addressed by the assessment (EPA 2006b). The following steps may be helpful during DQO development:

- Describe the conditions or circumstances surrounding the problem or situation and the reason for undertaking the survey.
- Describe the problem or situation as it is currently understood by briefly summarizing existing information.
- Conduct literature searches and interviews.
- Examine past or ongoing studies to ensure that the problem is correctly defined. Consider breaking complex problems into more manageable pieces.

Section 3.5 provides information on gathering existing site data and determining the usability of this data.

The initial classification of the site involves developing a conceptual model based on the existing information collected during the preliminary investigation. Conceptual models describe a site or facility and its environs and present hypotheses regarding the radionuclides for known and potential residual radioactive material (EPA 1987a, 1987b). The classification of the site is discussed in **Section 3.7.**

Several steps in the DQO process may be addressed initially during the HSA. This information or decision may be based on limited or incomplete data. As the site assessment progresses and as decisions become more difficult, the iterative nature of the DQO process allows for re-evaluation of preliminary decisions. This is especially important for classification of sites and survey units where the final classification is not made until the FSS is planned.

3.3 Site Identification

A site may already be known for its prior use and presence of radioactive materials. Elsewhere, potential radioactive materials sites may be identified through such situations and information as the following:

- records of authorization to possess or handle radioactive materials, including—
    - NRC or NRC Agreement State License
    - U.S. Department of Energy facility records
    - Naval Radioactive Materials Permit
    - U.S. Air Force Master Materials License
    - Army Radiation Authorization
    - State Authorization for Naturally Occurring and Accelerator Produced Radioactive Material (NARM)
- notification to government agencies of possible releases of radioactive substances
- citizens filing a petition under section 105(d) of the Superfund Amendments and Reauthorization Act of 1986 (EPA 1986)
- ground and aerial radiological surveys
- contacts with knowledge of the site

Once identified, the name, location, and current legal owner or custodian (where available) of the site should be recorded.

3.4 Preliminary Investigation

The preliminary investigation serves to collect readily available information concerning the facility or site and its surroundings. The investigation is designed to obtain sufficient information to provide initial categorization of the site or survey unit as impacted or non-impacted. Information on the potential distribution of residual radioactive material may be used for classifying each site or survey unit as Class 1, Class 2, or Class 3 and is useful for planning scoping and characterization surveys.

Table 3.1 provides a set of questions that can be used to assist in the preliminary investigation. Apart from obvious cases (e.g., NRC licensees), this table focuses on characteristics that identify a previously unrecognized or known but undeclared source of potential residual radioactive material. Furthermore, these questions may identify confounding factors for selecting reference sites.

Table 3.1: Questions Useful for the Preliminary Investigation

Question	Purpose of Question
1. Was the site ever licensed for the manufacture, use, or distribution of radioactive materials under Agreement State Regulations, U.S. Nuclear Regulatory Commission licenses, or Armed Services permits, or for the use of 91B material?	Indicates a higher probability that the area is impacted.
2. Did the site ever have permits to dispose of or incinerate radioactive material onsite? Is there evidence of such activities?	Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
3. Has the site ever had deep wells for injection or permits for such?	Indicates a higher probability that the area is impacted.
4. Did the site ever have permits to perform research with radiation-generating devices or radioactive materials except medical or dental X-ray machines?	Research that may have resulted in the release of radioactive material indicates a higher probability that the area is impacted.
5. As a part of the site's radioactive materials license, were there ever any soil moisture density gauges (americium-beryllium or plutonium-beryllium sources) or radioactive thickness monitoring gauges stored or disposed of onsite?	Leak-test records of sealed sources may indicate whether a storage area is impacted. Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
6. Was the site used to create radioactive material by activation?	Indicates a higher probability that the area is impacted.
7. Were radioactive sources stored at the site?	Leak-test records of sealed sources may indicate whether or not a storage area is impacted.
8. Is there evidence that the site was involved in the Manhattan Project or any Manhattan Engineering District activities (1942–1946)?	Indicates a higher probability that the area is impacted.
9. Was the site ever involved in the support of nuclear weapons testing (1945–1962)?	Indicates a higher probability that the area is impacted.
10. Were any facilities on the site used as a weapons storage area? Was weapons maintenance ever performed at the site?	Indicates a higher probability that the area is impacted.

Question	Purpose of Question
11. Was there ever any decontamination, maintenance, or onsite storage of ships, vehicles, or planes with residual radioactive material?	Indicates a higher probability that the area is impacted.
12. Is there a record of any aircraft accident at or near the site (e.g., depleted uranium counterbalances, thorium alloys, radium dials)?	May include other considerations, such as evidence of radioactive material that was not recovered.
13. Are there records indicating use or storage of radium dials and other radioactive luminous devices as a source?	Indicates a higher probability that the area is impacted.
14. Was there ever any radiopharmaceutical manufacturing, storage, transfer, or disposal onsite?	Indicates a higher probability that the area is impacted.
15. Was animal research ever performed at the site?	Evidence that radioactive material was used for animal research indicates a higher probability that the area is impacted.
16. Were naturally occurring radioactive material (NORM) or technologically enhanced naturally occurring radioactive material (TENORM)—such as uranium, thorium, or radium compounds—used in manufacturing, research, or testing at the site, or were these compounds stored at the site?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
17. Has the site ever been involved in the processing or production of NORM or TENORM (e.g., radium, fertilizers, phosphorus compounds, vanadium compounds, refractory materials, rare earth elements, or precious metals) or mining, milling, processing, or production of uranium or thorium?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
18. Were coal or coal products used onsite? If yes, did combustion of these substances leave ash or ash residues onsite? If yes, are runoff or production ponds onsite?	May indicate other considerations, such as a potential increase in background variability.
19. Was there ever any onsite disposal of material known to be high in naturally occurring radioactive material (e.g., monazite sands used in sandblasting)?	May indicate other considerations, such as a potential increase in background variability.

Question	Purpose of Question
20. Did the site contain or use pipe from the oil and gas industries?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
21. Is there any reason to expect that the site may contain radioactive material (other than previously listed)?	See **Section 3.7.**

Definition: 91B = "highly classified radioactive material covered under Section 91(b) of the Atomic Energy Act (AEA) of 1954 associated with current nuclear weapons material, legacy nuclear weapons maintenance wastes, residuals from nuclear weapons accident/incidents, some residuals from atmospheric testing of nuclear weapons, and residuals from nuclear reactor operations." (George Air Force Base, n.d.)

Appendix G of this document provides a general listing and cross-reference of information sources—each with a brief description of the information contained in each source.

3.4.1 Existing Radiation Data

Sources of useful information for an HSA include site files; monitoring data; former site evaluation data; and Federal, State, and local investigations or emergency actions. Existing site data may provide specific details about the identity, concentration, and areal distribution of residual radioactive material. However, these data should be examined carefully because—

- Previous survey and sampling efforts may not be compatible with HSA objectives or may not be extensive enough to characterize the facility or site fully.
- Measurement protocols and standards may not be known or compatible with HSA objectives (e.g., quality assurance/quality control [QA/QC] procedures, limited analysis rather than full-spectrum analysis) or may not be extensive enough to characterize the facility or site fully.
- Conditions may have changed since the site was last sampled (i.e., substances may have been released, migration may have spread the residual radioactive material, additional waste disposal may have occurred, or decontamination may have been performed).

Existing data can be evaluated using the Data Quality Assessment (DQA) process described in **Appendix D.** (Also see DOE 1987 and EPA 1980a, 1992a, 1992b, 2006a for additional guidance on evaluating data.)

3.4.1.1 Licenses, Site Permits, and Authorizations

The facility or site radioactive materials license and supporting or associated documents are potential sources of information for licensed facilities. If a license does not exist, there may be a permit or other document that authorized site operations involving radioactive material. These documents may specify the quantities of radioactive material authorized for use at the site, the chemical and physical form of the materials, operations for which the materials are (or were) used, locations of these operations at the facility or site, and total quantities of material used at the site during its operating lifetime.

EPA and State agencies maintain files on a variety of environmental programs. These files may contain permit applications and monitoring results with information on specific waste types and quantities, sources, type of site operations, and operating status of the facility or site. Some of these information sources are listed in Appendix G.

3.4.1.2 Operating Records

Records and other information sources useful for site evaluations include those describing onsite activities, current and past radiation control procedures, and past operations involving—

- demolition
- effluent releases
- discharge to sewers or onsite septic systems
- production of residues
- land filling
- waste and material storage
- pipe and tank leaks
- spills and accidental releases
- release of facilities or equipment from radiological controls
- onsite or offsite radioactive and hazardous waste disposal

Some records may be or may have been classified for national security purposes, and means should be established to review all pertinent records. Past operations should be summarized in chronological order, along with information about permits and approvals. Estimates of the total amount of radioactive material disposed of or released at the site and the physical and chemical form of the radioactive material should also be included. Records on waste disposal, environmental monitoring, site inspection reports, license applications, operational permits, waste disposal material balance and inventory sheets, and purchase orders for radioactive materials are useful for estimating total activity. Information on accidents—such as fires, flooding, spills, unintentional releases, or leakage—should be collected, because they indicate potential sources of residual radioactive material. Possible areas of localized radioactive material should be identified.

Site plats or plots, blueprints, drawings, and sketches of structures are especially useful to illustrate the location and layout of buildings on the site. Site photographs, aerial surveys, and maps can help verify the accuracy of these drawings or indicate changes after the drawings were prepared. Processing locations, waste streams to and from the site, and the presence of stockpiles of raw materials and finished product should be noted on these photographs and maps. Buildings or outdoor processing areas may have been modified or converted to other uses or configurations. The locations of sewers, pipelines, electric lines, water lines, etc., should also be identified. This information facilitates planning the site reconnaissance and subsequent surveys, developing a site conceptual model, and increasing the efficiency of the survey program.

Corporate contract files may also provide useful information during subsequent stages of the RSSI process. Older facilities may not have complete operational records, especially for obsolete or discontinued processes. Financial records may also provide information on purchasing and shipping that, in turn, help to reconstruct a site's operational history.

While operating records can be useful tools during the HSA, the investigator should be careful not to place too much emphasis on this type of data. These records are often incomplete and lack information on substances previously not considered hazardous. Out-of-date blueprints and drawings may not show modifications made during the lifetime of a facility, but they may be useful to identify additional areas that should be investigated.

3.4.2 Contacts and Interviews

Conduct interviews with current or previous employees to collect first-hand information about the site or facility and to verify or clarify information gathered from records. Interviews cover general topics, such as radioactive waste handling procedures. Results from interviews conducted early in the process are useful in guiding subsequent data collection activities.

Interviews scheduled late in the data gathering process can also be very useful. Questions can be directed to specific areas of the investigation that need additional information or clarification.

Photographs and sketches can be used to assist the interviewer and allow the interviewees to recall information of interest. Conducting interviews onsite where the employees performed their tasks often stimulates memories and facilitates information gathering. In addition to interviewing managers, engineers, and facility workers, interviews may be conducted with laborers and truck drivers to obtain information from their perspective.

The investigator should be cautious in the use of interview information. Whenever possible, anecdotal evidence should be assessed for accuracy, and results of interviews should be backed up with supporting data. To ensure that specific information is confirmed and properly recorded, it may be advisable to hire trained investigators and take affidavits.

3.5 Site Reconnaissance

The objective of the site reconnaissance or site visit is to gather sufficient information to support a decision regarding further action. Reconnaissance activity is not a risk assessment, a scoping survey, or a study of the full extent of residual radioactive material at a facility or site. The reconnaissance offers an opportunity to record information concerning hazardous site conditions as they apply to conducting future survey work. In this regard, information describing physical hazards, structural integrity of buildings, or other conditions defines potential problems that may impede future work. Site reconnaissance is most applicable to sites with less available information and may not be necessary at other sites having greater amounts of records, such as NRC licensed facilities.

To prepare for the site reconnaissance, begin by reviewing what is known about the facility or site and identify data gaps. Given the site-specific conditions, consider whether a site reconnaissance is necessary and practical. This type of effort may be deemed necessary if a site is abandoned or not easily observed from areas of public access, or if file searches disclose little information. These same circumstances may also make a site reconnaissance risky for health and safety reasons—in view of the many unknowns—and may make entry difficult. This investigative step may be less critical for active facilities whose operators grant access and provide requested information. Remember to arrange for proper site access and prepare an appropriate health and safety plan, if required, before initiating the site visit.

Investigators should acquire signed consent forms from the site or equipment owner to gain access to the property to conduct the reconnaissance. Investigators are to determine if State and Federal officials, and local individuals, should be notified of the reconnaissance schedule. If needed, local officials should arrange for public notification. Guidance on obtaining access to sites can be found in *Entry and Continued Access Under CERCLA* (EPA 1987c).

A study plan should be prepared before the site reconnaissance to anticipate every reconnaissance activity and identify specific information to be gathered. This plan should incorporate a survey of the site's surroundings and provide details for activities that verify or identify the location of nearby residents, worker populations, drinking water or irrigation wells, and foods, as well as other site environs information.

Materials and equipment for a site reconnaissance should be prepared in advance. This includes a camera to document site conditions, as well as health and safety monitoring instruments, including a radiation detection meter, a GPS receiver or extra copies of topographic maps to mark target locations, water distribution areas, and other important site features.

A logbook is critical to keeping a record of field activities and observations as they occur. The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) recommends that the logbook be completed in waterproof ink, preferably by one individual. Furthermore, each page of the logbook should be signed and dated, including the time of day, after the last entry on the page. Corrections should be documented and approved. Alternatively, a computerized logbook may also be used, with the adequate provision of controls to ensure appropriate quality assurance and version control. For example, logbook entries should be signed daily and closed out, so that future revisions would require date/time stamping and signature of the individual making changes.

3.6 Evaluation of Historical Site Assessment Information

The main purpose of the HSA is to determine the current status of the site or facility, but the data collected may also be used to differentiate sites that need further action from those that pose little or no threat to human health and the environment. The information gathered during this screening process can show the need for additional surveys or may be sufficient to recommend a site release. Because much of the information collected during HSA activities is qualitative, and analytical data may be of unknown quality, many decisions regarding a site are the result of professional judgment.

Historical analytical data indicating the presence of residual radioactive material in environmental media (surface soil, subsurface soil, surface water, ground water, air, or buildings) can be used to support the hypothesis that radioactive material was released at the facility or site. A decision that the site does not meet release criteria can be made regardless of the quality of the data, its attribution to site operations, or its relationship to background levels. In such cases, elevated results are sufficient to support the hypothesis—it is not necessary to definitively demonstrate that a problem exists. Conversely, historical analytical data can also be used to support the hypothesis that no release has occurred. However, these data should not be the sole basis for this hypothesis. If historical analytical data constitute the principal evidence for ruling out the presence of residual radioactive material, the data must be of sufficient quality to clearly demonstrate that a problem does not exist.

In most cases, it is assumed there will be some level of process knowledge available in addition to historical analytical data. If process knowledge suggests that no residual radioactive material should be present, and the historical analytical data also suggests that no residual radioactive material is present, the process knowledge provides an additional level of confidence and supports categorizing the area as non-impacted. However, if process knowledge suggests no residual radioactive material should be present, but the historical analytical data indicate the presence of residual radioactive material, the area will probably be categorized as impacted.

The following sections describe the recommended information to accurately and completely support a site release recommendation. If some of the information is not available, it should be identified as a data need for future surveys. Data needs are collected during Step 3 of the DQO process (Identify Inputs to the Decision) as described in **Appendix D, Section D.1.3.** **Section 3.6.5** provides information on professional judgment and how it may be applied to the decisionmaking process.

3.6.1 Identify Potential Sources of Residual Radioactive Material

An efficient HSA gathers information sufficient to identify the radionuclides used at the site, including their chemical and physical form. The first step in evaluating HSA data is to estimate the potential for residual radioactive material from these radionuclides.

Site operations are a strong indicator of the potential for residual radioactive material (NRC 1992a). An operation that handled only encapsulated sources is expected to have a low potential for residual radioactive material—assuming that the integrity of the sources was not compromised. A review of leak-test records for such sources may be adequate to demonstrate the low probability of residual radioactive material. A chemical manufacturing process facility would likely have residual radioactive material in piping, ductwork, and process areas, with a potential for residual radioactive material in soil where spills, discharges, or leaks occurred. Sites using large quantities of radioactive ores—especially those with outside waste collection and treatment systems—are likely to have residual radioactive material on the premises. If loose dispersible materials were stored outside or process ventilation systems were poorly controlled, then windblown surface deposition of residual radioactive material may be possible.

Consider how long the site was operational. If enough time elapsed since the site discontinued operations, radionuclides with short half-lives may no longer be present in significant quantities.

In this case, calculations demonstrating that residual activity could not exceed the DCGL may be sufficient to evaluate the potential residual radioactive material at the site. A similar evaluation can be made based on knowledge of a radionuclide's chemical and physical form. Such a determination relies on records of radionuclide inventories, chemical and physical forms, total amounts of material and activity in waste shipments, and purchasing records to document and support this decision. However, a number of radionuclides experience significant decay product ingrowth, which should be considered when evaluating existing site information.

3.6.2 Identify Potential Areas with Residual Radioactive Material

Information gathered during the HSA should be used to provide an initial categorization of the site areas as impacted or non-impacted.

Impacted areas are either known to contain residual radioactive material based on radiological surveillance or are suspected of containing it based on historical information. This includes areas where—

- Radioactive material was used and stored.
- Records indicate spills, discharges, or other unusual occurrences that could result in the spread of radioactive material.
- Radioactive material was buried or disposed.

Areas immediately surrounding or adjacent to these locations are also considered impacted because of the potential for inadvertent spread of radionuclides.

Non-impacted areas are those areas where there is no reasonable possibility for residual radioactive material based on site history or previous survey information. The criteria used for this distinction need not be as strict as those used to demonstrate final compliance. However, the reasoning for categorizing an area as non-impacted should be maintained as a written record.

All potential sources of radioactive material in impacted areas should be identified and their dimensions recorded (in two or three dimensions, to the extent they can be measured or estimated). Sources can be delineated and characterized through visual inspection during the site reconnaissance; interviews with knowledgeable personnel; and historical information concerning disposal records, waste manifests, and waste sampling data. The HSA should address potential residual radioactive material from the site whether it is physically within or outside of site boundaries. This approach describes the site in a larger context, but as noted in **Chapter 1,** MARSSIM's scope concerns releasing a site and does not include areas outside a site's boundaries.

3.6.3 Identify Potential Media with Residual Radioactive Material

The next step in evaluating the data gathered during the HSA is to identify media at the site with a potential for containing residual radioactive material. Identification of those media that do not contain residual radioactive material and those that may contain it is necessary for both preliminary area classification (**Section 4.4**) and planning subsequent survey activities.

This section provides information on evaluating the likelihood for release of radioactive material into the following environmental media: surface soil, subsurface soil, sediment, surface water, ground water, air, and buildings. Although MARSSIM's scope is focused on surface soils and building surfaces, other media will still need to be considered.

The evaluation will result in a finding either of suspected residual radioactive material or of no suspected residual radioactive material. The finding may be based on analytical data, professional judgment, or a combination of the two.

Subsequent sections describe the environmental media and pose questions pertinent to each type. Each question is accompanied by a commentary. Carefully consider the questions within the context of the site and the available data. Avoid spending excessive amounts of time on particular questions, because answers to every question are unlikely to be available at each site. Questions that cannot be answered based on existing data can be used to direct future surveys of the site. Also, keep in mind the numerous differences in site-specific circumstances and that the questions do not identify every characteristic that might apply to a specific site. Additional questions or characteristics identified during a specific site assessment should be included in the HSA report (**Section 3.9;** EPA 1991e).

3.6.3.1 Surface Soil

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, resuspension of particles for inhalation, and mixing from human disturbances. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Historically, this layer has often been represented as the top 15 centimeters (cm; 6 inches [in.]) of soil (40 CFR 192), but will vary depending on radionuclide, surface characteristics, measurement technique, and pathway modeling assumptions. For the purposes of MARSSIM, surface soil may be considered to include gravel fill, waste piles, concrete, or asphalt paving. For many sites where radioactive material was used, one first assumes that radioactive material on the site exists on surfaces, and the evaluation is used to identify areas of high and low probability of residual radioactive material (Class 1, Class 2, or Class 3 areas).

- **Were all radiation sources used at the site encapsulated sources?** A site where only encapsulated sources were used would be expected to have a low potential for residual radioactive material. A review of the leak-test records and documentation of encapsulated source location may be adequate to make a finding of no suspected residual radioactive material.

- **Were radiation sources used only in specific areas of the site?** Evidence that radioactive material was confined to certain areas of the site may be helpful in determining which areas are impacted and which are non-impacted.

- **Was surface soil regraded or moved elsewhere for fill or construction purposes?** This helps identify additional potential sites of radioactive material.

3.6.3.2 Subsurface Soil and Other Subsurface Media

Subsurface soil and other subsurface media are defined as any solid materials beneath the surface soil layer. The purpose of these subsurface investigations is to locate and define the lateral and vertical extent of the potential residual radioactive material in the subsurface. Subsurface measurements can be expensive, especially for beta- or alpha-emitting radionuclides. To effectively use project resources, subsurface investigations should be biased (e.g., limited to known or potential areas containing subsurface radioactive material). After identifying areas of subsurface concern, further subsurface investigations would be necessary to delineate the lateral and vertical extent of radioactive material during the remedial investigation and design phase. The latter would aid in planning the necessary resources (e.g., budgets, contractors, obtaining access) and to set the schedule for the remedial action phase.

- **Is there evidence of changes in surface features?** Understanding the development history of an area can aid the investigation in identifying subsurface areas of potential concern. Historically, industrial wastes potentially containing radioactive material were used as fill material (e.g., to fill in old streams, wetlands, low-lying areas) or as subgrade material (e.g., beneath buildings, basement floors). Changes in surface features over time can affect the distribution of radioactive material. Reviewing historical records can be of great benefit in identifying subsurface areas of potential concern and in providing subsequent cost effective and defensible graded approaches to better characterize the site. Examples of helpful records include aerial photographs, topography maps, railroad/road maps, navigation maps, Sanborn Fire Insurance Maps, construction photographs, postcards, and correspondence.

- **Are there areas of known or suspected residual radioactive material in surface soil?** Residual radioactive material in surface soil can migrate deeper into the soil. Surface soil sources should be evaluated based on radionuclide mobility, soil permeability, and infiltration rate to determine the potential for residual radioactive material in the subsurface. Computer modeling may be helpful for evaluating these types of situations.

- **Is there a ground water plume without an identifiable source?** Radioactive material in ground water indicates that a source of residual radioactive material is present. If no source is identified during the HSA, residual radioactive material in the subsurface is a probable source.

- **Is there potential for enhanced mobility of radionuclides in soils?** Radionuclide mobility can be enhanced by the presence of solvents or other chemicals that affect the sorption capacity of soil.

- **Is there evidence that the surface has been disturbed?** Recent or previous excavation activities are obvious sources of surface disturbance. Areas with developed plant life (forested or old growth areas) may indicate that the area remained undisturbed during the operating life of the facility. Areas where vegetation is removed during previous excavation activity may be distinct from mature plant growth in adjacent areas. If a site is not purposely replanted, vegetation may appear in a sequence starting with grasses that are later replaced by shrubs and trees. Typically, grasslands recover within a few years, sagebrush or low ground cover appears over decades, and mature forests may take centuries to develop.

- **Is there evidence of subsurface disturbance?** Non-intrusive, non-radiological measurement techniques may provide evidence of subsurface disturbance. Magnetometer surveys can identify buried metallic objects, and ground-penetrating radar can identify subsurface anomalies such as trenches or dump sites. Techniques involving special equipment are discussed in **Section 6.9.**

- **Are surface structures present?** Structures constructed during a site's operational history may cover residual radioactive material below ground. Some consideration for residual radioactive material that may exist beneath parking lots, buildings, or other onsite structures may be warranted as part of the investigation. There may be underground piping, drains, sewers, or tanks that caused the spread of residual radioactive material.

3.6.3.3 Surface Water

Surface waters include streams and rivers, lakes, coastal tidal waters, and oceans. Note that certain ditches and intermittently flowing streams also qualify as surface water. The evaluation determines whether radionuclides are likely to migrate to surface waters or their sediments. Where a previous release is not suspected, the potential for future release depends on the distance to surface water and the flood potential at the site. One can also consider the interaction between soil and water in relation to seasonal factors, including soil cracking because of freezing, thawing, and desiccation that influence the dispersal or infiltration of radionuclides.

- **Is surface water nearby?** The proximity of residual radioactive material to local surface water is essentially determined by runoff and radionuclide migration through the soil. The definition for *nearby* depends on site-specific conditions and the time performance period. If the terrain is flat, precipitation is low, and soils are sandy, *nearby* may be within several meters. If annual precipitation is high or occasional precipitation events are high, within 1,200 meters (3/4 mile) might be considered nearby.

- **Is the waste quantity particularly large?** Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance (i.e., a greater risk or hazard) than a *large* quantity of solid waste stored in watertight containers.

- **Is the drainage area large?** The drainage area includes the area of the site itself plus the upgradient area that produces runoff flowing over the site. Larger drainage areas generally produce more runoff and increase the potential for residual radioactive material in surface water.

- **Is precipitation heavy?** If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause precipitation to pool on the site. Otherwise, these characteristics may contribute to high runoff rates that carry radionuclides overland to surface water. Total annual precipitation exceeding one meter (40 in.), or a once in 2-years

24-hour precipitation event exceeding 5 cm (2 in.) might be considered “heavy.”

The amount of precipitation varies for locations across the continental United States from high (e.g., approximately 200 cm/year [y; 89 in./y], Mt. Washington, New Hampshire) to low values (e.g., approximately 10.7 cm/y [4.2 in./y], Las Vegas, Nevada). Certified data on precipitation rates for locations throughout the United States can be obtained from the National Centers for Environmental Information (https://www.ncdc.noaa.gov).

- **Is the infiltration rate low?** Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Paved sites prevent infiltration and generate runoff.
- **Are sources of residual radioactive material poorly contained or prone to runoff?** Proper containment that prevents radioactive material from migrating to surface water generally uses engineered structures such as dikes, berms, run-on and runoff control systems, and spill collection and removal systems. Sources prone to releases via runoff include leaks, spills, exposed storage piles, or intentional disposal on the ground surface. Sources not prone to runoff include underground tanks, aboveground tanks, and containers stored in a building.
- **Is a runoff route well defined?** A well-defined runoff route—along a gully, trench, berm, wall, etc.—will more likely contribute to migration to surface water than a poorly defined route. However, a poorly defined route may contribute to dispersion of radioactive material to a larger area of surface soil.
- **Has deposition of waste into surface water been observed?** Indications of this type of activity will appear in records from past practice at a site or from information gathered during personal interviews.
- **Is ground water discharge to surface water probable?** The hydrogeology and geographical information of the area around and inside the site may be sufficiently documented to indicate discharge locations.
- **Does analytical or circumstantial evidence suggest residual radioactive material in surface water?** Any condition considered suspicious can be considered circumstantial evidence.
- **Is the site prone to flooding?** The Federal Emergency Management Agency publishes flood insurance rate maps that delineate 100-year and 500-year flood plains. Ten-year floodplain maps may also be available. Generally, a site on a 500-year floodplain is not considered prone to flooding.

3.6.3.4 Ground Water

Proper evaluation of ground water includes a general understanding of the local geology and subsurface conditions. Of particular interest is descriptive information relating to subsurface stratigraphy, aquifers, and ground water use.

- **Are sources poorly contained?** Proper containment—which prevents radioactive material from migrating to ground water—generally uses engineered structures, such as liners, layers of low permeability soil (e.g., clay), and leachate collection systems.

- **Is the source likely to affect ground water?** Underground tanks, landfills,[3] surface impoundments, and lagoons are examples of sources that are likely to release residual radioactive material that migrates to ground water. Aboveground tanks, drummed solid wastes, or sources inside buildings are less likely to contribute to residual radioactive material in ground water.

- **Is waste quantity particularly large?** Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance (i.e., greater risk or hazard) than a *large* quantity of solid waste stored in watertight containers.

- **Is precipitation heavy?** If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause precipitation to pool on the site. Otherwise, these characteristics may contribute to high runoff rates that carry radionuclides overland to surface water. Total annual precipitation exceeding one meter (40 in.), or a once in 2-years 24-hour precipitation event exceeding 5 cm (2 in.) might be considered "heavy."

  The amount of precipitation varies for locations across the continental United States from high (e.g., approximately 200 cm/y [89 in/y] in Mt. Washington, New Hampshire) to low values (e.g., approximately 10.7 cm/y [4.2 in/y] in Las Vegas, Nevada). Certified data on precipitation rates for locations throughout the United States can be obtained from the National Centers for Environmental Information (https://www.ncdc.noaa.gov).

- **Is the infiltration rate high?** Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Unobstructed surface areas are potential candidates for further examination to determine infiltration rates.

- **Is the site located in an area of karst terrain?** In karst terrain, ground water moves rapidly through channels caused by dissolution of the rock material (usually limestone) that facilitates migration of radioactive material and chemicals.

- **Is the subsurface highly permeable?** Highly permeable soils favor downward movement of water that may transport radioactive materials. Well logs, local geologic literature, or interviews with knowledgeable individuals may help answer this question.

- **What is the distance from the surface to an aquifer?** The shallower the source of ground water, the higher the threat of residual radioactive material. It is difficult to determine whether an aquifer may be a potential source of drinking water in the future (e.g., next

[3] Landfills can affect the geology and hydrogeology of a site and produce heterogeneous conditions. It may be necessary to consult an expert on landfills and the conditions they generate.

1,000 years). Use the shallowest aquifer below the site when determining the distance to the surface.

- **Are suspected radionuclides highly mobile in ground water?** Mobility in ground water can be estimated based on the distribution coefficient (K_d) of the radionuclide. Elements with a high K_d, like thorium (e.g., K_d = 3,200 cm^3/gram [g]), are not mobile while elements with a low K_d, like hydrogen (e.g., K_d = 0 cm^3/g), are very mobile. EPA provides a compilation of K_d values. These values can be influenced by site-specific considerations such that site-specific K_d values need to be evaluated or determined. Also, the mobility of a radionuclide can be enhanced by the presence of solvents or other chemicals.

- **Does analytical or circumstantial evidence suggest residual radioactive material in ground water?** Evidence for residual radioactive material may appear in current site data; historical, hydrogeological, and geographical information systems records; or as a result of personal interviews.

3.6.3.5 Air

Evaluation of air is different than evaluation of other media with a potential for residual radioactive material. Air is evaluated as a pathway for resuspending and dispersing radioactive material.

- **Were there observations of releases of radioactive material into the air?** Direct observation of a release to the air might occur where radioactive materials are suspected to be present in particulate form (e.g., mine tailings, waste pile) or adsorbed to particulates (e.g., radioactive material in soil), and where site conditions favor air transport (e.g., dry, dusty, windy).

- **Does analytical or circumstantial evidence suggest a release to the air?** Other evidence for releases to the air might include areas of residual radioactive material in surface soil that do not appear to be caused by direct deposition or overland migration of radioactive material.

- **For radon exposure only, are there elevated amounts of radium (^{226}Ra) in the soil or water that could act as a source of radon in the air?** The source ^{226}Ra decays to ^{222}Rn, which is radon gas. Once radon is produced, the gas needs a pathway to escape from its point of origin into the air. Radon is readily released from water sources that are open to air. Soil, however, can retain radon gas until it has decayed (see **Section 6.8**). The rate that radon is emitted by a solid (i.e., radon flux) can be measured directly to evaluate potential sources of radon.

- **Is there a prevailing wind direction and a propensity for windblown transport of radioactive material?** Information pertaining to geography, ground cover (e.g., amount and types of local vegetation), meteorology (e.g., wind speed at 7 meters [23 feet] above ground level) for and around the site, and site-specific parameters related to surface soil characteristics enter into calculations used to describe particulate transport. Mean annual wind speed can be obtained from the National Weather Service surface station nearest to the site.

3.6.3.6 Structures

Structures used for storage, maintenance, or processing of radioactive materials are potential sources of residual radioactive material. The questions presented in **Table 3.1** help determine whether a building might be affected by residual radioactive material. The questions listed in this section are for identifying structures, or portions of structures, that might not be identified using **Table 3.1** but have a potential for residual radioactive material. **Section 4.8.3.1** also presents useful information on identifying structures with residual radioactive material.

- **Were adjacent structures used for the storage, maintenance, or processing of radioactive material?** *Adjacent* is a relative term for this question. A processing facility with a potential for venting radioactive material to the air could deposit residual radioactive material on buildings downwind. A facility with little potential for release outside of the structures handling the material would be less likely to deposit radioactive material on nearby structures.

- **Is a building, its addition, or a new structure located on a former radioactive waste burial site or on land with residual radioactive material?** Comparing past and present photographs or site maps and retrieving building permits or other structural drawings and records in relation to historical operations information will reveal site locations where structures may have been built over buried waste or land with residual radioactive material.

- **Was the building constructed using materials containing residual radioactive material?** Building materials (e.g., concrete, brick, plaster, cement, wood, metal, cinder block) may contain residual radioactive material.

- **Does the potentially non-impacted portion of the building share a drainage system or ventilation system with areas with potential residual radioactive material?** Technical and architectural drawings for site structures, along with visual inspections, are required to determine if this is a concern in terms of current or past operations.

- **Is there evidence that previously identified areas of residual radioactive material were remediated by painting or similar methods of immobilization?** Removable sources of residual radioactive material were sometimes immobilized by painting, partition, or the addition of floor layers (e.g., tiles, carpet). These sources may be more difficult to locate and may need special consideration when planning subsequent surveys.

3.6.4 Develop a Conceptual Model of the Site

Starting with project planning activities, gather and analyze available information to develop a conceptual site model. The model is essentially a site diagram showing locations of known radioactive material, areas of suspected residual radioactive material, types and concentrations of radionuclides in impacted areas, media with potential residual radioactive material, and locations of potential reference (background) areas. The diagram should include the general layout of the site, including buildings and property boundaries. When possible, one should produce three-dimensional diagrams. The conceptual site model will be upgraded and modified as information becomes available throughout the RSSI process. The process of developing this model is also briefly described in Attachment A of EPA 1996a.

The model is used to assess the nature and the extent of residual radioactive material; to identify potential sources of residual radioactive material, release mechanisms, exposure pathways, and human and environmental receptors; and to develop exposure scenarios. Further, this model helps identify data gaps and determine media to be sampled, and it assists staff in developing strategies for data collection. Site history and preliminary survey data generally are extremely useful sources of information for developing this model. The conceptual site model should include known and suspected sources of residual radioactive material, the types of radioactive material, and affected media. Such a model can also illustrate known or potential routes of migration and known or potential human and environmental receptors.

The site should be classified or initially divided into similar areas. Classification may be based on the operational history of the site or observations made during the site reconnaissance (see **Section 3.5**). After the site is classified using current and past site characteristics, further divide the site or facility based on anticipated future use. This classification can help (1) assign limited resources to areas that are anticipated to be released without restrictions, and (2) identify areas with little or no possibility of unrestricted release. **Figure 3.2** shows an example of how a site might be classified in this manner. Further classification of a site may be possible based on site disposition recommendations (unrestricted vs. release with passive controls).

3.6.5 Professional Judgment

In some cases, traditional sources of information, data, models, or scientific principles are unavailable, unreliable, conflicting, or too costly or time consuming to obtain. In these instances, professional expert judgment may be the only practical tool available to the investigator or regulator. Expert judgment, or “expert elicitation,” means using the judgments obtained from experts about their field of expertise that are explicitly stated and documented for review and appraisal by others. It is a formal, highly structured, and well-documented process for obtaining the judgment of multiple experts regarding a scientific inquiry or decisionmaking (NRC 1990). For most instances, the issue is not whether to use judgment, but whether to use it in an explicit and disciplined fashion or in an ad hoc manner. An important interrelated question is when and whose judgment should be used. For this guidance, it is often useful to formalize the elicitation and use of judgment for significant technical, environmental, and socioeconomic problems. For general applications, this type of judgment is a routine part of scientific investigation where knowledge is incomplete. For MARSSIM guidance, professional judgment can be used as an independent review of historical data to support decision-making during the HSA or the use of statistical tools or methodology. Professional or expert judgment should be used as necessary, particularly in situations where data are not reasonably obtainable by collection, experimentation, field measurements, or when the cost of data collection is prohibitive.

Typically, the process of recruiting professionals for expert judgment should be documented and as unbiased as possible. The credentials of the selected individual or individuals should enhance the credibility of the elicitation, and their ability to communicate their reasoning is a primary determinant of the quality of the results. Qualified expert professionals can be identified

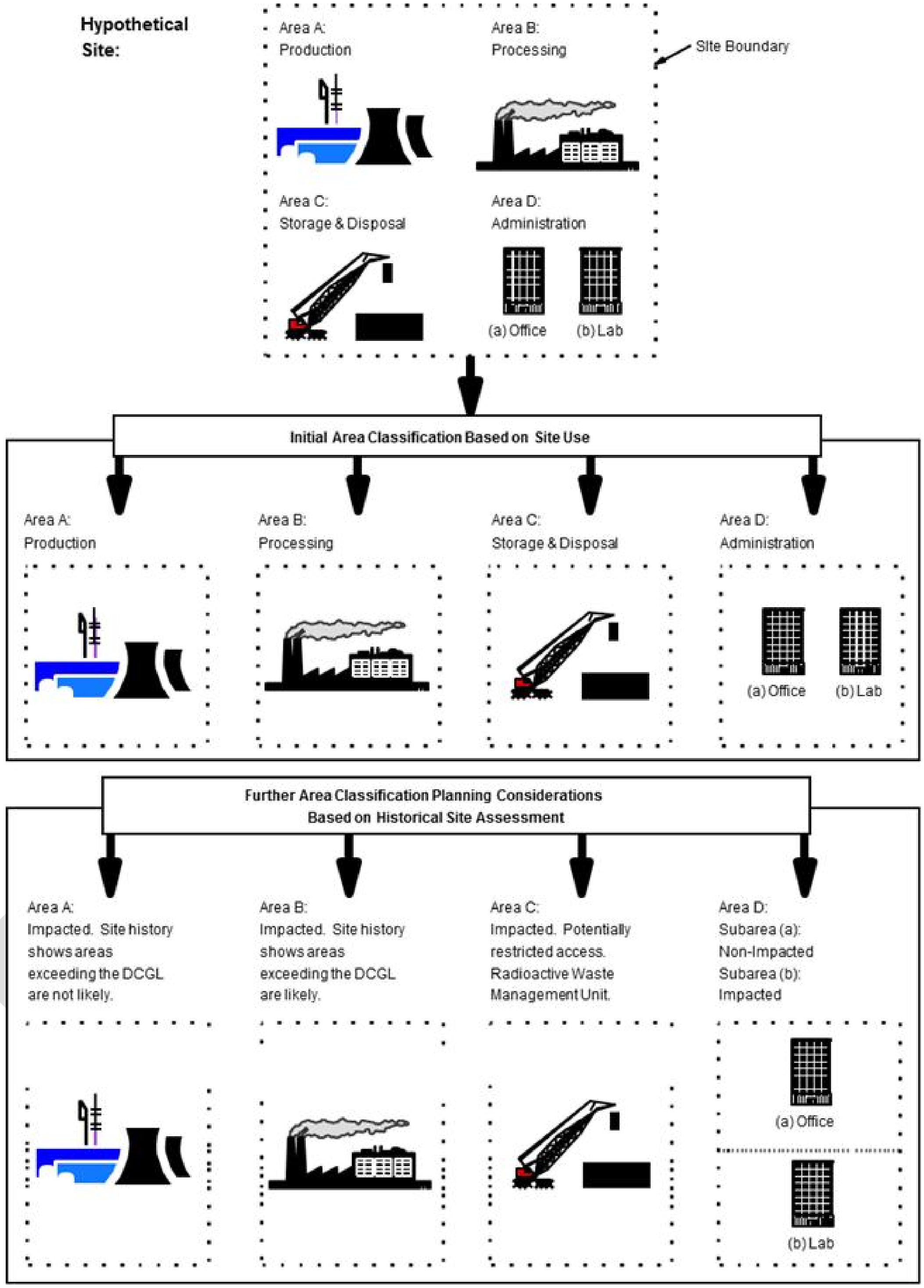

Figure 3.2: Example Showing How a Site Might be Categorized Before Cleanup Based on the Historical Site Assessment

by different sources, including the planning team, professional organizations, government agencies, universities, consulting firms, and public interest groups. The selection criteria for the professionals should include potential conflict of interest (economic or personal), evidence of expertise in a required topic, objectiveness, and availability.

3.7 Determining the Next Step in the Site Investigation Process

Upon completion, the HSA will support one of three possible recommendations:

1. An emergency action may be necessary to reduce the risk to human health and the environment, such as a Superfund removal action, which is discussed in detail by EPA (EPA 1988a).
2. The site or area is categorized as impacted, and further investigation is needed before a decision regarding final release can be made. The area may be classified as Class 1, Class 2, or Class 3, and a scoping survey or a characterization survey may be performed as necessary. Information collected during the HSA can be very useful in planning these subsequent survey activities.
3. The site or area is categorized as non-impacted, a term that is applied where there is no reasonable potential to contain radionuclide concentration(s) or radioactive material above background (10 CFR 50). The site or area can be released.

As stated in **Section 1.1,** the purpose of this manual is to describe a process-oriented approach for demonstrating that the concentration of residual radioactive material does not exceed the release criteria. The highest probability of demonstrating this can be obtained by sequentially following each step in the RSSI process. In some cases, however, performing each step in the process is not practical or necessary. This section provides information on how the results of the HSA can be used to determine the next step in the process.

The best method for determining the next step is to review the purpose for each type of survey described in **Chapter 5.** For example, a scoping survey is performed to provide sufficient information for determining (1) whether the present residual radioactive material warrants further evaluation, and (2) initial estimates of the level of effort for decontamination and for preparing a plan for a more detailed survey. If the HSA demonstrates that this information is already available, do not perform a scoping survey. On the other hand, if the information obtained during the HSA is limited, a scoping survey may be necessary to narrow the scope of the characterization survey.

The exception to conducting additional surveys before an FSS is the use of HSA results to release a site. Generally, the analytical data collected during the HSA are not adequate to statistically demonstrate compliance for impacted areas as described in **Chapter 8.** This means that the decision to release the site will be based on professional judgment. This determination will ultimately be decided by the responsible regulatory agency.

3.8 Historical Site Assessment Report

A narrative report is generally the best format to summarize what is known about the site, what is assumed or inferred, activities conducted during the HSA, and all researched information. Cite a supporting reference for each factual statement given in the report. Attach copies of references (i.e., those not generally available to the public) to the report. The narrative portion of the report should be written in plain English and avoid the use of technical terminology.

A sample HSA report format is provided in **Example 1.** Additional information not identified in the outline may be requested by the regulatory agency at its discretion. The level of effort to produce the report should reflect the amount of information gathered during the HSA.

3.9 Review of the HSA

The planning team should ensure that someone (a first reviewer) conducts a detailed review of the HSA report for internal consistency and as a QC mechanism. A second reviewer with considerable site assessment experience should then examine the entire information package to ensure consistency and to provide an independent evaluation of the HSA conclusions. The second reviewer also evaluates the package to determine if special circumstances exist where radioactive material may be present but not identified in the HSA. Both the first reviewer and the second independent reviewer should examine the HSA written products to ensure internal consistency in the report's information, summarized data, and conclusions. The site review ensures that the HSA's recommendations are appropriate.

An important QA objective is to find and correct errors. A significant inconsistency indicating either an error or a flawed conclusion, if undetected, could contribute to an inappropriate recommendation. Identifying such a discrepancy directs the HSA investigator and site reviewers to re-examine and resolve the apparent conflict.

Under some circumstances, experienced investigators may have differing interpretations of site conditions and draw differing conclusions or hypotheses regarding the likelihood of residual radioactive material. Any such differences should be resolved during the review. If a reviewer's interpretations contradict those of the HSA investigator, the two should discuss the situation and reach a consensus. This aspect of the review identifies significant points about the site evaluation that may need detailed explanation in the HSA narrative report to fully support the conclusions. Throughout the review, the HSA investigator and site reviewers should keep in mind the need for conservative judgments in the absence of definitive proof to avoid underestimating the presence of residual radioactive material, which could lead to an inappropriate HSA recommendation.

Example 1: HSA Report Format

1. Glossary of Terms, Acronyms, and Abbreviations
2. Executive Summary
3. Purpose of the Historical Site Assessment
4. Property Identification
    1. Physical Characteristics
        1. Name—CERCLIS ID# (if applicable) owner/operator name, address
        2. Location—street address city county state geographical coordinates
        3. Topography—USGS 7.5-minute quadrangle or equivalent
        4. Stratigraphy
    2. Environmental Setting
        1. Geology
        2. Hydrogeology
        3. Hydrology
        4. Meteorology
5. Historical Site Assessment Methodology
    1. Approach and Rationale
    2. Boundaries of Site
    3. Documents Reviewed
    4. Property Inspections
    5. Personal Interviews
6. History and Current Usage
    1. History—years of operation, type of facility, description of operations, regulatory involvement permits and licenses, waste handling procedures
    2. Current Usage—type of facility, description of operations, probable source types and sizes, description of spills or releases, waste manifests, radioactive inventories, emergency or removal actions
    3. Adjacent Land Usage—sensitive areas, such as wetlands or preschools
7. Findings
    1. Potential Sources of Residual Radioactive Material
    2. Potential Areas with Residual Radioactive Material
        1. Impacted Areas—Known and Potential
        2. Non-Impacted Areas
    3. Potential Media with Residual Radioactive material
    4. Related Environmental Concerns
8. Conclusions
9. References
10. Appendices
    A. Conceptual Model and Site Diagram Showing Classifications
    B. List of Documents
    C. Photo Documentation Log
        a. Original Photographs of the Site and Pertinent Site Features

4 CONSIDERATIONS FOR PLANNING SURVEYS

4.1 Introduction

4.1.1 Purpose

This chapter is intended to introduce the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) user to general considerations for planning MARSSIM-based surveys by presenting areas of consideration common to Radiation Surveys and Site Investigations (RSSIs) with an emphasis on final status surveys (FSSs).[1] Detailed technical information about planning surveys will follow in the subsequent chapters. For the purposes of this chapter, it is assumed that a Historical Site Assessment (HSA) has been performed, and the results are available to the survey design team.

4.1.2 Scope

The emphasis in MARSSIM is on FSSs of surface soil and surfaces of buildings and outdoor areas to demonstrate compliance with cleanup regulations. However, MARSSIM discusses four types of surveys:

- Scoping
- Characterization
- Remedial Action Support (RAS)
- Final status

These survey types are discussed in more detail in **Chapter 5.** The emphasis on FSSs should be kept in mind during the design phase of all surveys. The topics discussed in this chapter focus on planning the FSS.

4.1.3 Overview of Survey Planning

In the following sections of this chapter, you will be introduced to many potentially unfamiliar concepts, terms, definitions, etc., specifically related to planning surveys. Informal definitions will be given in this chapter; however, the reader should refer to the **Glossary** for complete definitions. The following topics related to survey planning are discussed in this chapter:

- *Data Quality Objectives (DQO) process:* The DQO process is used to develop performance and acceptance criteria that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.
- *Survey types:* There are four MARSSIM survey types: scoping, characterization, RAS, and final status. The emphasis of this chapter will be on FSSs.

[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

- *Unity rule:* The unity rule is used when more than one radionuclide is present at a concentration that is distinguishable from background and where a single concentration comparison does not apply. In this case, the mixture of radionuclides is compared against default concentrations by applying the unity rule. This is accomplished by determining: (1) the ratio between the concentration of each radionuclide in the mixture, and (2) the concentration for that radionuclide in an appropriate listing of default values. The sum of the ratios for all radionuclides in the mixture should not exceed 1.
- *Radionuclides and derived concentration guideline levels (DCGLs):* The design team needs to determine the radionuclides of concern and final form of the DCGLs. The DCGLs are typically based on dose (or risk) pathway modeling, which is used to determine release criteria expressed in measurable radiological quantities. These can be a soil concentration, surface (areal) concentration, or external dose (or exposure) rate.
- *Area and site considerations:* Properly classifying areas as impacted or non-impacted, identifying survey units, and selecting background reference areas is critical for the successful execution of a FSS.
- *Statistical considerations:* MARSSIM recommends the use of statistical hypothesis testing in all but the simplest of surveys (See **Appendix B**). The MARSSIM user must be conversant with the statistical concepts discussed in the manual and should consider incorporating a statistician in the design team.
- *Measurements:* The detection capabilities of all the measurement (sampling included) techniques must be evaluated to ensure that the data and measurement quality objectives are met.
- *Site preparation:* Site preparation includes efforts to gain permission to access the site, ensuring that the survey team and equipment can operate safely, and establishing the logistical means to perform the survey should be started early.
- *Health and safety:* The health and safety of the workers is a high priority, so each site must have a documented health and safety plan.
- *Survey design examples:* A few simplified examples are presented in **Section 4.12** to illustrate the process for planning surveys.

4.2 Data Quality Objectives Process

DQOs were introduced in **Chapter 1,** expanded upon in **Chapter 2,** and discussed in detail in **Appendix D.** The survey design team must be familiar with the DQO process to properly design a survey. The DQO process can be summarized in seven steps:

1. State the problem.
2. Identify the decisions to be made.
3. Identify inputs to the decision.
4. Define the study boundaries.
5. Develop a decision rule.

6. Specify limits on decision errors.
7. Optimize the survey design.

4.2.1 Planning Phase

Using the DQO process allows the survey design team to use a graded approach to ensure that the level of effort meets the design goals in a technically defensible and cost-effective manner. The intent of any survey is to ensure that the decision makers have the appropriate type, quantity, and quality of environmental data needed to make the correct decision. DQOs are qualitative and quantitative statements derived from the DQO process that do the following:

- *Clarify the study objective:* The first step in any survey is to determine the objectives of the survey (DQO Steps 1 and 2). Depending on the data available from the previous RSSI activities (e.g., HSA review), the objectives of a survey can range from augmenting HSA information to be used as input in designing a characterization survey to releasing a survey unit. An important part of this clarification is the determination of the initial condition of each survey unit: The survey unit is assumed to be “not clean” (Scenario A) or “clean” (Scenario B). See **Section 2.5.1** and **Sections D.1.1 and D.1.2** of **Appendix D** for more details.

- *Define the most appropriate type of data to collect:* Once the objectives of the survey have been agreed upon, the design team needs to determine what data need to be collected (DQO Step 3). Implicit in this step is the determination of the radionuclides of concern, choice of equipment, detection limits, analytical methods, statistical tests, etc., that will be used to meet the objectives of the survey.

- *Determine the most appropriate conditions for collecting the data:* In general, the “study boundaries” of a survey (DQO Step 4) are spatial; for example, the selection of the survey units. However, if the objective of the survey is to collect data for classification, then the spatial boundary of the survey might be the entire site under consideration. Throughout the RSSI process, decisions need to be made; for example, based on a review of the HSA’s conclusions and the results of scoping/characterization surveys, the decision maker will determine survey unit boundaries and classifications.

- *Specify limits on decision errors that will be used as the basis for establishing the quantity and quality of data needed to support the decision:* To make decisions, the outputs of the survey must be in a form amenable to decision-making (DQO Step 5). MARSSIM recommends the use of statistical hypothesis testing to make decisions to release a survey unit. Because of the overall uncertainty in the surveying process, there is always a chance of a decision error (e.g., incorrectly concluding that a survey unit meets the release criteria, when in fact it does not). The chance of a decision error cannot be eliminated; however, it can be controlled (DQO Step 6). The survey design team must be aware of the chance of decision errors and take measures to control them (e.g., collecting more samples, using more precise measurement techniques, and using better surveying and sampling designs).

When the previous steps are completed, the survey design team can optimize the survey plan (DQO Step 7); the team might need to work through this step several times to arrive at the best design. **Appendix D** discusses the planning phase of the data life cycle in detail. The MARSSIM user should read and be conversant with **Appendix D.**

Regardless of the survey type under consideration, the DQOs remain the overarching guide for planning; the design team needs to explain the "who, what, where, when, why, and how" for a survey.

4.2.2 Quality System

MARSSIM requires that all environmental data collection and use take place in accordance with a site-specific systematic planning process that incorporates industry-established quality assurance and quality control (QA/QC). The goal of a QA/QC program is to identify and implement sampling and analytical methodologies which limit the introduction of error into analytical data. For MARSSIM data collection and evaluation, a quality system is needed to ensure that radiation surveys produce results that are of the type and quality needed and expected for their intended use. A quality system is a management system that describes the elements necessary to plan, implement, and assess the effectiveness of QA/QC activities. This system establishes many functions, including—

- quality management policies and guidelines for the development of organization- and project-specific quality plans
- criteria and guidelines for assessing data quality
- assessments to ascertain the effectiveness of QA/QC implementation
- training programs related to QA/QC implementation.

A quality system ensures that MARSSIM decisions will be supported by sufficient data of adequate quality and usability for their intended purpose, and it further ensures that such data are authentic, appropriately documented, and technically defensible. MARSSIM uses the project-level components of a quality system as a framework for planning, implementing, and assessing environmental data collection activities.

In accordance with the environmental data quality system described in **Appendix D,** all environmental data collection and use are to take place in accordance with a site-specific systematic planning process (SPP) that consists of planning, implementation, and assessment phases. The results of the SPP are usually documented in a Quality Assurance Project Plan (QAPP). A QAPP integrates all technical and quality aspects and defines in detail how specific QA/QC activities will be implemented during the survey project will be developed. The Uniform Federal Policy (UFP) for QAPPs (EPA 2005a, 2005b, 2005c) was developed to provide procedures and guidance for consistently implementing the national consensus standard ANSI/ASQ E-4, Quality Systems for Environmental Data and Technology Programs, for the collection and use of environmental data. The UFP for QAPPs is presented in three volumes:

- Part 1, UFP-QAPP Manual (EPA-505-B-04-900A, DTIC ADA 427785) (EPA 2005a.)
- Part 2A, UFP-QAPP Workbook (EPA-505-B-04-900C, DTIC ADA 427486) (EPA 2005c.)
- Part 2B, Quality Assurance/Quality Control Compendium: Minimum QA/QC Activities (EPA-505-B-04-900B, DTIC ADA 426957) (EPA 2005b.)

Using this scientific, logical approach to planning for data collection and assessment at a site helps ensure that the amounts and types of data collected are appropriate for decisionmaking and that the physical, environmental, chemical, and radiological characteristics of the site are adequately defined. The development of a QAPP is one of the first team-based QA/QC activities performed in the project planning stage.

The objective of the UFP-QAPP is to provide a single national consensus document for consistently and systematically implementing the project-specific requirements of ANSI/ASQ E4 (ASQC 1995) and help ensure the quality, objectivity, utility, and integrity of environmental data. Information on selecting the number and type of QC measurements for a specific project are provided in **Section 3.4;** Tables 4, 5, and 6 of the UFP-QAPP Part 1; and Worksheet 28 of the UFP-QAPP Part 2A.

Minimum QA/QC activities are specified for all environmental data collection and use in the UFP-QAPP Part 2B. However, this matrix of minimum requirements is not meant to be a replacement for a site-specific QAPP. A wide range of site-specific guidelines for data collection activities specified in the survey plan should be determined that relate to the ultimate use of the data. These guidelines include, but are not limited to—

- types of decisions that will be supported by the data
- project quality objectives
- acceptance criteria for data quality indicators (also known as measurement performance criteria)
- survey plan, including location of environmental and QC samples and measurements
- types of radionuclides and analyses that require laboratory analysis (on-site, field, or fixed lab)

The QA/QC activities specified in the QA matrix represent a minimum list of activities. Other QA/QC activities may be added, depending on the decisions to be made and on site-specific conditions. The matrix of minimum QA/QC activities is organized by—

- survey type (i.e., scoping or characterization) for surveys prior to the FSS
- data uses (e.g., confirmatory measurements) for RAS surveys
- data type (i.e., screening versus definitive data)
- project stage (i.e., plan, implement, assess, decide)

4.3 Survey Types

4.3.1 Scoping

MARSSIM defines a scoping survey as "a type of survey that is conducted to identify (1) radionuclides present, (2) relative radionuclide ratios, and (3) general concentrations and extent of residual radioactive material." In conjunction with an HSA, the results of a scoping survey can help determine (1) preliminary radionuclides of concern, (2) interim site and survey unit boundaries, (3) initial area classifications, (4) data gaps, and (5) initial estimates of the level of effort for remediation, and (6) information for planning a more detailed survey, such as a characterization survey. Methods for planning, conducting, and documenting scoping surveys are described in **Section 5.2.1.**

4.3.2 Characterization

MARSSIM defines a characterization survey as “a type of survey that includes facility or site sampling, monitoring, and analysis activities to determine the extent and nature of residual radioactive material. Characterization surveys provide the basis for acquiring necessary technical information to develop, analyze, and select appropriate cleanup techniques.” Characterization surveys can be developed to meet a very broad range of objectives, many of which are outside the scope of MARSSIM. The guidance in **Section 5.2.2** concentrates on providing characterization survey planning information with an emphasis on the FSS design.

4.3.3 Remedial Action Support

MARSSIM defines remedial action as “Those actions that are consistent with a permanent remedy taken instead of, or in addition to, removal action in the event of a release or threatened release of a hazardous substance into the environment, to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment.” A RAS survey supports remediation activities and is used to monitor the effectiveness of remediation efforts intended to reduce residual radioactive material to acceptable levels. The general objectives of an RAS are to (1) support remediation activities, (2) determine when a site or survey unit is ready for the FSS, and (3) provide updated estimates of site-specific parameters to use for planning the FSS. Methods for planning, conducting, and documenting an RAS are described in **Section 5.2.3.**

4.3.4 Final Status

4.3.4.1 Survey

MARSSIM defines an FSS as “measurements and sampling to describe the radiological conditions of a site, following completion of remediation activities (if any) in preparation for release.” An FSS is performed to demonstrate that a survey unit meets the agreed-upon release criteria. In other words, that FSS is designed to answer the question, “Does the concentration of residual radioactive material in each survey unit satisfy the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations (restricted release)?” The primary objective of MARSSIM is the FSS. The design of FSSs is discussed in detail in **Section 5.3,** with the remainder of MARSSIM expanding on the design, execution, and assessment of FSSs.

Figure 4.1 illustrates the sequence of activities described in this chapter and their relationship to the survey design process.

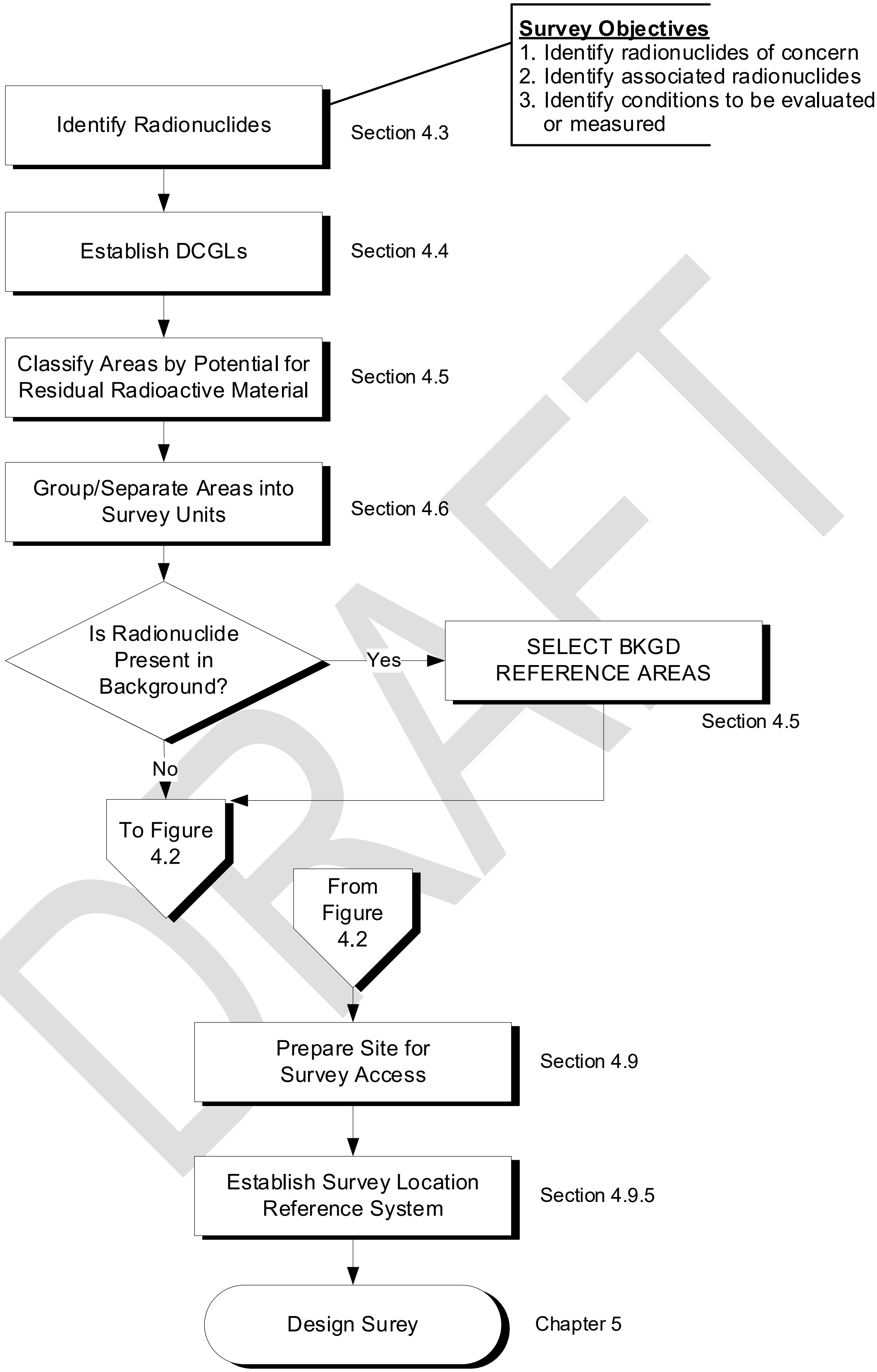

Figure 4.1: Sequence of Preliminary Activities Leading to an FSS Design

4.3.4.2 Verification Process

Historically, regulators commissioned verification surveys after the completion of an FSS. However, the application of the DQO process to the verification process has led to the development of more effective processes, such as in-process decommissioning inspections (Abelquist, 2014). For example, NRC (2008) and DOE (2011c) require verification inspections of some sort; these documents can be used as guides for including verification processes in the FSS design project. The personnel who plan and execute an FSS should be familiar with independent verification (IV) process and be prepared to work with regulators and their contractors to support the verification process during all phases of the FSS. Abelquist (2014) provides an example of decommissioning inspection plan that might be useful when designing an FSS.

Bailey (2008) summarized the experiences from IV activities of Oak Ridge Institute for Science and Education (ORISE) in support of U.S. Department of Energy decommissioning projects. In conclusion, Bailey (2008) states that—

> Independent verification should be integrated into the planning stages rather than after the cleanup contractor has completed the remediation work and demobilized from the site. The IV of onsite remediation and FSS activities should be coordinated and if possible implemented in parallel with the contractor to minimize schedule impacts. A well-implemented and thorough IV program for a site requires IV involvement throughout the D&D [Decontamination and Decommissioning] process. Independent verification is not a substitute for routine contractor quality assurance; however, IV activities often improve the contractor's performance. IV recommendations often improve the contractor's FSS procedures and results, while increasing the probability of complete remediation and documentation.

4.3.5 Simplified Procedures

The design team should be aware that under certain conditions (e.g., sites where only small quantities of radioactive materials exempted from or not requiring a specific license) a simplified procedure might be able to be used to demonstrate regulatory compliance. The design team should refer to **Appendix B** and seek regulatory approval before using this simplified procedure.

4.3.6 A Note on Subsurface Assessments

Many users might need to assess subsurface residual radioactive materials. Strictly speaking, this is beyond the scope of MARSSIM; however, the general concepts contained in MARSSIM (e.g., the DQO process, statistical survey and sampling design, etc.) may be appropriate to address subsurface contamination. As always, any approach to site decommissioning needs to be discussed with the appropriate regulatory authorities.

4.3.7 Uranium Mill Tailings Radiation Control Act of 1978 Sites

At Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) sites, EPA's Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (see 40 CFR 192) are applicable. However, the technical requirements in these standards are not always consistent with some of the recommendations in MARSSIM. Specifically, the soil cleanup standards for ^{226}Ra and ^{228}Ra are specified as averages over an area of 100 square meters (m^2). Additional details for planning at UMTRCA site are provide in **Section 4.12.9.**

4.4 The Unity Rule

The unity rule is used to ensure that the total dose (risk) from all sources (or media) and all radionuclides associated with each source does not exceed the release criteria. It is to be used when more than one radionuclide is present and distinguishable from background and a single concentration does not apply. Essentially, this means that if measurements of different quantities are made at a location, then the unity rule must be used. For example, the unity rule would be used if two radionuclides are measured in each soil sample or if gross alpha and gross beta measurements are made at each location and the results are being compared to specific DCGLs.

The total amount of anything, whether dose, counts, or activity, is simply the sum of its parts (M_i):

$$\text{Total} = M_1 + M_2 + \cdots + M_i + \cdots + M_n = \sum_{i=1}^{n} M_i \qquad (4\text{-}1)$$

Dividing both sides of **Equation (**4-1) by the total yields the following fundamental equation (**Equation (**4-2)):

$$1 = f_1 + f_2 + \cdots + f_i + \cdots + f_n = \sum_{i=1}^{n} f_i \qquad (4\text{-}2)$$

The basic statement of this equation is that sum of all fractions must add to unity (1).

When using the sum of fractions to demonstrate compliance in MARSSIM, each fraction is determined by dividing each “part” (e.g., the concentration of residual radioactive material due to a specific radionuclide/source) by the respective release criterion (e.g., a derived concentration guideline level [DCGL]). In an FSS for a survey unit to be released, the dose or risk from all radionuclides and all sources in a survey unit must be less than or equal to the applicable release criterion, and the sum of fractions for multiple radionuclides/sources must be less than or equal to unity:

$$\text{Total Dose or Risk} = \sum_{i=1}^{n} (\text{Dose or Risk Component})_i \leq \text{Release Criterion} \qquad (4\text{-}3)$$

Dividing the terms in **Equation (**4-3) by the applicable release criterion:

$$\frac{\text{Total Dose or Risk}}{\text{Release Criterion}} = \sum_{i=1}^{n} \left(\frac{\text{Dose or Risk Component}}{\text{Release Criterion}} \right)_i \leq 1 \qquad (4\text{-}4)$$

If the dose/risk components and release criteria are expressed as concentrations (e.g., express the dose/risk as concentration and release criterion as DCGLs as discussed above), **Equation (**4-4) can be written in terms of concentrations (see **Equation (**4-5)):

$$\sum_{i=1}^{n} \left(\frac{\text{Dose or Risk Component}}{\text{Release Criterion}} \right)_i = \sum_{i=1}^{n} \frac{\mathrm{C}_i}{\mathrm{DCGL}_i} \leq 1 \qquad (4\text{-}5)$$

where

- C_i is the concentration of the ith component (e.g., radionuclide or source) leading to dose or risk.
- DCGL_i is the derived concentration guideline level of the ith component (e.g., radionuclide or source) leading to dose or risk.

This is the traditional form of the unity rule as used and defined in MARSSIM.

Other applications of **Equation (**4-1) or derivatives, such as deriving a gross activity DCGL, will be covered in the corresponding section of this and other chapters as needed.

4.5 Radionuclides

4.5.1 Radionuclides of Concern

During the design of an FSS, the survey team should thoroughly review of all the remediation activities conducted before the FSS to determine the radionuclides of concern and their expected concentrations in each survey unit. The team should also determine if the concentrations of the radionuclides of concern in the background need to be accounted for in the FSS design; for example, if a radionuclide is not present in the background, the FSS can be designed based on the one-sample Sign test.

If neither remedial action nor HSA data exist, then the survey design team should make the identification of the radionuclides of concern a primary objective of the team’s actions. Whether through an HSA, a scoping survey, a characterization survey, or some combination of them, the team must make an initial characterization of the types, concentrations, and distribution of the residual radioactive material at the site.

4.5.2 Release Criteria and Derived Concentration Guideline Levels

The decommissioning process ensures that residual radioactive material will not result in individuals being exposed to unacceptable levels of radiation dose or risk. Regulatory agencies establish radiation dose standards based on risk considerations and scientific data relating dose to risk. These radiation dose standards are the fundamental release criteria; however, they are not measurable. To translate these release criteria into measurable quantities, residual levels of radioactive material corresponding to the release criteria are derived (calculated) by analysis of various pathways (e.g., direct radiation, inhalation, and ingestion) and scenarios (e.g., resident farmer, industrial, recreational) through which exposures could occur.

These DCGLs are usually presented in terms of surface or mass activity concentrations of radioactive material (typically becquerels [Bq]/m^2, disintegrations per minute/centimeters squared [dpm/100 cm^2], Bq/kilogram [Bq/kg], or picocurie/gram [pCi/g], respectively). The details of the derivation of DCGLs are beyond of the scope of MARSSIM. However, the survey design team should understand how DCGLs were derived, because the models and assumptions used to derive DCGLs can drive how measurements are made. For example, if DCGLs for soil were derived based on an assumption that the residual radioactive material was restricted to the top 15 cm of soil, a condition verified in a characterization survey, then for the FSS it would not be appropriate to collect soil samples from the top 30 cm of soil. In many cases, generally applicable DCGLs can be obtained from the relevant regulatory agency. In other cases, DCGLs derived for site-specific conditions can be used with permission of the relevant regulatory agency.

There are two types of DCGLs ($DCGL_W$ and $DCGL_{EMC}$)[2] applicable to satisfying decommissioning objectives:

- The $DCGL_W$ is the mean[3] concentration of residual radioactive material within a survey unit that corresponds to release criteria (e.g., regulatory limit in terms of dose or risk).
- The $DCGL_{EMC}$ accounts for the smaller area of elevated residual radioactive material and is typically derived based on dose (or risk) pathway modeling. The $DCGL_{EMC}$ is always greater than or equal to the $DCGL_W$.

The contributions to dose or risk from both the uniform area and areas of elevated residual radioactive material, if applicable, must meet the condition expressed in **Equation 8-4** in **Section 8.6.2.** The development of regulatory requirements leading to the establishment of a $DCGL_{EMC}$ is beyond the scope of MARSSIM and is determined strictly through the requirements of regulatory agencies. Therefore, it is important to work with the applicable regulatory agency to determine whether requirements for a $DCGL_{EMC}$ should be consistent with the approach presented in MARSSIM or those in regulatory documents. When properly justified to and accepted by the regulatory agency, no $DCGL_{EMC}$ requirement may be needed at all. $DCGL_{EMC}$s and associated requirements for areas of elevated radioactive material should be clearly stated and properly approved, and surveys should demonstrate compliance with those requirements. More discussion about elevated areas of radioactive material and their consideration during radiological survey activities can be found in **Section 5.3.5.**

To prove compliance with requirements for discrete radioactive particles, some surveys have used the MARSSIM Elevated Measurement Comparison (EMC) process (see **Section 8.6.1**). As discussed in **Section 4.12.8,** the MARSSIM EMC process might not apply to discrete radioactive particles; the survey design team should use the DQO process to address such particles in surface soils or building surfaces. More discussion about discrete radioactive

[2] The "W" in $DCGL_W$ colloquially refers to "wide-area" or "average." The "EMC" in $DCGL_{EMC}$ refers to the Elevated Measurement Comparison.
[3] The mean is sum of the values divided by the number of measurements and is commonly called the average.

particles and their consideration during radiological survey activities can be found in **Section 4.12.8.**

The MARSSIM user should remember five things about release criteria and DCGLs:

- The fundamental release criteria are dose or risk based and cannot be measured.
- The fundamental release criteria are translated into measurable DCGLs.
- The determination of acceptable DCGLs must be coordinated with the regulator.
- The derivation of radionuclide-specific DCGLs is beyond the scope of MARSSIM.
- The application of radionuclide-specific DCGLs to derive operational DCGLs for FSSs is the responsibility of MARSSIM user.

4.5.3 Applying DCGLs

This section focuses on introducing the application and modifications of DCGLs to derive operational DCGLs for various situations commonly encountered while planning FSSs. An operational DCGL is any modification or combination of radionuclide-specific DCGLs to derive measurable quantity (e.g., a gross beta activity DCGL). The simplest application of a DCGL is when a single radionuclide is distributed uniformly throughout a survey unit. When multiple radionuclides are present in a survey unit, (1) the ratios of the concentrations of radionuclides are roughly constant (correlated), or (2) the concentrations are unrelated. There are statistical tests that can be performed to calculate the degree of correlation among the concentrations. Ultimately, sound judgment must be used when interpreting the results of the calculations. If there is no physical reason for the concentrations to be correlated, then they are likely not. However, if there is sound evidence of correlation, then that evidence should be used. The survey design team should consult closely with the appropriate regulatory agency during the design phase.

Fundamentally, the measurement of residual radioactive material involves one or more of the following:

- radionuclide-specific analyses
- gross activity measurements
- external radiation measurements

The choice of the operational DCGL depends on the types of measurements being made. If multiple radionuclides are considered using gross activity measurements, then it might be acceptable to use the smallest DCGL of the radionuclides present. To use surrogate measurements to demonstrate compliance, all significant radionuclides should be identified, the contributions of the various radionuclides should be known, and DCGLs should be developed for each of the radionuclides of concern. If there is a well-established correlation between radionuclide concentrations, then a weighted gross activity DCGL or surrogate-based DCGL might be acceptable. If no correlation exists or a combination of the above options is proposed, then the unity rule must be used.

4.5.3.1 DCGLs for a Single Radionuclide

For a single radionuclide, compliance can be easily demonstrated if all the measurements in the survey unit are below the DCGL. Otherwise, an appropriate statistical test must be used. This is straightforward when there is one radionuclide (e.g., Sr/Y-90) where radioactive decay products are included in the DCGL. If the radioactive decay products are not included in the DCGL, and the radioactive decay products are present, the survey team must use one of the methods outlined below. Additionally, the methods described below can be used for radionuclides that are not part of the same decay chain (e.g., presence of a mix of fission products, such as Sr-90 and Cs-137).

If a DCGL for the parent of a serial decay chain includes contributions from the progeny, then the direct application of that DCGL is possible. It is incumbent on the design team to determine if the radionuclides of concern are parents of a decay series and if progeny are accounted for in all DCGLs. For example, values for natural thorium (Th-nat) and natural uranium (U-nat) typically include progeny; however, the design team must confirm this for each case. For information on serial radioactive decay, see **Section 4.5.3.8.**

4.5.3.2 Most Conservative DCGL Approach for Multiple Radionuclides

If there are multiple radionuclides in a survey unit, then it might be possible to use the lowest (most restrictive) DCGL. Note that if $DCGL_{min}$ is the lowest of the DCGLs, then **Equation (**4-6) applies, and $DCGL_{min}$ may be applied to the total activity concentration rather than using the unity rule.

$$\frac{C_1}{DCGL_1}+\frac{C_2}{DCGL_2}+\cdots+\frac{C_n}{DCGL_n}\leq\frac{(C_1+C_2+\cdots+C_n)}{DCGL_{min}}\leq 1 \qquad (4\text{-}6)$$

The goal is then to demonstrate that the ratio of the total concentration of all radionuclides to $DCGL_{min}$ is less than 1, or alternatively that the total concentration of all radionuclides is less than $DCGL_{min}$. Although this option may be considered, in many cases it will be too conservative to be useful. Furthermore, the ease of detection must be taken into account during the DQO process if use of the $DCGL_{min}$ is being considered.

4.5.3.3 DCGLs for Multiple Radionuclides in Known Ratios (Surrogate Measurements)

For sites with multiple radionuclides, it may be possible to measure just one of the radionuclides and still demonstrate compliance for all radionuclides present by using surrogate measurements. If there is an established ratio among the concentrations of the radionuclides in a survey unit, then the concentration of every radionuclide can be expressed in terms of any one of them. The measured radionuclide is often called a *surrogate* radionuclide for the others. In this case, the unity rule can be used to derive a new, modified DCGL for the surrogate radionuclide, which accounts for the dose or risk contributions of the other radionuclides that are not measured.

The fundamental aspect of the unity rule is that the sum of the ratios of the concentrations to the DCGLs for each radionuclide should be less than or equal to one, as shown in **Equation (**4-7)**:**

$$\sum_{i=1}^{n} \frac{\mathrm{C}_i}{\mathrm{DCGL}_i} \leq 1 \tag{4-7}$$

where

- C_i is the concentration of the ith radionuclide.
- DCGL_i is the DCGL of the ith radionuclide.

The terms in the denominator are the original, unmodified DCGLs for all the radionuclides in the survey unit. However, when using a surrogate radionuclide, the design team needs to ensure that the DCGL for the surrogate radionuclide is modified ($\mathrm{DCGL_{S\text{-}mod}}$) to account for the presence of all the radionuclides. This is done by applying the unity rule as shown in **Equation (**4-8**:**

$$\frac{\mathrm{C}_s}{\mathrm{DCGL_{S\text{-}mod}}} \leq 1 \tag{4-8}$$

where

- C_s is the concentration of the surrogate radionuclide.
- $\mathrm{DCGL_{S\text{-}mod}}$ is the modified DCGL for the surrogate radionuclide.

Here, $\mathrm{DCGL_{S\text{-}mod}}$ is the DCGL for the surrogate radionuclide modified so that it represents all radionuclides that are present in the survey unit. The $\mathrm{DCGL_{S\text{-}mod}}$ is a variation of the unity rule that uses established ratios as shown below in **Equation (**4-9)**:**

$$\mathrm{DCGL_{S\text{-}mod}} = \frac{1}{\left(\frac{1}{\mathrm{DCGL_{S\text{-}unmod}}} + \frac{R_2}{\mathrm{DCGL}_2} + \cdots + + \frac{R_i}{\mathrm{DCGL}_i} + \cdots + \frac{R_n}{\mathrm{DCGL}_n}\right)} \tag{4-9}$$

where

- $\mathrm{DCGL_{S\text{-}unmod}}$ is the DCGL of the surrogate radionuclide before modification.
- DCGL_i is the DCGL of the ith radionuclide for $i = 2, \ldots n$.
- R_i is the established ratio of the concentration of the ith radionuclide to the concentration of the surrogate radionuclide for $i = 2, \ldots n$.

$\mathrm{DCGL_{S\text{-}mod}}$ is then used for survey design purposes described in **Chapter 5.** An example calculation of a surrogate DCGL and additional discussion are shown in **Section 4.12.2.1.**

This scheme is applicable only when radionuclide-specific measurements of the surrogate radionuclide are made. It is unlikely to apply in situations where the surrogate radionuclide appears in background, as background variations would increase the uncertainty in the calculation of the surrogate measurements to unacceptable levels.

When using surrogates, it is often difficult to establish a consistent ratio between two or more radionuclides. Rather than follow prescriptive guidance on acceptable levels of variability for the surrogate ratio, a more reasonable approach may be to review the data collected to establish the ratio and to use the DQO process to select an appropriate ratio from that data. The DQO process should be used to assess the feasibility of use of surrogates. The benefit of using the surrogate approach is avoiding the need to perform costly wet chemistry analyses on each sample. This benefit should be considered relative to the difficulty in establishing the surrogate ratio, as well as the potential consequence of unnecessary investigations that result from decision errors, which may arise from using a "conservative" surrogate ratio (i.e., determining that the site is dirty when the site is clean). Selecting a conservative surrogate ratio ensures that potential exposures from individual radionuclides are not underestimated. The surrogate method can only be used with confidence when dealing with the same media in the same surroundings—for example, soil samples with similar physical and geological characteristics. The planning team will need to consult with the regulatory agency for concurrence on the approach used to determine the surrogate ratio.

The potential for shifts or variations in the radionuclide ratios means that the surrogate method should be used with caution. Physical or chemical differences between the radionuclides may produce different migration rates, causing the radionuclides to separate and changing the radionuclide ratios. Remediation activities have a reasonable potential to alter the surrogate ratio established prior to remediation. MARSSIM recommends that when the ratio is established prior to remediation, additional post-remediation samples should be collected to ensure that the data used to establish the ratio are still appropriate and representative of the existing site condition. If these additional post-remediation samples are not consistent with the pre-remediation data, surrogate ratios should be re-established.

4.5.3.4 Gross Activity DCGLs for Multiple Radionuclides in Known Ratios

For situations where multiple radionuclides with their own DCGLs are present, a gross activity DCGL can be developed. This approach enables field measurement of gross activity (e.g., Bq/m^2), rather than determination of individual radionuclide activity, for comparison to the DCGL. The gross activity DCGL for surfaces with multiple radionuclides is calculated as follows:

1. Determine the relative fraction, f_i of the total activity contributed by each of the n radionuclides present for $i = 1, \ldots n$.

2. Obtain the DCGL_i for each ith radionuclide present for $i = 1, \ldots n$.

3. Substitute the values f_i and DCGL_i in the following equation (**Equation (**4-10)) for $i = 1, \ldots n$.

$$\text{DCGL}_{\text{gross}} = \frac{1}{\left(\frac{f_1}{\text{DCGL}_1} + \frac{f_2}{\text{DCGL}_2} + \cdots + \frac{f_i}{\text{DCGL}_i} + \cdots + \frac{f_n}{\text{DCGL}_n}\right)} \tag{4-10}$$

This process can be used to calculate a gross activity DCGL to be used as a DCGL_W or a DCGL_EMC. See **Appendix O.4** for the derivation. The example in **Section 4.12.2.3** illustrates the calculation of a gross activity DCGL.

Just as in the case of surrogate radionuclides, note that **Equation (**4-10) might not work for sites having unknown or highly variable relative fractions of radionuclides throughout the site. In these situations, the best approach may be to select the most conservative surface DCGL from the mixture of radionuclides present (**Section 4.5.3.2**) or the unity rule (**Section 4.5.3.5**). If the radionuclide with the most restrictive DCGL cannot be measured or is hard to detect with field instruments, the DQOs must be revisited to determine the best approach. If the mixture contains radionuclides that cannot be measured using field survey equipment, laboratory analyses of surface materials may be necessary. Check with the regulator whether the use of a gross activity DCGL is appropriate for the site.

4.5.3.5 DCGLs for Multiple Radionuclides with Unrelated Concentrations

If the concentrations of the different radionuclides appear to be unrelated in the survey unit, the surrogate approach cannot be used. There is little choice but to measure the concentration of each radionuclide and use the unity rule. The alternative would involve performing gross measurements (e.g. alpha or beta) and applying the most restrictive $DCGL_W$ to all radionuclides.

Recall from **Section 4.4** that the fundamental release criterion is that the sum of all the radiation dose from all the residual radionuclides in a survey unit must be less than or equal to the dose or risk criteria. In terms of DCGLs, the unity rule states that for a survey unit to meet the release criteria, the sum of the ratios of the concentrations of each radionuclide to their respective DCGLs must be less than or equal to one, as shown in **Equation (**4-11)**:**

$$\frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots + \frac{C_i}{DCGL_i} + + \cdots + \frac{C_n}{DCGL_n} \leq 1 \qquad (4\text{-}11)$$

where

- C_i is the concentration of the ith radionuclide for $i = 1, \dots n$.
- $DCGL_i$ is the DCGL of the ith radionuclide for $i = 1, \dots n$.

By using the unity rule in this manner, the design team creates an effective DCGL of 1. Note that the DCGL is no longer expressed as a concentration; it is a unitless sum of fractions. To apply the unity rule, the design team must calculate the *sum of the ratios* (SOR) or *weighted sum* (T) of the ratios in the survey unit for each quantity measured at a given location, as illustrated in **Equation (**4-12) and **Example 4.12.4.**

$$T = \frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots + \frac{C_i}{DCGL_i} + \cdots + \frac{C_n}{DCGL_n} \qquad (4\text{-}12)$$

where

- C_i is the concentration in the sample of the ith radionuclide for $i = 1, \dots n$.
- $DCGL_i$ is the DCGL of the ith radionuclide for $i = 1, \dots n$.

In a given sample, the concentration of each radionuclide is divided by its DCGL (normalization). This weighted sum, T, and its standard deviation, $\sigma(T)$, will be used in the statistical tests to determine whether a survey unit can be released. The standard deviation in the weighted sum is calculated as shown in **Equation (**4-13)**:**

$$\sigma(T) = \sqrt{\left[\frac{\sigma(C_1)}{DCGL_1}\right]^2 + \left[\frac{\sigma(C_2)}{DCGL_2}\right]^2 + \cdots + \left[\frac{\sigma(C_i)}{DCGL_i}\right]^2 + \cdots + \left[\frac{\sigma(C_n)}{DCGL_n}\right]^2} \quad (4\text{-}13)$$

where

- $\sigma(C_i)$ is the estimate of uncertainty in the concentration in the sample of the ith radionuclide for $i = 1, \ldots n$.
- $DCGL_i$ is the DCGL of the ith radionuclide for $i = 1, \ldots n$.

Note that if there is a fixed ratio between the concentrations of some radionuclides but not others, a combination of the methods in **Sections 4.5.3.4 and 4.5.3.5** may be used. The appropriate value of the DCGL with the concentration of the measured surrogate radionuclide should replace the corresponding terms in **Equations (**4-12) **and (**4-13)**. Example 4.12.4** illustrates the calculation of the weighted sum and its associated uncertainty for two radionuclides.

During the planning stage, data from characterization, scoping, or other surveys can be used to estimate the values of T and $\sigma(T)$ in the survey unit to determine the number of samples needed for the statistical tests.

Although this chapter does not discuss interpreting the data from an FSS (**Chapter 8**), a note on how T is used can be helpful at this point. If the sum of the normalized concentrations is below 1.0 for every sample in a survey unit, compliance has been demonstrated. If a survey unit has several individual locations where T_i exceeds 1, this does not mean that the survey unit fails to meet the release criteria. If any individual T_i exceeds 1, then, as for the case for a single radionuclide, an appropriate statistical test and the elevated measurement comparison test must be performed.

4.5.3.6 The Use of External Radiation Measurements as a Surrogate

In lieu of using measurements of radionuclide concentrations to determine compliance with release criteria, the DQO process can be used to determine if in situ measurements of external radiation levels (e.g., exposure rates) can be used, particularly for radionuclides that deliver the majority of their dose through the direct radiation pathway. This approach can be desirable because external radiation measurements are generally easier to make and less expensive than measuring radionuclide concentrations.

This method requires that a consistent ratio for the surrogate and unmeasured radionuclides be established. The appropriate exposure rate DCGL could also account for radionuclides that do not deliver the majority of their dose through the direct radiation pathway. This is accomplished by determining the fraction of the total activity represented by radionuclides that do deliver the majority of their dose through the direct radiation pathway and weighting the exposure rate limit by this fraction (see surrogate discussion above). Note that the previously mentioned considerations for establishing consistent ratios also apply to this surrogate approach. The regulatory agency should be consulted before using this surrogate approach.

4.5.3.7 Small Areas of Elevated Activity

The concept of the elevated measurement comparison and $DCGL_{EMC}$ for small areas of elevated activity was introduced in **Section 4.5.2.** The $DCGL_{EMC}$ accounts for the smaller area of elevated residual radioactive material and is equal to or greater than the $DCGL_W$. Recall that the development of regulatory requirements leading to the establishment of a $DCGL_{EMC}$ is beyond the scope of MARSSIM and is determined strictly through the requirements of regulatory agencies. Therefore, it is important to work with the applicable regulatory agency to determine whether requirements for establishing a $DCGL_{EMC}$ should be consistent with the approach presented in MARSSIM or those in regulatory documents.

All the methods used to modify individual DCGLs to account for multiple radionuclides can be used to modify the $DCGL_{EMC}$. When the ratios between the radionuclides is unknown, the unity rule inequality for the EMC is as shown below in **Equation (**4-14)**:**

$$\frac{C_1}{DCGL_{EMC,1}}+\frac{C_2}{DCGL_{EMC,2}}+\cdots+\frac{C_i}{DCGL_{EMC,i}}+\cdots+\frac{C_n}{DCGL_{EMC,n}}\leq 1 \qquad (4\text{-}14)$$

In **Equation (**4-14)**,** C_i is concentration of the ith radionuclide for i = 1, … n, and $DCGL_{EMC,i}$ is the $DCGL_{EMC}$ for ith radionuclide for i = 1, … n.

The use of **Equation (**4-14) may not be appropriate for scanning. For scanning, minimum detectable concentration (MDC) considerations are a little more nuanced than for discrete sampling. For example, when scanning for areas with potentially elevated concentrations of residual radioactive material, the scan MDC should be below the DCGL—preferably at a fraction (approximately 50 percent) of the DCGL. In a Class 1 survey unit, the scan MDC should be less than the $DCGL_{EMC}$. Additional information is provided in **Sections 5.3.5.1 and 5.3.5.2.** The radionuclide yielding the lowest detector response may or may not have the most restrictive DCGL.

As illustrated in **Equation (**4-15)**,** to use the surrogate (known ratios) method for the elevated measurement comparison, the $DCGL_{EMC}$ for the surrogate radionuclide is replaced by—

$$DCGL_{EMC,S\text{-}mod}=\frac{1}{\frac{1}{DCGL_{EMC,S\text{-}unmod}}+\frac{R_2}{DCGL_{EMC,2}}+\cdots+\frac{R_i}{DCGL_{EMC,i}}+\cdots+\frac{R_n}{DCGL_{EMC,n}}} \qquad (4\text{-}15)$$

where

- $DCGL_{EMC,S\text{-}unmod}$ is the unmodified $DCGL_{EMC}$ for the first radionuclide.
- R_i is the concentration ratio of the ith radionuclide to the first radionuclide for $i = 2, \ldots n$.
- $DCGL_{EMC,i}$ is the $DCGL_{EMC}$ for the ith radionuclide for $i = 2, \ldots n$.

When dealing with discrete radioactive particles (hot particles), the MARSSIM EMC process is not valid when the instrumentation dose-to-rate conversion factor modeling assumes a “point source" as opposed to an "area source" or "plane source." This violates the assumption inherent in the dose or risk model of an activity concentration averaged over some definable area. The FSS planning team should use the DQO process to address discrete radioactive particles, if there is a reasonable potential for them to be present. See **Section 4.12.8** for more information on release criteria for discrete radioactive particles.

4.5.3.8 A Note on Serial Radioactive Decay

For decay series (e.g., thorium and uranium) whose radionuclides emit alpha, beta, and gamma radiation, compliance with building surface activity DCGLs may be demonstrated by assessing alpha, beta, or gamma radiations. However, relying on the use of alpha surface measurements often proves problematic because of the highly variable level of alpha attenuation by rough, porous, and dusty surfaces. Beta measurements typically provide a more accurate assessment of thorium and uranium on most building surfaces because surface conditions cause significantly less attenuation of beta particles than alpha particles. Beta measurements, therefore, may provide a more accurate determination of surface activity than alpha measurements. The presence of gamma-emitting radionuclides can introduce uncertainty into the beta measurements, and field measurement techniques need to be used to account for the gamma interference at each beta measurement location.

The relationship of beta and alpha emissions from decay chains or various enrichments of uranium should be considered when determining the surface activity for comparison with the DCGL values. When the initial member of a decay chain has a long half-life, the concentration of radioactive material associated with the subsequent members of the series will increase at a rate determined by the individual half-lives until all members of the decay chain are present at activity levels equal to the activity of the parent. This condition is known as secular equilibrium. **Section 4.12.2.1** provides an example of the calculation of beta activity $DCGL_W$ for thorium-232 in equilibrium with its decay products.

4.5.4 Investigation Levels

The survey design should include the development of investigation levels during the DQO process for the FSS. A measurement result is compared to an investigation level to indicate when additional action might be necessary (e.g., a measurement that exceeds the $DCGL_W$ in a Class 2 area). Investigation levels can be radionuclide-specific levels of radioactive material or an instrument response (e.g., counts per minute). Additional discussions of investigation levels are in **Section 5.3.8.**

4.5.5 Conclusions

The foregoing discussion of DCGLs highlights the following:

- Measurements can be made for specific radionuclides, typically through gamma spectrometry or radiochemical analyses.
- The FSS design team should be familiar with the operational DCGLs and their applications.
- Gross activity measurements—typically gross alpha or beta concentrations—can be made, especially on surfaces.
- Measurement of surrogate quantities can be used based on known relationships among the various radionuclides.

- The use of surrogates or ratios determined from data collected before the FSS must be approved by the appropriate regulatory authorities, and if remediation or other activities occur which could affect the ratios, additional support for the assumed ratios or revisions to the ratios is needed.
- The unity rule can be used to determine the DCGLs for use in the design of the FSS when multiple radionuclides/sources are present.
- If DCGLs are modified for use of surrogates, that modification will affect instrument selection.

The choice of how the DCGLs are applied and measured affects the statistical methods, background reference unit selection, and other design features of a survey. For example, MARSSIM recommends using the Wilcoxon Rank Sum (WRS) test if the radionuclides are present in the background or if gross activity measurements are made (see **Section 8.2.3**).

4.6 Area and Site Considerations

4.6.1 Area Classification

All areas of a site will not have the same potential for residual radioactive material and, accordingly, will not need the same level of survey coverage to demonstrate compliance with the established release criteria. The process will be more efficient if the survey is designed so that areas with higher potential for residual radioactive material (based in part on results of the HSA in **Chapter 3**) will receive a higher degree of survey effort. The following is a discussion of site area classifications.

Non-impacted areas: Areas that have no reasonable potential for residual radioactive material and do not need any level of survey coverage. Those areas have no radiological impact from site operations and are typically identified during the HSA (**Chapter 3**). Background reference areas are normally selected from non-impacted areas (**Section 4.6.3**).

Impacted areas: Areas that have some potential for containing residual radioactive material. They can be classified into three classes:

- *Class 1 areas:* Areas that have, or had prior to remediation, a potential for residual radioactive material above the $DCGL_W$ (based on site operating history) or known residual radioactive material (based on previous radiological surveys). Examples of Class 1 areas include—
  - site areas previously subjected to remedial actions
  - locations where leaks or spills are known to have occurred
  - former burial or disposal sites
  - waste storage sites
  - areas with residual radioactive material in discrete solid pieces of material having high specific activity

  Note that areas containing residual radioactive material in excess of the $DCGL_W$ prior to remediation should be classified as Class 1 areas. Justification is not required for a Class 1 designation, unlike a Class 2 or Class 3 designation. The less restrictive the classification, the greater the justification required.

- *Class 2 areas:* Areas that have, or had prior to remediation, a potential for residual radioactive material or known residual radioactive material but are not expected to exceed the $DCGL_W$. To justify a Class 2 designation, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that no individual measurement would exceed the $DCGL_W$. Other justifications may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 2 for the FSS include—
    - locations where radioactive materials were present in an unsealed form
    - residual radioactive material potentially along transport routes
    - areas downwind from stack release points
    - upper walls, roof support frameworks, and ceilings of some buildings or rooms subjected to airborne radioactive material
    - areas where low concentrations of radioactive materials were handled
    - areas on the perimeter of former buffer or radiological control areas
- *Class 3 areas:* Any impacted areas that are not expected to contain any residual radioactive material or are expected to contain levels of residual radioactive material at a small fraction of the $DCGL_W$, based on site operating history and previous radiological surveys. To justify a Class 3 designation, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence either that there is no residual radioactive material or that any levels of residual radioactive material are a small fraction of the $DCGL_W$. Other justifications for an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 3 include—
    - buffer zones around Class 1 or Class 2 areas
    - areas with very low potential for residual radioactive material but insufficient information to justify a non-impacted classification

Classification is a critical step in the survey design process, as well as for the FSS (see **Table 2.2**). Class 1 areas have the greatest potential for residual radioactive material and, therefore, receive the highest degree of survey effort, followed by Class 2 and then Class 3 areas. All areas should be considered Class 1 areas unless some basis for classification as Class 2 or Class 3 is provided.

The criteria used for designating areas as Class 1, 2, or 3 should be described in the FSS plan. Compliance with the classification criteria should be demonstrated in the FSS report. A thorough analysis of HSA findings (**Chapter 3**) and the results of scoping and characterization surveys provide the basis for an area's classification. As a survey progresses, reevaluation of this classification may be necessary based on newly acquired survey data. For example, if residual radioactive material at concentrations that are a substantial fraction of the $DCGL_W$ is identified in a Class 3 area, an investigation and reevaluation of that area should be performed to determine if the Class 3 area classification is appropriate. Typically, the investigation will result in part or all of the area being reclassified as Class 1 or Class 2. If survey results identify residual radioactive material in a Class 2 area exceeding the DCGL or suggest that there may be a reasonable potential that residual radioactive material is present in excess of the DCGL, an investigation should be initiated to determine whether all or part of the area should be reclassified as Class 1. More information on investigations and reclassifications is provided in **Section 5.3.8.**

4.6.2 Identification of Survey Units

A survey unit is a physical area consisting of structures or land areas of specified size and shape for which a separate decision will be made whether that survey unit exceeds the release criteria. This decision is made as a result of the FSS. Therefore, the survey unit is the primary entity for demonstrating compliance with the release criteria.

To facilitate survey design and ensure that the number of survey data points for a specific site are relatively uniformly distributed among areas of similar potential for residual radioactive material, the site is divided into survey units that share a common history or other characteristics or are naturally distinguishable from other portions of the site. A site may be divided into survey units at any time before the FSS. Areas that have been classified can be one survey unit or multiple survey units. For example, HSA or scoping survey results may provide sufficient justification for partitioning the site into Class 1, 2, or 3 areas. Note, however, that dividing the site into survey units is critical only for the FSS; scoping, characterization, and RAS surveys may be performed without dividing the site into survey units.

A survey unit cannot include areas that have different classifications. A survey unit's characteristics should be consistent with exposure pathway modeling that is used to convert dose or risk into radionuclide concentrations. For indoor areas classified as Class 1, each room may be designated as a survey unit. Indoor areas may also be subdivided into several survey units of different classification, such as separating floors and lower walls from upper walls and ceilings (and other upper horizontal surfaces) or subdividing a large warehouse based on floor area.

Survey units should be limited in size based on classification, exposure pathway modeling assumptions, and site-specific conditions. The suggested areas for survey units are provided in **Table 4.1.**

Table 4.1: Suggested Area for Survey Units

Classification	Suggested Area for Survey Units	
	Structures (Floors, Walls, and Ceilings)	Land Areas
Class 1	Up to 100 m^2	Up to 2,000 m^2
Class 2	Up to 1,000 m^2	Up to 10,000 m^2
Class 3	No Limit	No Limit

Abbreviation: m^2 = square meters

The limitation on survey unit size ensures that the density of the measurements/samples is commensurate with the potential of residual radioactive materials in excess of the $DCGL_W$. The rationale for selecting a larger survey unit area should be developed using the DQO process (**Section 2.3**) and fully documented.

Special considerations may be necessary for survey units with structure surface areas up to 10 m^2 or land areas up to 100 m^2. In this case, the number of data points obtained from the statistical tests is unnecessarily large and not appropriate for smaller survey unit areas. Instead, some specified level of survey effort should be determined based on the DQO process and with the concurrence of the regulatory agency. For such small survey units, scan-only surveys or in situ measurement may be more appropriate. The data generated from these smaller survey units should be obtained based on judgment, rather than on systematic or random design, and compared individually to the DCGLs.

One example special case for FSSs occurs at UMTRCA sites at which the radioactive materials are from the processing of uranium or thorium ores for their source material content. See **Section 4.12.9** and **Appendix O.6** for more details for UMTRCA sites.

4.6.3 Selection of Background Reference Areas

Certain radionuclides may also occur at significant levels as part of background in the media of interest (e.g., soil, building material). Examples include members of the naturally occurring uranium, thorium, and actinium series; potassium-40 (^{40}K); carbon-14 (^{14}C); and tritium (^{3}H). ^{137}Cs and other radionuclides are also present in background as a result of fallout (Wallo et al., 1994). Establishing a distribution of background concentrations is necessary to identify and evaluate contributions attributable to site operations. Determining background levels for comparison with the conditions determined in specific survey units entails conducting surveys in one or more reference areas to define the background radiological conditions of the site. NUREG-1505 (NRC 1998a) provides additional information on background reference areas.

The recommended site background reference area should have similar physical, chemical, geological, radiological, and biological characteristics as the survey unit being evaluated. Background reference areas should be selected from non-impacted areas, but they are not limited to natural areas undisturbed by human activities. In some situations, a reference area may be contiguous to the survey unit being evaluated, as long as the reference area does not have any residual radioactive material resulting from site activities. For example, background measurements may be taken from core samples of a building or structure surface or pavement. This option should be discussed with the regulatory agency during survey planning. Reference areas should not be part of the survey unit being evaluated.

Reference areas provide a location for background measurements that are used for comparisons with survey unit data. The radioactive material present in a reference area would ideally be the same as in the survey unit, had the survey unit never been affected by site operations. If a site includes physical, chemical, geological, radiological, or biological variability that is not represented by a single reference background area, selecting more than one reference area may be necessary. Additionally, the concentration of some radionuclides may vary over short (hours to days), medium (months or years), or long (centuries) time frames. NUREG-1501 (NRC 1994a) provides more detailed information about sources of temporal variability and methods to account for this variability.

It may be difficult to find a reference area within a residential or industrial complex for comparison to a survey unit if the radionuclides of potential concern are naturally occurring. Background may vary greatly due to different construction activities that have occurred at the site. Examples of construction activities that change background include—

- leveling
- excavating
- adding fill dirt
- importing rocks or gravel to stabilize soil or underlay asphalt
- manufacturing asphalt with different matrix rock
- using different pours of asphalt or concrete in a single survey unit; layering asphalt over concrete
- layering different thicknesses of asphalt, concrete, rock, or gravel
- covering or burying old features, such as railroad beds or building footings

Background variability may also increase due to the concentration of fallout in low areas of parking lots or under downspouts, where runoff water collects and evaporates. Variations in background of a factor of five or more can occur in the space of a few meters.

There are a number of possible actions to address these concerns. NUREG-1505 (NRC 1998a) provides a methodology for considering variability in reference area concentrations. Reviewing and reassessing the selection of reference areas may also be necessary. Selecting different reference areas to represent individual survey units is another possibility. More attention may also be needed in selecting survey units and their boundaries with respect to different areas of potential or actual background variability. More detailed scoping or characterization surveys may be needed to better understand background variability. Using radionuclide-specific measurement techniques instead of gross radioactive material measurement techniques may also be necessary. If a background reference area that satisfies the above recommendations is not available, consultation with the regulatory agency is recommended. Alternate approaches may include using published studies of radionuclide distributions. However, published reports may not truly reflect the conditions at the site.

Verifying that a background reference area is appropriate for a survey can be accomplished using the techniques described or referenced in **Chapter 8.** Verification provides assurance that assumptions used to design the survey are appropriate and defensible. This approach can also prevent decision errors that may result from selecting an inappropriate background reference area.

If the radionuclides of interest do not occur in background, or the background levels are known to be a small fraction of the $DCGL_W$ (e.g., < 10 percent), the survey unit radiological conditions may be compared directly to the specified $DCGL_W$, and reference area background surveys are not necessary. If the background is not well defined at a site and the decision maker is willing to accept the increased probability of incorrectly failing to release a survey unit (Type II error), the reference area measurements can be eliminated and the Sign test performed as described in **Section 8.3.**

4.7 Statistical Considerations

The primary practical objective of an FSS survey is to answer the question, "Can this survey unit be released to the satisfaction of the regulator?" In other words, the design team needs to be able to *confidently* demonstrate compliance (or non-compliance) with the dose- or risk-based release criteria expressed as a measurable quantity (DCGL). This need for a demonstrable, quantitative confidence necessitates planning for statistical hypothesis testing.

The statistical concepts used in MARSSIM were introduced in **Section 2.5.** This chapter reinforces and builds on those concepts with respect to the design of an FSS. The MARSSIM user should be familiar with the statistical discussions throughout **Chapters 2, 5, and 8** and **Appendices D and I.** Consultations with statisticians can be very valuable for surveys that rely on statistical methods for their design and assessment of the collected data.

4.7.1 Basic Terms

Before designing an FSS, the planning team should be familiar with the following statistical terms:

- sample[4] mean
- sample standard deviation
- sample median
- parametric and nonparametric tests
    - Sign test
    - Wilcoxon Rank Sum[5] (WRS) test
    - Student's *t* test
- Type I and Type II errors
- statistical power
- lower boundary of the gray region (LBGR)
- upper boundary of the gray region (UBGR)
- relative shift (Δ/σ)
- null and alternative hypotheses

The MARSSIM user will encounter these and other statistical terms many times in this document and while designing, performing, and assessing the results of an FSS. The use of these terms will be kept to a minimum in this chapter, but this in no way diminishes their importance. For this chapter, statistical terms will be defined when they are introduced.

4.7.2 Recommended Statistical Tests

How well a statistical test meets its objective depends on the difference between the assumptions used to develop the test and the actual conditions being measured. Parametric tests, such as the Student's *t* test, rely upon the results fitting some known distribution, like a

[4] The term "sample" here is a statistical term and should not be confused with laboratory samples. For the calculation of basic statistical quantities above, data may consist of scan data, direct measurement data, or laboratory sample data. See also the glossary definition of sample.

[5] This test is also called the Mann-Whitney U test, Mann-Whitney-Wilcoxon test, or Wilcoxon-Mann-Whitney test.

normal distribution. Nonparametric statistics are recommended in MARSSIM because they are based on less restrictive assumptions than parametric tests. MARSSIM recommends the use of the WRS test if the radionuclides of concern are present in the background or if gross activity measurements are made. If the radionuclides of concern are not present in the background or present only to a slight degree, then the Sign test is recommended.

4.7.3 Considerations on the Choice of a Statistical Test

The choice of a statistical test should be part of the DQO process during the design phase of the FSS. The choice of the statistical test is influenced by how the DCGLs are expressed (gross activity, radionuclide-specific, sum or ratios [unity rule]), the distribution of residual radioactive material in the survey unit (relatively uniform vs. small areas of elevated activity), number of reference units needed, etc. Concurrently, the number of samples needed depends on the DCGL, the standard deviation of the residual radioactive material in both the survey and reference units, the desired confidence in the conclusions (Type I and Type II errors), and the statistical test under consideration (see **Sections 5.3.3 and 5.3.4** for details, and see example calculations in **Sections 4.12.3 and 4.12.4**). Ensuring a reasonable level of confidence that any areas of elevated activity are detected might require additional samples.

Once the FSS is completed, the assumptions used to select the statistical test are examined to determine whether the conditions are met for the test. As part of the DQO process, the design team should plan for the possibility that the initial assumptions were not correct.

4.7.4 Deviations from MARSSIM Statistical Test Recommendations

The guidance and recommendations in MARSSIM are meant to be a set of practices generally acceptable for use in designing an FSS. However, the flexibility of the DQO process allows for the use of more cost-effective methods, if they are acceptable to the regulator. An example is presented in **Section 4.12.7.**

4.7.5 An Important Statistical Note

For FSSs, the parameter of interest is the mean concentration of residual radioactive material in a survey unit. The nonparametric statistical tests recommended in MARSSIM are tests of the median value. For data that are from a skewed right distribution, the mean could significantly exceed the median. Therefore, the team planning the FSS should include a comparison step in the survey to ensure that mean is less than the $DCGL_W$. See **Section 8.2.2.**

4.8 Measurements

Based on the potential radionuclides of interest, their associated radiations, how the DCGLs are expressed, the types of media (e.g., soil, structure surfaces), and number of measurements to be evaluated, the detection capabilities of various measurement methods (which consist of a combination of a measurement technique and instrument) must be determined and documented. Note that “measurements” includes both direct (field) measurements and laboratory analyses.

4.8.1 Quality Control and Quality Assurance

For both field measurements (**Chapter 6**) and laboratory analyses (**Chapter 7**), the FSS design team must plan to collect data to evaluate the performance of measurement and analytical methods (including data collection). These data are called measurement and instrument performance indicators. The DQO and MQO processes are used to determine which indicators are important and included in the QAPP. Examples of measurement and instrument performance indicators are shown below:

- *Instrument background readings:* Background readings before and after a series of measurements are used as part of the process to ensure that an instrument was functioning properly.
- *Instrument response checks:* Checking the instrument response with the same source in the same geometry over the course of surveying can help ensure that the instrument was working properly during the survey.
- *Field blanks:* These are samples prepared in the field using certified clean sand, soil, or other media and sent to the laboratory for analysis. Field blanks are used to assess contamination associated with sampling and laboratory procedures.
- *Performance evaluation samples:* These are used to assess the overall bias and errors in the laboratory's analytical processes.

4.8.2 Measurement Quality Objectives

Although specifically for laboratory analyses, the performance characteristics discussed in the Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP) (NRC 2004) should be considered when establishing Measurement Quality Objectives (MQOs). This list is not intended to be exhaustive:

- the method's uncertainty at a specified concentration, usually at the UBGR (expressed as a standard deviation)
- the method's detection capability (expressed as the minimum detectable concentration, or MDC)
- the method's quantification capability (expressed as the minimum quantifiable concentration, or MQC)
- the method's range, which defines the method's ability to measure the radionuclide of concern over some specified range of concentration
- the method's specificity, which refers to the ability of the method to measure the radionuclide of concern in the presence of interferences
- the method's ruggedness, which refers to the relative stability of method performance for small variations in method parameter values

Project-specific method performance characteristics should be developed as necessary and may or may not include the characteristics listed here. When lists of performance characteristics that affect measurability have been identified, the planning team should develop MQOs describing the project-specific objectives for potential measurement techniques. Potential measurement techniques should then be evaluated against the MQOs to determine whether they are capable of meeting the objectives for measurability.

The International Organization for Standardization *Guide to the Expression of Uncertainty in Measurement* (ISO 1993), National Institute of Standards and Technology Technical Note 1297 (NIST 1994), MARLAP (NRC 2004), Multi-Agency Radiation Survey and Assessment of

Materials and Equipment Manual (MARSAME) (NRC 2009), and **Chapter 6** of this manual provide information on determining measurement uncertainty. **Chapter 6** of this manual and NRC report NUREG-1507 (NRC 1997a) discuss the concept of detection capabilities and provide guidance on determining detection capabilities and selecting appropriate measurement methods. Although MARSAME and MARLAP include the concept of quantification capability, MARSSIM takes a different approach by incorporating requirements for quantification capability into detection capability with the requirement that the MDC be less than the UBGR and by recommending that the MDC be less than 50 percent of the UBGR (See **Chapter 6**). **Chapter 6** also discusses instruments and survey techniques for scans and direct measurements, and **Chapter 7** provides information on sampling and laboratory analysis. **Appendix H** describes typical field and laboratory equipment, plus associated cost and instrument capabilities.

4.8.3 Selecting a Measurement Technique

Instruments should be identified for each of the three types of measurement techniques planned for the FSS: (1) scanning, (2) direct, and (3) laboratory measurements. Scanning and direct measurements are referred to as field measurements. In some cases, the same instrument or type of instrument may be used for performing several measurement techniques. For example, a gas proportional counter can be used for surface scanning measurements and laboratory measurements of smear samples. Once the instruments are selected, appropriate measurement techniques and standard operating procedures (SOPs) should be developed and documented. The measurement techniques describe how the instrument will be used to perform the required measurements.

4.8.3.1 Scanning Measurements

Scanning is an in situ measurement technique performed by moving a portable radiation detector at a specified speed and distance next to a surface to detect radiation. Scanning measurements are generally used to locate areas that exceed investigation levels and areas of elevated activity that might be missed (e.g., measurements made with a systematic grid). In general, MARSSIM does not recommend “scan-only” FSSs. However, through the DQO process and consultation with the regulator, an FSS based on scanning measurements alone might be allowed. Items that should be kept in mind while investigating a scan-only survey are—

- data and location logging
- reproducibility of the measurements (e.g., fixing a detector at a constant distance from a surface)
- MDCs
- scanning speed and operator training
- data integrity and security
- selecting an appropriately sized area for elevated measurement comparison calculations

Additional information can be found in **Chapter 6.**

4.8.3.2 Direct Measurements

A direct measurement is an in situ measurement of radioactive material obtained by placing the detector near the surface or media being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly. Making direct measurements is analogous to collecting samples, and the results are often treated in a similar manner. Direct measurement of alpha, beta, and gamma radiation for an FSS requires that instruments and techniques be used that meet the DQOs and MQOs (e.g., MDC). When selecting instruments and techniques, the design team needs to consider—

- type and amounts of radionuclides potentially present
- required detection limits
- distance from the surface being monitored and field of view
- type of measurement—rate or scaler (integrated) (e.g., counts in 5 minutes)
- duration of integrated counts
- radiation background (including interferences from nearby radiation sources)

All direct measurements and their locations should be recorded. Additional information can be found in **Chapter 6.**

4.8.3.3 Laboratory Measurements

When planning for collecting samples as part of an FSS, the design team should use the DQO process to determine the need for sample collection and laboratory analyses. All laboratories under consideration to analyze samples should have written procedures that document their analytical capabilities for the radionuclides of concern and a QA/QC program that documents adherence to established criteria. The survey design team should also consider any appropriate laboratory accreditation. Accreditation, QA/QC, and other appropriate documentation should be available for review by the survey design team (with appropriate restrictions for proprietary or other controlled information). Once a qualified laboratory has been chosen, the design team should involve the laboratory early in the design process and maintain communication throughout execution and data evaluation and interpretation. **Chapter 7** contains more information on the sampling and preparation for laboratory measurements.

Additionally, MARLAP (NRC 2004) contains extensive information “for the planning, implementation, and assessment of projects that require laboratory analysis of radionuclides.” Like MARSSIM, MARLAP aims to provide a flexible approach to ensure that the radioanalytical data are of the right quality and appropriate for the needs of the user.

Some items that should be considered when planning for laboratory analyses include the following:

- sample media
- number of samples
- type and number of QC samples
- amount of material needed by the laboratory
- analytical bias and precision
- detection limits

- costs
- required turnaround time
- sample preservation and shipping requirements
- measurement documentation requirements
- sample tracking needs (e.g., chain of custody requirements)

4.8.3.4 Selecting a Radioanalytical Laboratory

It is advisable to select a radiochemical laboratory as early as possible in the survey planning process so that it may be consulted on the analytical methodology and the sampling activities. Federal procurement procedures may require additional considerations beyond the method described here. The procurement of laboratory services usually starts with the development of a request for proposal that includes a statement of work describing the analytical services to be procured. The careful preparation of the statement of work is essential to the selection of a laboratory capable of performing the required services in a technically competent and timely manner.

Six criteria that should be considered are:

- well-documented procedures, instrumentation, and trained personnel to perform the necessary analyses
- surveyors who are experienced in performing the same or similar analyses
- satisfactory performance evaluation results from formal monitoring or accreditation programs
- adequate capacity to perform all analyses within the desired timeframe
- internal QC program
- protocols for method performance documentation, sample tracking and security, and documentation of results

The design team should review that laboratory's documentation concerning MDC calculations, reporting procedures, calibrations, QA/QC, and accreditation to ensure that the FSS DQOs will be met. More details can be found in **Section 7.4.**

When samples are collected for laboratory analyses, communications between the project manager, field personnel, and laboratory personnel are vital to a successfully executed FSS. The survey design team should strive to establish communications with the laboratory early in the design process; when this is not possible, a radiochemist or health physicist with radiochemical training should be consulted. Additional information on laboratory communications is in **Section 7.3.**

4.8.4 Selection of Instruments for Field Measurements

4.8.4.1 Reliability and Robustness

Choose reliable instruments that are suited to the physical and environmental conditions at the site and capable of meeting the MQOs. The MQOs should include the measurement method uncertainty, which is typically established at the UBGR (usually the $DCGL_W$). The required measurement method uncertainty is perhaps the most important MQO to be established during the planning process. Determining a realistic value for the measurement method uncertainty for field measurements is a challenging calculation, typically requiring the use of specialized software. However, ensuring that the measurement method uncertainty meets the requirement set for it at the UBGR will ensure that the measurement method can reliably perform measurements at the most critical concentration level for the survey.

4.8.4.2 Detection Capability

The detection capability (sensitivity) or the ability to detect radiation or radioactive material with some quantifiable level of confidence is a critical factor in the design of an FSS. This capability is most often referred to as the MDC for direct measurements, or the scan MDC for scanning measurements. The formal MARSSIM definition of the MDC is "the a priori activity concentration that a specific instrument and technique that has a specified probability (typically 95 percent) of producing a net count (or count rate) above the critical level." Informally, the MDC is the concentration of radioactive material that can be reliably detected; if radioactive material is present at the MDC with a specified probability of 95 percent, then the measurement process will determine its presence 95 percent of the time. The MDC is a factor of both the instrumentation and the technique or procedure being used. For scanning, human factors also need to be taken into account. Details on how to calculate MDCs are given in **Section 6.3.** The design team should be aware that there are other methods to calculate MDCs (especially for direct and laboratory measurements) discussed in the scientific literature. The DQO process should be used to determine which method best suits the needs of the FSS. This method and results should be approved by the appropriate regulatory agency.

Having low MDCs is valuable when designing the FSS. If measured values are less than the MDC, then the values can be quite variable and lead to high values for the standard deviation (σ) of the measured values in the survey unit or reference area. High values for σ can be accommodated in the statistical tests described in **Chapter 8** for the FSS, but a large number of measurements are needed to account for the variability.

Early in the project, low MDCs help in the identification of areas that can be classified as non-impacted or Class 3 areas. These decisions are usually based on fewer numbers of samples, and each measurement is evaluated individually. Using an optimistically low estimation of the MDC (see **Section 2.3.5**) for these surveys may result in the misclassification of a survey unit and cleaning up an area with no residual radioactive material or, alternatively, performing an FSS in an area with residual radioactive material. Selecting a measurement technique with a well-defined MDC or a conservative estimate of the MDC ensures the usefulness of the data for making decisions for planning the FSS. For these reasons, MARSSIM recommends that a realistic or conservative estimate of the MDC be used instead of an optimistic estimate.

4.8.4.3 Dynamic Range

The expected concentration range for a radionuclide of concern can be an important factor in the overall measurement method performance. Most radiation measurement techniques are capable of measuring over a wide range of radionuclide concentrations. However, if the expected concentration range is large, the range should be identified as an important measurement method performance characteristic, and an MQO should be developed. The MQO for the acceptable range should be a conservative estimate. This will help prevent the selection of measurement techniques that cannot accommodate the actual concentration range.

4.8.4.4 Calibration

Calibration refers to the determination and adjustment of the instrument response in a particular radiation field of known intensity. Proper calibration procedures are essential to providing confidence in measurements made to demonstrate compliance with release criteria. The FSS design team should review and understand **Section 6.6.4.**

The instrument should be calibrated for the radiations and energies of interest at the site (**Section 6.6.4**). Instrument calibrations should be traceable to an accepted standards organization, such as the National Institute of Standards and Technology (NIST).[6] Operational checks of instrument performance should be conducted routinely and frequently to ensure that the instrument response is maintained within acceptable ranges and that any changes in instrument background are not attributable to radioactive contamination of the detector.

Considerations for the use and calibration of instruments include—

- the radiation type for which the instrument is designed
- the radiation energies within the range of energies for which the instrument is designed
- the environmental conditions for which the instrument is designed
- the influencing factors, such as magnetic and electrostatic fields, for which the instrument is designed
- the orientation of the instrument, such that geotropic (gravity) effects are not a concern
- the manner the instrument is used, such that it will not be subject to mechanical or thermal stress beyond that for which it is designed

As a minimum, each measurement system (detector/readout combination) should be calibrated annually, and the response of the detector to a check source should be established following calibration (ANSI 2013). Instruments may require more frequent calibration if recommended by the manufacturer. Recalibration of field instruments is also required if an instrument fails a performance check or if it has undergone repair or any modification that could affect its response. The system should be calibrated to minimize potential errors during data transmission and retransmission. The user may decide to perform calibrations following industry-recognized procedures (ANSI 1997, NCRP 1978, NCRP 1985, NCRP 1991, ISO 1988, HPS 1994a, HPS 1994b), or the user can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization. Calibrations should include devices used to determine the position or location of samples or measurements, as recommended by the manufacturer.

Additional technical details about instrument efficiencies and example calculations are contained in **Section 4.12.5.**

4.8.4.5 Specificity

Specificity is the ability of the measurement method to measure the radionuclide of concern in the presence of interferences. To determine whether specificity is an important measurement

[6] The NIST policy on traceability can be found here: https://www.nist.gov/calibrations/traceability.

method performance characteristic, the planning team will need information about expected concentration ranges for the radionuclides of concern and other chemical and radionuclide constituents, along with chemical and physical attributes of the soil or surface being measured. The importance of specificity depends on—

- the chemical and physical characteristics of the soil or surface
- the chemical and physical characteristics of the residual radioactive material
- the expected concentration range for the radionuclides of concern

If potential interferences are identified (e.g., inherent radioactive material, similar radiations), an MQO should be established for specificity.

4.8.4.6 Instrumentation Examples

Table 4.2 presents a list of common radionuclides along with recommended instruments for field measurement methods that have proven effective based on past survey experience in the decommissioning industry. This table provides a general indication of the detection capability of commercially available instruments for field measurements. As such, **Table 4.2** may be used to provide an initial evaluation of instrument capabilities for some common radionuclides at the example DCGLs listed in the table. For example, consider a surface with ^{241}Am. **Table 4.2** indicates that ^{241}Am is detectable at the example DCGLs and that viable direct measurement instruments include gas-flow proportional (alpha mode) and alpha scintillation detectors.

Many radiation detection instruments can be used for both direct and scanning measurements. The example DCGLs in **Table 4.2** are given for direct measurements only. Issues of detectability (MDC) for scanning are more complicated than for direct measurements and depend on things such as human response, height above the surface, and scanning speed.

Table 4.2 should not be interpreted as providing specific values for an instrument's detection capability, which is discussed in **Section 6.7.** In addition, NRC draft report NUREG-1506 (NRC 1995) and NUREG-1507 (NRC 1997a) provide further information on factors that may affect survey instrumentation selection.

4.8.5 Selection of Sample Collection Methods

Sample characteristics—such as sample depth, volume, area, moisture level, and composition, as well as sample preparation techniques that may alter the sample—are important planning considerations for DQOs. Sample preparation may include, but is not limited to, removing extraneous material, homogenizing, splitting, drying, compositing, and doing final preparations of samples. Dose or risk pathway modeling should be representative of actual survey conditions, to the extent practical, and modeling limitations should be well documented and assessed. The sampling method should then consider assumptions made in the dose or risk pathway modeling used to determine radionuclide DCGLs. For example, the actual depth and area of residual radioactivity in the survey unit should be reflected in the modeling, and sampling should be compatible with how the source was represented in the modeling. If a direct measurement or scanning technique is used, it should also consider the compatibility of the technique with the assumptions made in the dose or risk pathway modeling.

Table 4.2: Examples of Field Measurement Instruments

Nuclide	Structure Surfaces		Land Areas		Example Instruments		
	Example DCGL[a] (Bq/m^2)	Detectable	Example DCGL[a] (Bq/kg)	Detectable	Surface Activity	Soil Activity	Exposure Rate
^{3}H	2.0×10^{8}	No	4.1×10^{3}	No	ND[b]	ND	ND
^{14}C	6.2×10^{6}	Yes	4.4×10^{2}	No	GPβ	ND	ND
^{54}Mn	5.4×10^{4}	Yes	5.6×10^{2}	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{55}Fe	7.5×10^{6}	No	3.7×10^{5}	No[c]	ND	ND (ISγ)	ND(ISγ)
^{60}Co	1.2×10^{4}	Yes	1.4×10^{2}	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{63}Ni	3.0×10^{6}	Yes	7.8×10^{4}	No	GPβ	ND	ND
^{90}Sr	1.5×10^{4}	Yes	6.3×10^{1}	No[c]	GPβ, GM	ND (GM, GPβ)	ND
^{99}Tc	2.2×10^{6}	Yes	7.0×10^{2}	No	GPβ, GM	ND	ND
^{137}Cs	4.7×10^{4}	Yes	4.1×10^{2}	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{152}Eu	—	Yes	3.2×10^{2}	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
^{226}Ra (C)[d]	—	Yes	2.6×10^{1}	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ
^{232}Th (C)[d]	—	Yes	4.1×10^{1}	Yes	GPα, αS, GPβ	γS, ISγ	PIC, γS, ISγ
^{238}U (C)	—	Yes	1.9×10^{1}	Yes	GPα, αS, GPβ, ISγ	γS, ISγ, GPβ	PIC, γS, ISγ
^{239}Pu	—	Yes	8.5×10^{1}	No[c]	GPα,αS	ND (ISγ)	ND
^{241}Am	—	Yes	7.8×10^{1}	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ

Abbreviations: Bq = becquerels; m^2 = square meters; kg = kilograms; GPα = gas-flow proportional counter (α mode); GM = Geiger-Mueller survey meter; GPβ = gas-flow proportional counter (β mode); PIC = pressurized ionization chamber; αS = alpha scintillation survey meter; γS = gamma scintillation (gross); ISγ = in situ gamma spectrometry.

[a] Example DCGLs are provided only for discussion and are based on values given in NRC Report NUREG-1757 (Rev. 2), Volume 1, Tables B.1 and B.2 (NRC 2006). Example DCGLs should not be used in place of approved DCGLs.

[b] ND = Not detectable.

[c] Possibly detectable at limits for areas of elevated activity.

[d] For decay chains having two or more radionuclides of significant half-life that reach secular equilibrium, the notation “(C)” indicates the direct measurement techniques assume the presence of decay products in the chain.

Conceptual models reflected in commonly used codes used to derive DCGLs should be understood. For example, if surficial residual radioactive material exists at a thickness less than 15 cm (6 inches), commonly used codes either assume or allow the residual radioactive material to be uniformly mixed throughout a larger thickness to simulate such processes as soil mixing due to plowing. Yu et al. (1993) allows both the thickness of contamination and the mixing depth to be specified. NRC (1992b) assumes the residual radioactivity is located in the top 15 cm of soil. Similarly, models may be based on dry weight, which may necessitate either drying samples or data transformation to account for dry weight. The DQOs and subsequent direction to the laboratory for analysis might include removal of material not relevant for characterizing the sample, such as pieces of glass, twigs, rocks, pebbles, or leaves. In all cases, it is important to understand the modeling assumptions and how the data collected will be compared to DCGLs derived from the modeling to ensure the fidelity of the statistical survey results.

Both sample depth and area are considerations in determining appropriate sample volume, and sample volume is a key consideration for determining the laboratory MDC. The depth should also correlate with the conceptual model developed in **Chapter 3** and upgraded throughout the RSSI process. For example, if data collected during the HSA indicate that residual radioactive material may exist to a certain depth, then samples should be deep enough to support the survey objectives, such as for the scoping or characterization survey. Taking samples as a function of depth might also be a survey design objective, such as for scoping, characterization, or remediation support. Although some models and codes may allow for the input of (or can be manipulated to consider) heterogeneous radionuclide distributions, other models and codes may assume uniform residual radioactivity. In cases where the models are incapable of representing the complexity of the sources, data may need to be processed for use in the model. Impacts associated with the modeling simplifications should be well understood and documented.

Additionally, the design team needs to consider sampling both data needs and data quality indicators as determined from the DQO process. The design team should review the information in **Section 7.2** when designing the sampling portion of the FSS plan. The decision maker and the survey planning team need to identify the data needs for the survey being performed, including—

- type of samples to be collected or measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.3**)
- number of samples to be collected (**Sections 5.3.3–5.3.5**)
- type and frequency of field QC samples to be collected (**Section 4.9**)
- amount of material to be collected for each sample (**Sections 4.7.3 and 7.5**)
- sampling locations and frequencies (**Section 5.3.7**)
- SOPs to be followed or developed
- measurement method uncertainty (**Section 6.4**)
- target detection capabilities for each radionuclide of interest (**Section 6.3**)
- cost of the methods being evaluated (cost per analysis and total cost) (**Appendix H**)

- necessary turnaround time
- sample preservation and shipping requirements (**Section 7.6**)
- specific background for each radionuclide of interest (**Section 4.5**)
- DCGL for each radionuclide of interest (**Section 4.3**)
- measurement documentation requirements (**Section 5.3.11**)
- sample tracking requirements (**Section 7.8**)

In addition to the above items, the design team needs to consider the following data quality indicators:

- precision
- bias
- representativeness
- comparability
- completeness
- others as discussed in **Section 7.2.2.6**

See **Section 7.2** for a detailed discussion of the DQOs and MQOs for sampling.

Under some circumstances, it might be useful to assess the radionuclide concentrations on different size fractions to better assess transport processes assumed in some dose models. **Chapters 6 and 7** present more detail regarding the application of these survey planning considerations.

4.8.6 Selection of Measurement Techniques

In practice, the DQO process is used to obtain a proper balance among the use of various measurement techniques (scanning, direct, and laboratory). In general, there is an inverse correlation between the cost of a specific measurement technique and the detection levels being sought. Depending on the survey objectives, important considerations include survey costs and choosing an appropriate measurement method.

A certain minimum number of direct measurements or samples may be needed to demonstrate compliance with the release criteria based on certain statistical tests (see **Section 5.3.2**). Alternatively, if there is sufficient detection capability and an acceptable level of measurement method uncertainty, a scan-only survey technique can (with the proper application of the DQO process and regulatory approval) be used to demonstrate compliance with the $DCGL_W$. The potential for areas of elevated residual radioactive material may also have to be considered for designing scanning surveys, as the need to identify areas of elevated activity may affect the number of measurements. Some measurements may provide information of a qualitative nature to supplement other measurements. An example of such an application is in situ gamma spectrometry to demonstrate the absence (or presence) of specific radionuclides.

Assuming the residual radioactive material can be detected, either directly or by measuring a surrogate radionuclide in the mixture, the next decision point depends on whether the radionuclide being measured is present in background. Gross measurement methods will likely be more appropriate for measuring concentrations of radioactive materials on surfaces in structures, scanning for locations of elevated activity, and determining exposure rates. Radionuclide-specific measurement techniques, such as gamma spectrometry, provide a marked increase in detection capability over gross measurements because of their ability to screen out contributions from other sources. **Figure 4.2** illustrates the sequence of steps in determining the type of survey design needed—that is, whether field measurement techniques can be applied at a particular site along with sampling or if a scan-only design is more appropriate. The selection of appropriate instruments for scanning, direct measurement, and sampling and analysis should be survey specific.

4.8.7 Data Conversion

Radiation survey data are usually obtained in units, such as the number of counts per unit time, which have no intrinsic meaning relative to DCGLs. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. Alternatively, the DCGL can be converted into the same units used to record survey results. Either method relies on understanding the instrument response (efficiency). The FSS design team should use the DQO process to determine and document the proper methods used to compare instrument results and DCGLs. Additional details are provided in **Sections 4.12.6 and 6.7.**

4.8.8 Additional Planning Considerations Related to Measurements

4.8.8.1 Selecting a Field Service Provider

The survey design team should start the process of selecting a service provider to perform field data collection early in the planning process. Six criteria that should be considered are—

- validated SOPs
- experience with similar data collection activities
- satisfactory performance evaluations or technical review results
- adequate capacity to perform the all the data collection activities
- internal QC program
- protocols for method performance documentation, sample tracking and security, and documentation of results

More details can be found in **Section 6.5.**

4.8.8.2 Radon Measurements

In some cases, radon may be detected within structures that do not contain residual radioactive material; conversely, some structures that contain residual radioactive material may not yield detectable radon or thoron. Consult with your regulator for the applicability of radon or thoron measurements as part of a site survey.

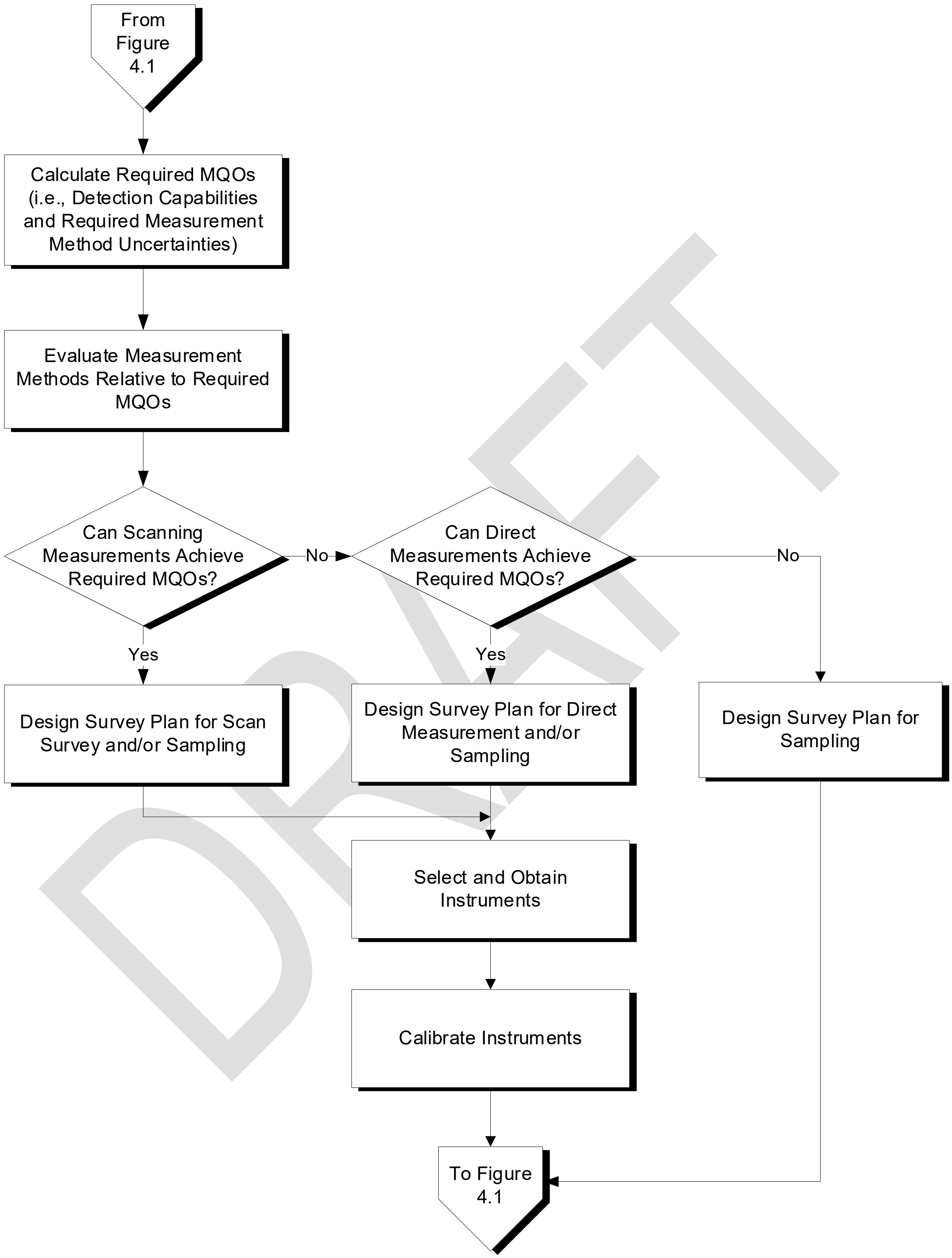

Figure 4.2: Flow Diagram for Field Survey Design

If radon is a concern for the FSS, the design team should work with the appropriate regulatory agency to determine the applicability of radon or thoron measurements. Because of the widespread nature of indoor air radon, many states have developed requirements for certification/qualification of people who perform radon services. Therefore, as part of the qualifications for the service provider, determine whether the measurement provider or the laboratory analyzing the measurements is required to be certified by the state or locality where the work is being performed. State radon contacts can be found at https://www.epa.gov/radon/find-information-about-local-radon-zones-and-state-contact-information.

More details can be found in **Section 6.8.**

4.8.8.3 Specialized Equipment

The survey team must plan for using any specialized equipment other than radiation detectors (e.g., global positioning systems [GPS], local microwave or sonar beacons and receivers, laser positioning systems, etc.). Because these specialized systems are continuously being modified and developed for site-specific applications, it is not possible to provide detailed descriptions of every system. **Section 6.9** provides examples of specialized equipment that have been applied to radiation surveys and site investigations.

4.9 Site Preparation

Site preparation involves obtaining consent for performing the survey, establishing the property boundaries, evaluating the physical characteristics of the site, accessing surfaces and land areas of interest, and establishing a reference coordinate system. Site preparation may also include removing equipment and materials that restrict access to surfaces. The presence of furnishings or equipment will restrict access to building surfaces and add additional items that the survey should address.

4.9.1 Consent for Survey

When facilities or sites are not owned by the organization performing the surveys, consent from the site or equipment owner should be obtained before conducting the surveys. All appropriate Federal, State, Tribal, and local officials, as well as the site owner and other affected parties, should be notified of the survey schedule. **Section 3.6** discusses consent for access, and additional information based on the Comprehensive Environmental Response, Compensation, and Liability Act is available from EPA (EPA 1987c).

4.9.2 Property Boundaries

Property boundaries may be determined from property survey maps furnished by the owners or from plat maps obtained from city or county tax maps. Large-area properties and properties with obscure boundaries or missing survey markers may require the services of a professional land surveyor. A professional land surveyor can also tie a site radiological survey grid into the existing land survey of the site or to an official State or municipal survey grid. Such a tie-in has the advantage of making the radiological survey grid reproducible in the future.

If the radiological survey is only performed inside buildings, a tax map with the buildings accurately located will usually suffice for site/building location designation.

4.9.3 Physical Characteristics of the Site

The physical characteristics of the site will have a significant impact on the complexity, schedule, and cost of a survey. These characteristics include the number and size of structures, type of building construction, wall and floor penetrations, pipes, building condition, total area, topography, soil type, and ground cover. In particular, the accessibility of structures and land areas (**Section 4.9.4**) has a significant impact on the survey effort. In some cases, survey techniques (e.g., in situ gamma spectrometry or scanning surveys discussed in **Chapter 6**) can preclude or reduce the need to gain physical access or use intrusive techniques. This should be considered during survey planning.

4.9.3.1 Structures

Building design and condition will have a marked influence on the survey efforts. The time involved in conducting a survey of building interior surfaces is essentially directly proportional to the total surface area, recognizing that upper wall and ceiling areas require more time than floor and lower wall surveys. For this reason, the degree of survey coverage decreases as the potential for residual radioactive material decreases. Judgment measurements and sampling, which are performed in addition to the measurements performed for certain survey designs, are recommended in areas likely to have accumulated deposits of residual radioactive material. As discussed in **Section 8.5,** judgment measurements and samples are compared directly to the appropriate DCGL.

The condition of surfaces after remedial action may affect the survey process. Removing radioactive material that has penetrated a surface usually involves removing the surface material. As a result, the floors and walls of remediated facilities are frequently badly scarred or broken up and are often very uneven. Such surfaces are more difficult to survey, because it is not possible to maintain a fixed distance between the detector and the surface. In addition, scabbled or porous surfaces may significantly attenuate radiations—particularly alpha and low-energy beta particles. Use of monitoring equipment on wheels is precluded by rough surfaces, and such surfaces also pose an increased risk of damage to fragile detector probe faces. These factors should be considered during the calibration of survey instruments; NRC report NUREG-1507 (NRC 1997a) provides additional information on how to address these surface conditions. The condition of the building should also be considered from a safety and health standpoint before a survey is conducted. A structural assessment may be needed to determine whether the structure is safe to enter.

Expansion joints, stress cracks, drains, and penetrations into floors and walls for piping, conduit, anchor bolts, etc., are potential sites for accumulation of residual radioactive material and pathways for migration into subfloor soil and hollow wall spaces. Drains, sewers, and septic systems can contain residual radioactive material, and wall/floor interfaces are also likely locations for residual radioactive material. Coring, drilling, or other such methods may be necessary to gain access for surveying. Intrusive surveying may require permitting by local regulatory authorities. Additionally, suspended ceilings may cover areas of potential residual radioactive material, such as ventilation ducts and fixtures. There may be other materials introduced that were not part of the original construction—such as floor tiles, partitions, insulation, additional concrete slabs, and paint—that may cover residual radioactive material.

Exterior building surfaces will typically have a low potential for residual radioactive material; however, there are several locations that should be considered during survey planning. If there are roof exhausts or roof accesses that allow for radioactive material movement, or if the facility is proximal to the air effluent discharge points, the possibility for residual radioactive material on the roof should be considered. Because roofs are periodically resurfaced, radioactive material may be trapped in roofing material, and sampling this material may be necessary. Such roof drainage points as driplines along overhangs, downspouts, and gutters are also important survey locations. Roofs may also accumulate radioactive material from fallout, or roof materials may contain elevated levels of naturally occurring radioactive material (e.g., elevated uranium in roof tar). Wall penetrations for process equipment, piping, and exhaust ventilation are potential locations for exterior residual radioactive material. Window ledges and outside exits (doors, doorways, landings, stairways, etc.) are also building exterior surfaces that should be addressed.

4.9.3.2 Building Materials

In addition to radiological surveys of the building surfaces described in **Section 4.8.3.1,** it may also be necessary to survey any building materials removed from the building as part of its demolition, remediation, or renovation. Guidance for the design and implementation of radiological surveys of these materials is provided in MARSAME (NRC 2009).

4.9.3.3 Land Areas

Depending on site processes and operating history, the radiological survey may include varying portions of the land areas. Open land or paved areas with a potential for residual radioactive material should include storage areas (e.g., equipment, product, waste, and raw material), liquid waste collection lagoons and sumps, areas downwind (based on predominant wind directions on an average annual basis, if possible) of stack release points, and surface drainage pathways. Additionally, roadways and railways that may have been used for transport of improperly contained radioactive materials could also have an accumulation of residual radioactive material.

Building modifications should be reviewed to assess any expansions that might cover former land disposal areas. Other land areas—such as wetlands, marshlands, or low-lying surface areas—where waste material was used as fill material need to be assessed for potential residual radioactive material. In some instances, the waste material is covered with clean backfill material to grade to ground surface. Archived aerial photos, historical maps, and interviews can be used to assess the potential presence of such areas.

Buried piping, underground tanks, fill areas, sewers, spill areas, and septic leach fields that may have received radioactive liquids are locations of possible residual radioactive material that may necessitate sampling of subsurface soil (**Section 7.5.3**). Information regarding soil type (e.g., clay, sand) may provide insight into the retention or migration characteristics of specific radionuclides. The need for special sampling by coring or split-spoon equipment should be anticipated for characterization surveys.

If radioactive waste has been removed, surveys of excavated areas will be necessary before backfilling with clean fill. If the waste is to be left in place, subsurface sampling around the burial site perimeter to assess the potential for future migration may be necessary.

Additionally, rivers, harbors, shorelines, and other outdoor areas with a potential for residual radioactive material may require survey activities including environmental media (e.g., sediment and biota) associated with these areas.

4.9.4 Clearing to Provide Access

In addition to the physical characteristics of the site, a major consideration is how to address difficult-to-access areas that have a potential for residual radioactive material. Difficult-to-access areas may need significant effort and resources to perform adequate surveys. This section provides a description of common difficult-to-access areas that may have to be considered. The level of effort expended to access such areas should be commensurate with the potential for residual radioactive material. For example, the potential for the presence of residual radioactive material behind walls should be established before significant effort is expended to remove drywall.

4.9.4.1 Structures

When necessary, structures and indoor areas should be sufficiently cleared to permit completion of the survey. Clearing includes providing access to interior surfaces (e.g., drains, ducting, tanks, pits, ceiling areas, and equipment) by removing covers, disassembly, or other means of producing adequate openings.

Such building features as ceiling height, construction materials, ducts, pipes, etc., will determine the ease of accessibility of various surfaces. Scaffolding, cranes, lifts, or ladders may be necessary to reach some surfaces, and dismantling portions of the building may be required.

The presence of furnishings and equipment will restrict access to building surfaces and add additional items that the survey should address. Any remaining equipment indirectly involved in the process may need to be dismantled to evaluate the radiological status, particularly of difficult-to-access parts of the equipment. Removing or relocating certain furnishings, such as laboratory benches and hoods, to obtain access to floors and walls may also be necessary. The amount of effort and resources dedicated to such removal or relocation activities should be commensurate with the potential for residual radioactive material. Where the potential is low, a few spot-checks may be sufficient to provide confidence that covered areas are free of residual radioactive material. In other cases, complete removal may be warranted. Guidance for the survey and assessment of materials and equipment is included in the MARSAME Manual.

Piping, drains, sewers, sumps, tanks, and other components of liquid-handling systems present special difficulties because of the difficulty in accessing interior surfaces. Process information, operating history, and preliminary monitoring at available access points will assist in evaluating the extent of sampling and measurements included in the survey. Some specialized survey techniques for drains and sewers have been developed and are effective for the measurement of some radionuclides.

If the building is constructed of porous materials (e.g., wood, concrete, masonry, etc.) and the surfaces were not sealed, residual radioactive material may be found in the walls, floors, and other surfaces. It may be necessary to obtain cores of these surfaces for laboratory analysis.

Another accessibility problem is the presence of residual radioactive material beneath tile or other floor coverings. This often occurs because the covering was placed over surfaces containing residual radioactive material, or the joints in tile were not sealed to prevent penetration. The practice in some facilities has been to “fix” radioactive material (particularly alpha emitters) by painting over the surface of the affected area. Thus, actions to obtain access to surfaces, such as removing wall and floor coverings (including paint, wax, or other sealer) and opening drains and ducts, may be necessary to enable representative measurements of the residual radioactive material. This material may also require a radiation survey to ensure no radioactive material was transferred during the removal process. If alpha radiation or very low energy beta radiation is to be measured, the surface should be free of overlying material, such as dust and water, which may significantly attenuate the radiations.

4.9.4.2 Land Areas

If ground cover needs to be removed or if other obstacles limit access by survey personnel or necessary equipment, the time and expense of making land areas accessible should be considered. In addition, contamination control procedures need to be developed to prevent the spreading of radioactive material during ground cover removal or the use of heavy equipment.

Whenever possible, the property owner should perform the removal or relocation of equipment and materials that require special precautions to prevent damage or maintain inventory accountability. Clearing open land of brush and weeds will usually be performed by a professional land-clearing organization under subcontract arrangements. However, survey personnel may perform minor land-clearing activities as needed.

An important consideration prior to clearing is the possibility of bio-uptake of radionuclides in the plant material to be cleared. Special precautions to avoid exposure of personnel involved in clearing activities may be necessary. Radiological screening surveys should be performed to ensure that cleared material or equipment does not contain residual radioactive material.

The extent of site clearing in specific areas depends primarily on the potential for residual radioactive material to exist in those areas where—

- The radiological history or results of previous surveys indicate a low potential for residual radioactive material in an area; it may be sufficient to perform only minimum clearing to establish a reference coordinate system.
- Residual radioactive material is known to exist, or a high potential for it necessitates completely clearing an area to provide access to all surfaces.
- New findings as the survey progresses indicate that additional clearing is needed.

Open land areas may be cleared by heavy machinery (e.g., bulldozers, bushhogs, and hydroaxes). However, care should be exercised to prevent relocation of surface radioactive material or damage to such site features as drainage ditches, utilities, fences, and buildings. Minor land clearing may be performed using manually operated equipment, such as brush hooks, power saws, knives, and string trimmers. Brush and weeds should be cut to the minimum practical height necessary to facilitate measurement and sampling activities (approximately 15 cm). Care should be exercised to prevent unnecessary damage to or removal of mature trees, shrubs, or historical or cultural resources.

Potential ecological or cultural damage that might result from an extensive survey should be considered. If a survey is likely to result in significant or permanent damage to environmental or cultural resources, appropriate environmental and cultural analyses should be conducted prior to initiating the survey.

4.9.5 Reference Coordinate System

4.9.5.1 Establishment

Reference coordinate systems are established at the site to—

- Facilitate the selection of measurement and sampling locations.
- Provide a mechanism for referencing a measurement to a specific location so that the same survey point can be located again.

A survey reference coordinate system consists of a grid of intersecting lines referenced to a fixed site location or benchmark. Typically, the lines are arranged in a perpendicular pattern, dividing the survey location into squares or blocks of equal area; however, other types of patterns (e.g., three-dimensional, polar) have been used.

The reference coordinate system used for a particular survey should provide a level of reproducibility consistent with the objectives of the survey. For example, commercially available single-frequency GPS devices can typically locate a position to within approximately 5 m, while dual-frequency receivers and augmentation systems can provide real-time precision on the order of a few centimeters. On the other hand, a metal bar can be driven into the ground to provide a long-term reference point for establishing a local reference coordinate system. Some States have official grid systems, and if such a system exists in a particular State, consideration should be given to tying a site grid into the official State grid.

Reference coordinate system patterns on horizontal surfaces are usually identified numerically on one axis and alphabetically on the other axis, or in distances in different compass directions from the grid origin. Examples of structure interior and land area grids are shown in **Figures 4.3–4.5.** Grids on vertical surfaces may include a third designator, indicating position relative to floor or ground level. Overhead measurement and sampling locations (e.g., ceiling and overhead beams) are referenced to corresponding floor grids.

For surveys of Class 1 and Class 2 areas, basic coordinate system patterns at 1–2 m intervals on structure surfaces and at 10–20 m intervals of land areas may be sufficient for the purpose of identifying FSS locations with a reasonable level of effort. Gridding of Class 3 areas may also be necessary to facilitate referencing of survey locations to a common system or origin but, for practical purposes, may typically be at larger intervals (e.g., 5–10 m for large structural surfaces and 20–50 m for land areas). For the FSS, the required scanning percentages, number of discrete survey locations for direct measurements, and number of sample locations will depend on the classification of the survey unit (see **Chapter 5**).

Reference coordinate systems on structure surfaces are usually marked by chalk lines or paint along the entire grid line or at line intersections. Land area reference coordinate systems are usually marked by wooden or metal stakes driven into the surface at reference line intersections. The selection of an appropriate marker depends on the characteristics and routine uses of the surface. Where surfaces prevent installation of stakes, the reference line intersection can be marked by painting.

Three basic coordinate systems are used for identifying points on a reference coordinate system. The reference system shown in **Figure 4.3** references grid locations using numbers on the vertical axis and letters on the horizontal axis. The reference system shown in **Figure 4.4** references distances from the (0,0) point using the compass directions N (north), S (south), E (east), and W (west). The reference system shown in **Figure 4.5** references distances along and to the R (right) or L (left) of the baseline.

In addition, a less frequently used reference system is the polar coordinate system, which measures distances along transects from a central point. Polar coordinate systems are particularly useful for survey designs to evaluate effects of stack emissions, where it may be desirable to have a higher density of samples collected near the stack and fewer samples with increasing distance from the stack.

Figure 4.5 shows an example grid system for an outdoor land area. The first digit or set of digits includes an L or R (separated from the first set by a comma) to indicate the distance from the baseline in units (m) and the direction (left or right) from the baseline. The second digit or set of digits refers to the perpendicular distance from the (0,0) point on the baseline and is measured in hundreds of units. Point A in the example of a reference coordinate system for survey of site grounds, **Figure 4.5,** is identified as (100R, 2+00) (i.e., 200 m from the baseline and 100 m to the right of the baseline). Fractional distances between reference points are identified by adding the distance beyond the reference point and are expressed in the same units used for the reference coordinate system dimensions. Point B on **Figure 4.5** is identified as (25R, 1+30).

Open land reference coordinate systems should be referenced to a location on an existing State or local reference system or to a U.S. Geological Survey (USGS) benchmark. (This may require the services of a professional land surveyor.) GPS is capable of locating reference points in terms of latitude and longitude (**Section 6.9.2** provides descriptions of positioning systems.)

Following the establishment of the reference coordinate system, a drawing is prepared by the survey team or the land surveyor. This drawing indicates the reference lines, site boundaries, and other pertinent site features and provides a legend showing the scale and a reference compass direction.

4.9.5.2 Quality System Considerations

The concept of the quality system was introduced in **Section 4.2.2.** The process used to develop the reference coordinate system should be recorded in the survey planning documentation (e.g., the QAPP). Any deviations from the requirements developed during planning should be documented when the reference coordinate system is established.

When the survey reference coordinate system is referenced to a fixed site location or benchmark on a known geographic coordinate system (GCS) or projected coordinate system (projection) (e.g., a State system), or the survey reference coordinate system itself uses a known GCS or projection rather than one of the three basic coordinate systems described in **Section 4.9.5.1,** then the following information should be provided about the actual GCS or projection used:

- name
- units used (e.g., feet, meters, etc.)
- zone
- datum
- spheroid
- method used to determine/obtain the coordinates (e.g., GPS)
- estimates of the accuracy and precision of the coordinates
- transformations used to convert from coordinates from one system to another

Ideally, this information should be provided in the spatial reference section of the metadata for the GIS layer containing the data. If a GPS was used to obtain the coordinates, then information should be included about the differential corrections made to the original GPS measurements.

It should be noted that the reference coordinate systems described in this section are intended primarily for reference purposes and do not necessarily dictate the spacing or location of survey measurements or samples. Establishment of a measurement grid to demonstrate compliance with the DCGLs is discussed in **Section 5.3.7** and **Chapter 8.**

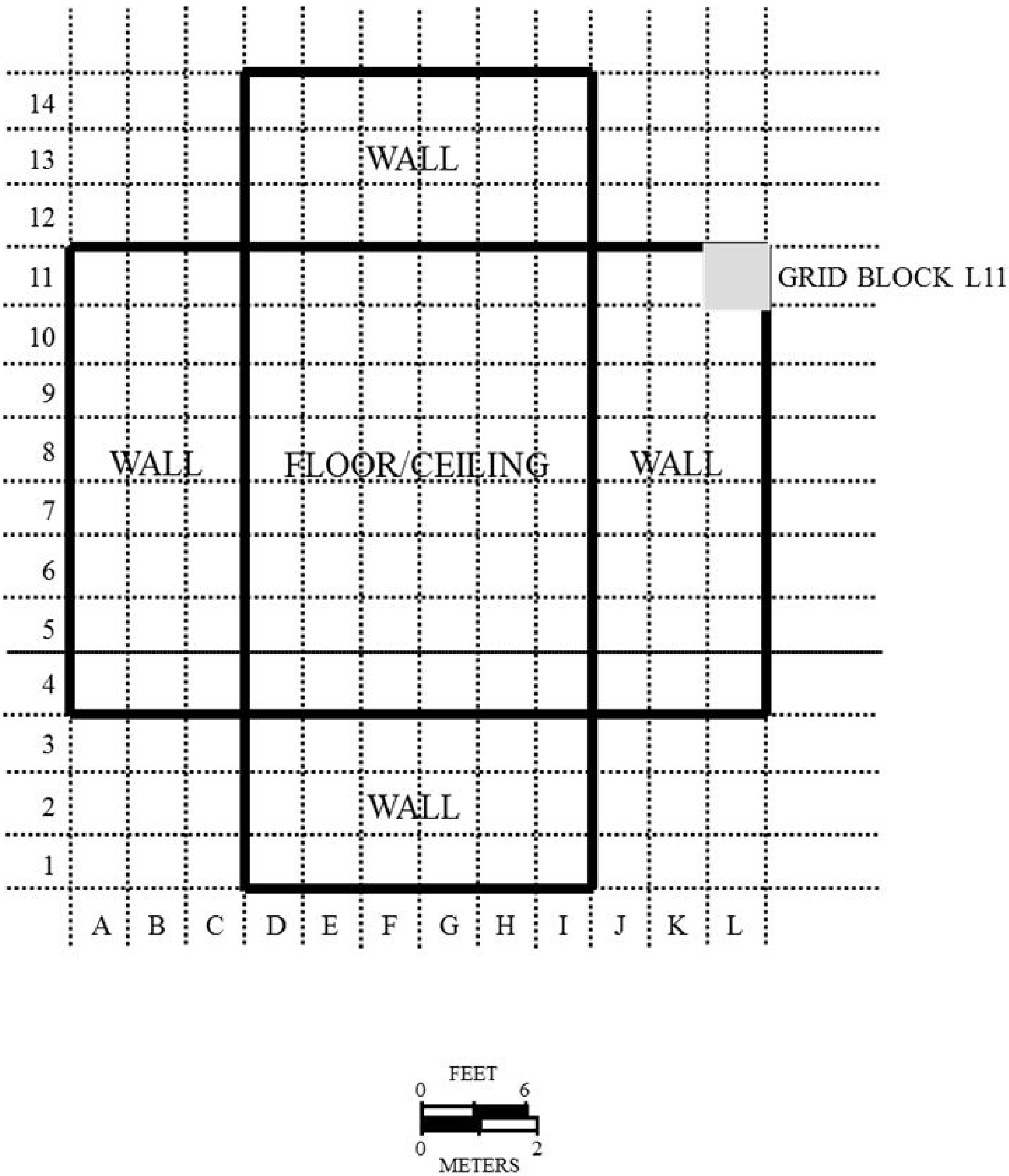

Figure 4.3: Indoor Grid Layout with Alphanumeric Grid Block Designation: Walls and Floors are Diagramed as Though They Lay Along the Same Horizontal Plane

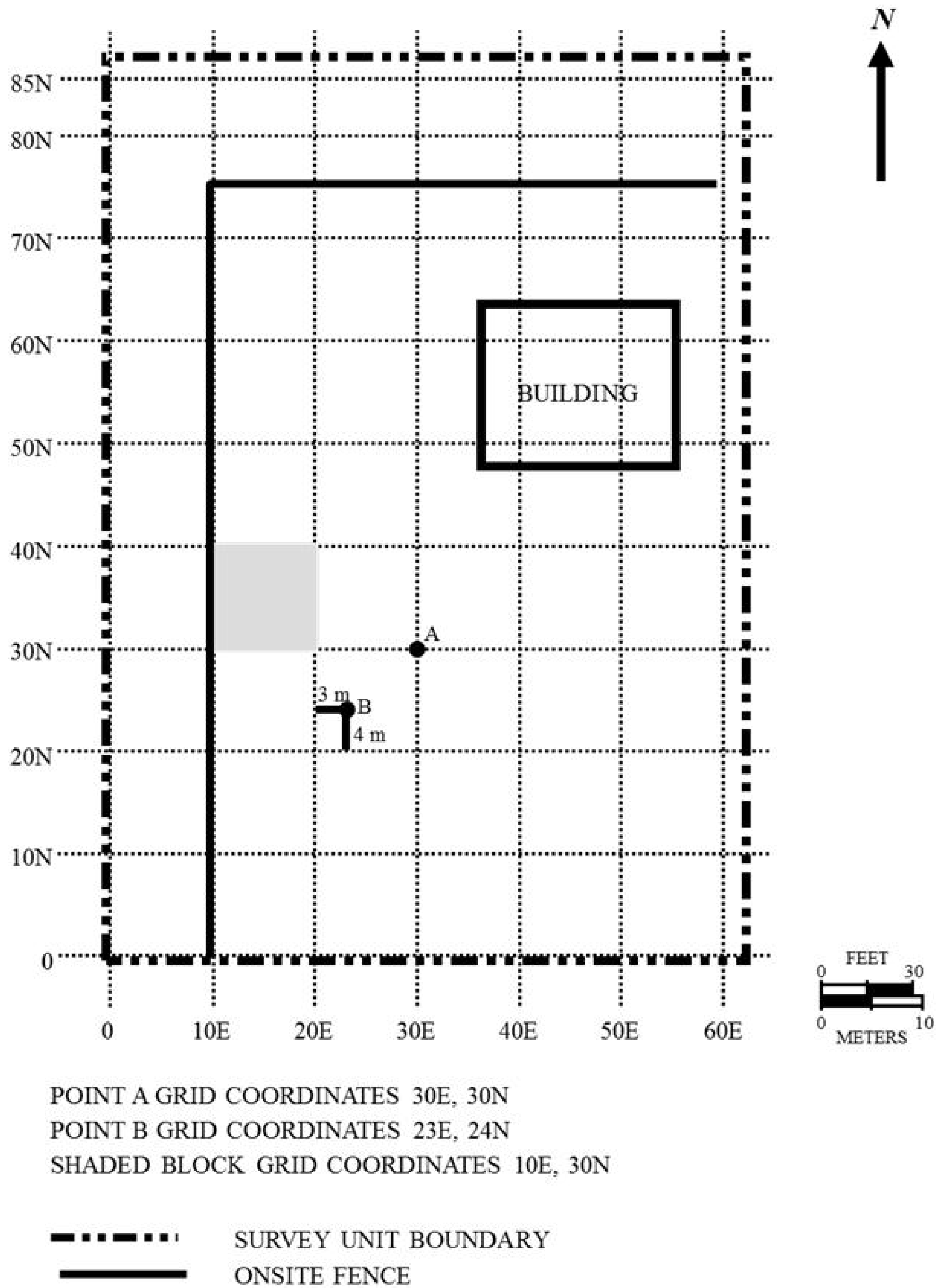

Figure 4.4: Example of a Grid System for Survey of Site Grounds Using Compass Directions

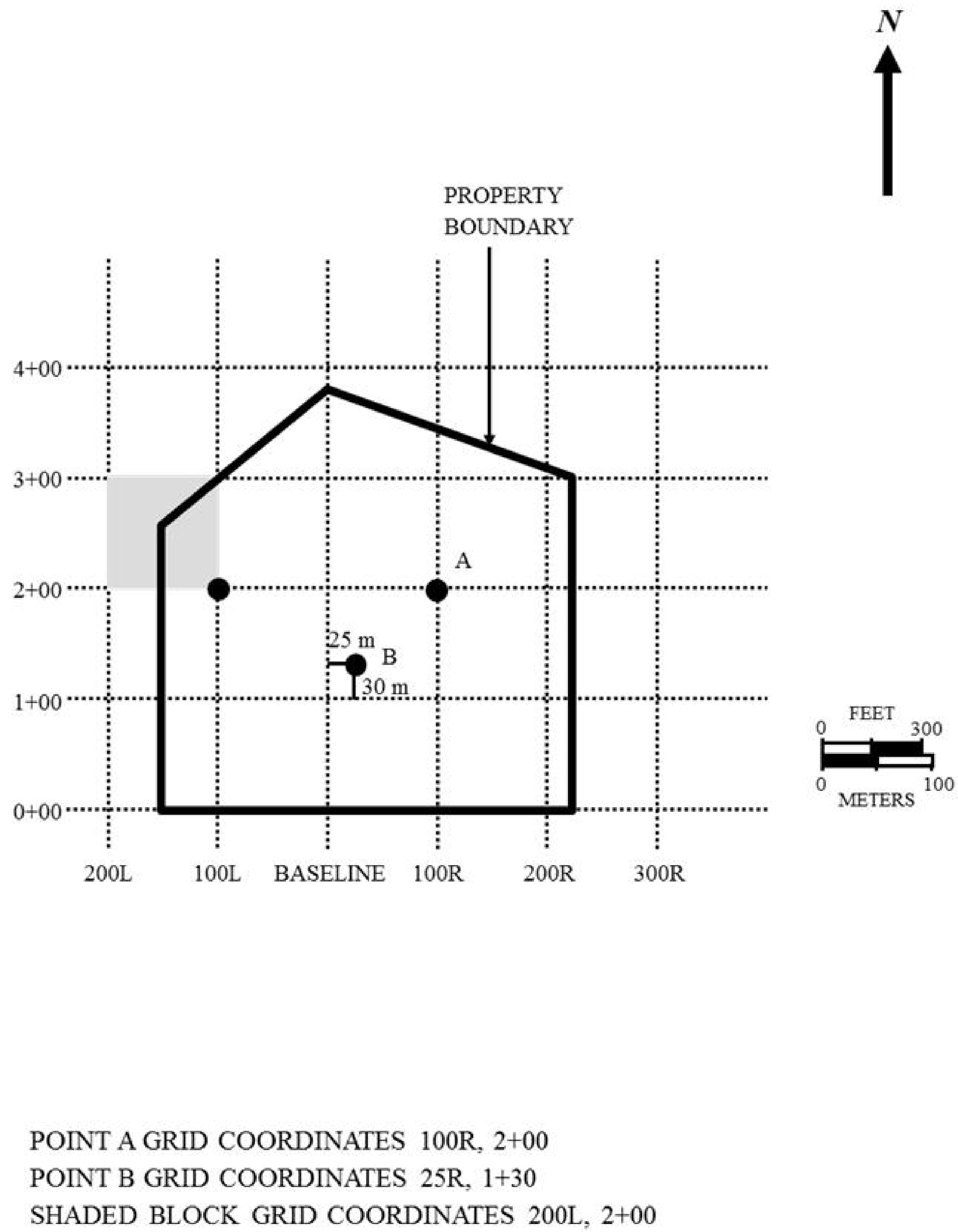

Figure 4.5: Example of a Grid System for Survey of Site Grounds Using Distances Left or Right of the Baseline

4.10 Health and Safety

Health and safety are emphasized as issues potentially affecting the implementation of MARSSIM surveys. The focus of the health and safety program is minimizing environmental and physical hazards (e.g., confined spaces, unstable surfaces, heat and cold stress) where these issues may affect how a survey is designed and performed. Work areas and procedures that present potential safety hazards must be identified and evaluated to warn personnel of potential hazards. Personnel must be trained about potential physical and chemical safety hazards (e.g., inhalation, adsorption, ingestion, injection/puncturing) and the potential for injury (e.g., slips, trips, falls, burns). In addition, the presence or possibility of such environmental hazards as poison ivy; ticks carrying Lyme disease; and poisonous snakes, spiders, rodents, or insects should be noted. These hazards can affect the safety and health of the workers, as well as the schedule for performing the survey. Some physical hazards require special procedures or precautions. Steep slopes might require special gear for surveyors and instruments or might call for dispensations from the regulatory agency to reduce or eliminate survey efforts in such areas. The potential presence of unexploded ordnance (UXO) requires qualified explosive ordnance disposal personnel to clear the survey unit of UXO and accompany survey personnel during the survey.

A job safety analysis (JSA) should be performed prior to implementing a survey. The JSA offers an organized approach to the task of locating problem areas for material handling safety (OSHA 2002). The JSA should be used to identify hazards and provide inputs for drafting a health and safety plan (HASP). The HASP will address the potential hazards associated with survey activities and should be prepared concurrently with the survey design. The HASP identifies methods to minimize the threats posed by the potential hazards. The information in the HASP may influence the selection of a measurement technique and disposition survey procedures. Radiation work permits (RWPs) may be established to control access to radiologically controlled areas. RWPs contain requirements from the JSA, such as dosimetry and personal protective equipment (PPE), as well as survey maps illustrating predicted dose rates and related radiological concerns (e.g., removable or airborne radioactive material). Hazard work permits (HWPs) may be used in place of RWPs at sites with primarily physical or chemical hazards.

The JSA systematically carries out the basic strategy of accident prevention through the recognition, evaluation, and control of hazards associated with a given job, as well as the determination of the safest, most efficient method of performing that job. This process creates a framework for deciding among engineering controls, administrative controls, and PPE for the purpose of controlling or correcting unsafe conditions. Examples of these controls include—

- engineering controls, which are physical changes in processes or machinery (e.g., installing guards to restrict access to moving parts during operation), storage configuration (e.g., using shelves in place of piles or stacks)
- administrative controls, which are changes in work practices and organization (e.g., restricted areas where it is not safe to eat, drink, smoke, etc.), including the placement of signs to warn personnel of hazards
- PPE, which are clothing or devices worn by employees to protect against hazards (e.g., gloves, respirator, full-body suits)

Correction measures may incorporate principles of all of the controls listed above. The preferred method of control is through engineering controls, followed by administrative controls, and then PPE.

Proper handling procedures for hazardous substances are documented in site-specific health and safety plans. Compliance with all control requirements is mandatory to maintain a safe working environment. Personnel must regard control requirements as a framework to facilitate health and safety, while still taking responsibility for their own well-being. Being wary of safety hazards remains an individual responsibility, and personnel must be aware of their surroundings at all times in work areas.

4.11 Documentation

Concurrently with the FSS design, the design team should begin to draft the FSS report. In many cases before the FSS is started, the regulator will require a report documenting the proposed sampling and surveying plan, including ancillary documentation such as the QAPP. The FSS report should present a complete and unambiguous record of the radiological status of the survey unit, relative to the established DCGLs. To the extent possible, this should be self-contained and contain a minimum of information incorporated by reference. Reporting requirements for the FSS should be developed during planning and clearly documented in the QAPP. The text below describes some of the information needed for review of an FSS:

Example 1: Information Needed for an FSS Review

A review by the U.S. Nuclear Regulatory Commission of the final status survey (FSS) documentation is undertaken to “verify that the results of the FSS demonstrate that the site, area, or building meet the radiological criteria for license termination” (NRC, 2006). The information needed by the NRC for a review is summarized below. For more details, see NRC (2006).

- an overview of the results of the FSS
- a summary of the derived concentration guideline levels
- a discussion of any differences from prior submissions
- a description of the method by which the number of samples was determined for each survey unit
- a summary of the values used to determine the number of samples and a justification for these values
- the results for each survey unit
- analytical methods used
- detection limits
- estimates of uncertainties or sample standard deviations
- a description of any changes in initial survey unit assumptions relative to the extent of residual radioactive material
- a description of how “as low as reasonably achievable” practices were employed to achieve final activity levels

In addition to the items above, the design team should have the following information available (NRC, 2006):

- the results of previously conducted in-process inspections and confirmatory surveys
- the licensee's quality assurance/quality control program
- confirmation that the changes to prior submissions are not significant and are technically correct
- issues (a) identified by intervenors and stakeholders and (b) raised in allegations to assure such issues have been satisfactorily resolved
- descriptions of the survey units to determine if any special survey situations are present
- results of elevated measurement comparisons
- results of the appropriate statistical tests (e.g., Wilcoxon Rank Sum and Sign tests) to confirm that results indicate compliance
- specific parts of the FSS and supporting data that affect the FSS but that were not available when the decommissioning or license termination plan was approved

4.12 Application of Survey Planning Concepts with Example Calculations

This section is intended to expand on the content presented in this chapter, provide a general overview, and familiarize the MARSSIM user with the application of the concepts in **Sections 4.4 through 4.7** to planning FSSs.[7] Greater detail appears in the chapters that follow.

4.12.1 Scenario A or Scenario B?

Occasionally, the design team will need to determine the appropriate scenario for use in statistical hypothesis testing as the basis for the FSS. Under Scenario A, it is assumed that the concentration of residual radioactive material equals or exceeds the release criteria. For Scenario B, it is assumed that the concentration of residual radioactive material meets the release criteria (i.e., less than the action level [AL]). Historically, MARSSIM recommended the use of Scenario A, which put the burden of proof that the survey unit met the release criteria on the individuals designing the survey. In Scenario B, the burden of proof is no longer on the individuals designing the survey and thus should be used with caution and only in those situations where Scenario A is not an effective alternative.

The basic problem is one of being able to distinguish residual radioactive material from background. If a radionuclide has a relatively small $DCGL_W$ and is present in the background with a relatively large variation, then it requires a large number of measurements to determine if the residual concentration exceeds the $DCGL_W$. The choice of Scenario A or Scenario B should be based on which null hypothesis is easier to live with if false (NRC 1998a). If the $DCGL_W$ is large relative to the measurement or background variation, then Scenario A should be chosen (NRC 1998a). This is likely the more common situation. Conversely, if the $DCGL_W$ is small

[7] **Appendix A** contains a detailed example of MARSSIM applied to executing FSS for a single radionuclide. This example builds on examples in **Chapters 5 and 8.**

relative to the measurement or background variation, then Scenario B should be chosen (NRC 1998a).

The MARSSIM user should review the information in **Section 5.3.1** and NRC (1998a) for more information on selecting the appropriate scenario. The remainder of the examples in this section are based on Scenario A.

4.12.2 DCGL Calculations

4.12.2.1 Decay Series

In this example, the surface activity $DCGL_W$ for natural thorium (Th-nat) is 1,000 Bq/m^2 (600 dpm/100 cm^2), and all of its decay products are in secular equilibrium—that is, for each disintegration of thorium-232 (^{232}Th), a total of six alpha and four beta particles are emitted in the thorium decay series. Note that in this example, the surface activity $DCGL_W$ of 1,000 Bq/m^2 is assumed to apply to the total activity from all members of the decay chain. In this situation, the corresponding alpha activity $DCGL_W$ should be adjusted to 600 Bq/m^2 (360 dpm/100 cm^2), and the corresponding beta activity $DCGL_W$ to 400 Bq/m^2 (240 dpm/100 cm^2), in order to be equivalent to 1,000 Bq/m^2 of natural thorium surface activity. For a surface activity $DCGL_W$ of 1,000 Bq/m^2, the beta activity $DCGL_W$ is calculated as shown in **Equation (**4-16)**:**

$$\mathbf{DCGL_{W,\,\beta}} = \left(\mathbf{DCGL_{W,\,Total}}\right) \times \left(\textbf{fraction of decays that emit } \beta\,\textbf{s}\right)$$

$$= \frac{\left(\frac{\textbf{1,000 Bq of chain}}{\textbf{m}^2}\right) \times \left(\frac{\textbf{4 } \beta \textbf{ Bq}}{\textbf{Bq of } ^{232}\textbf{Th}}\right)}{\frac{\textbf{10 Bq of chain}}{\textbf{1 Bq of } ^{232}\textbf{Th}}} = \frac{\textbf{400 } \beta \textbf{ Bq}}{\textbf{m}^2} \qquad (4\text{-}16)$$

For this example, the beta activity $DCGL_W$ corresponding to the $DCGL_W$ for natural thorium is 400 beta particles/second/square meter.

To demonstrate compliance with the beta activity $DCGL_W$ for this example, measurements of beta count rates must be converted to activity using a weighted beta efficiency that accounts for the energy and yield of each beta particle. For decay chains that have not achieved secular equilibrium, the relative activities between the different members of the decay chain can be determined as previously discussed for surrogate ratios.

4.12.2.2 Surrogate DCGL

This example illustrates and discusses the application of the surrogate method.

Determining the Surrogate Ratio

Ten soil samples within the survey unit were collected and analyzed for ^{137}Cs and ^{90}Sr to establish a surrogate ratio. The ratios of ^{90}Sr to ^{137}Cs were as follows: 6.6, 5.7, 4.2, 7.9, 3.0, 3.8, 4.1, 4.6, 2.4, and 3.3. An assessment of this example data set results in a mean ^{90}Sr to ^{137}Cs surrogate ratio of 4.6, with a standard deviation of 1.7, as shown below using **Equations 8.1 and 8.2:**

$$\text{Mean} = \frac{6.6 + 5.7 + \cdots + 2.4 + 3.3}{10} = 4.6$$

$$\sigma = \frac{(6.6 - 4.6)^2 + (5.7 - 4.6)^2 + \cdots + (2.4 - 4.6)^2 + (3.3 - 4.6)^2}{10 - 1} = 1.7$$

There are various approaches that may be used to develop a surrogate ratio from this data, but each must consider the variability and level of uncertainty in the data. One may consider the variability in the surrogate ratio by selecting the 95 percent upper confidence level (UCL) of the surrogate ratio (to yield a conservative value of ^{90}Sr from the measured ^{137}Cs), which is 8.0 in this case, as shown below using **Equation 8.3:**

$$\text{UCL} = 4.6 + 1.96 \times 1.7 = 8.0$$

Similarly, one may select the most conservative value from the data set (in this case, 7.9).

At sites where surrogates are used, a correlation coefficient should be calculated to validate the relationship between the radionuclides. In addition, the radioactive ingrowth and decay of radionuclides should be evaluated. Surrogates are most appropriate for sites where the radionuclides are contained in insoluble particulates. The sources of insoluble particulates include the following:

- *Sites processing minerals, such as monazite, thorite, thorianite, and zircon:* The gamma radiation from the decay products here are a useful surrogate for the decay chain, and the insolubility of the minerals precludes changes in the ratios of the parent and progeny.

- *Sites with residual radioactive material from corrosion products from nuclear reactors:* In this case, the gamma radiation from ^{60}Co is typically used as a surrogate for other radionuclides, including iron-59 (^{59}Fe), iron-55 (^{55}Fe), cobalt-57 (^{57}Co), chromium (^{51}Cr), manganese (^{54}Mn), nickel-57 (^{57}Ni), and nickel-63 (^{63}Ni). Note that at this kind of site, the shorter-lived radionuclides will decay more rapidly than the ^{60}Co, and appropriate decay corrections will need to be evaluated.

- *Sites with plutonium isotopes and americium-241 (^{241}Am):* At these sites, the gamma radiation from ^{241}Am is a useful surrogate for plutonium-249 (^{239}Pu) and plutonium-240 (^{240}Pu). Note that at this kind of site, plutonium-241 (^{241}Pu) will continue to decay to ^{241}Am; therefore, the appropriate decay corrections will need to be made.

- *Sites with thoriated metal (e.g., nickel, tungsten, or magnesium):* The gamma radiation from thorium progeny here can be used as a surrogate, but a thorough evaluation is required to verify that sufficient time has passed to permit the thorium and its progeny to be near a state of secular equilibrium.

Once an appropriate surrogate ratio is determined and approved by the appropriate regulatory agency, the planning team needs to consider how compliance will be demonstrated using surrogate measurements. That is, the planning team must modify the DCGL of the measured radionuclide to account for the inferred radionuclide. This calculation is shown below.

<u>Surrogate DCGL Calculation</u>

The modified DCGL for ^{137}Cs must be reduced using **Equation (**4-9)**:**

$$\text{DCGL}_{\text{Cs-mod}} = \frac{1}{\left(\frac{1}{\text{DCGL}_{\text{Cs}}} + \frac{\text{R}_{\text{Sr/Cs}}}{\text{DCGL}_{\text{Sr}}}\right)}$$

where DCGL_{Cs} is the DCGL of ^{137}Cs; DCGL_{Sr} is the DCGL of ^{90}Sr, and $\text{R}_{\text{Sr/Cs}}$ is the ratio of the concentrations of ^{90}Sr to ^{137}Cs. Assuming that the DCGL_{Sr} is 150 Bq/kg, the DCGL_{Cs} is

100 Bq/kg, and the ratio of ^{90}Sr to ^{137}Cs is 8 (e.g., from a post-remediation characterization survey), the modified DCGL for ^{137}Cs ($DCGL_{Cs\text{-}mod}$) can be calculated using **Equation (**4-9)**:**

$$DCGL_{Cs\text{-}mod} = \frac{1}{\left(\frac{1}{100\ \text{Bq kg}^{-1}} + \frac{8}{150\ \text{Bq kg}^{-1}}\right)} = 16\ \text{Bq kg}^{-1}$$

The modified DCGL for ^{137}Cs ($DCGL_{Cs\text{-}mod}$) is 16 Bq kg^{-1}.

4.12.2.3 Gross Activity DCGL for Radionuclides in Known Ratios

<u>Determining the Radionuclide Ratios</u>

As with the surrogate ratio method, the determination of the relative ratios should be determined through the DQO process and with regulatory approval. Care must be taken to ensure that ratios are applicable to the FSS conditions (e.g., ratio measurements are made just before starting the FSS).

<u>General Gross Activity DCGL Calculation</u>

For this example, assume that 40 percent of the total surface activity was contributed by a radionuclide with a DCGL of 8,300 Bq/m^2 (5000 dpm/100 cm^2), 40 percent by a radionuclide with a DCGL of 1,700 Bq/m^2 (1000 dpm/100 cm^2), and 20 percent by a radionuclide with a DCGL of 830 Bq/m^2 (500 dpm/100 cm^2). Using **Equation (**4-10)**,**

$$DCGL_{gross} = \frac{1}{\frac{f_1}{DCGL_1} + \frac{f_2}{DCGL_2} + \frac{f_3}{DCGL_3}}$$

$$= \frac{1}{\frac{0.40}{8{,}300\ \text{Bq/m}^2} + \frac{0.40}{1{,}700\ \text{Bq/m}^2} + \frac{0.20}{830\ \text{Bq/m}^2}}$$

$$= 1{,}900\ \text{Bq/m}^2$$

the gross activity DCGL is 1,900 Bq/m^2 (1,100 dpm/100 cm^2).

> Note: If the relative amounts (ratios) were derived from data collected before remediation, then the relative amounts need to be confirmed or verified after remediation but before the FSS.

4.12.2.4 Unity Rule DCGL for Radionuclides with Unrelated Concentrations

For a given survey unit, data from previous surveys yield the radionuclide concentrations.

- Mean ^{60}Co concentration = 41 ± 32 (1σ) Bq/kg.
- Mean ^{137}Cs concentration = 188 ± 153 (1σ) Bq/kg.

The $DCGL_W$ values for ^{60}Co and ^{137}Cs are 130 Bq/kg (3.6 pCi/g) and 410 Bq/kg (11 pCi/g), respectively. Since the concentrations of the two radionuclides appear to be unrelated in the survey unit, the surrogate approach cannot be employed.

The weighted sum (calculated using **Equation (**4-12)) is

$$T = \frac{C_{Co\text{-}60}}{DCGL_{Co\text{-}60}} + \frac{C_{Cs\text{-}137}}{DCGL_{Cs\text{-}137}} = \frac{41\ \text{Bq/kg}}{130\ \text{Bq/kg}} + \frac{188\ \text{Bq/kg}}{410\ \text{Bq/kg}} = 0.77$$

The standard deviation of the weighted sum (calculated using **Equation 4-13**) is

$$\sigma(T) = \sqrt{\left[\frac{\sigma(C_{Co\text{-}60})}{DCGL_{Co\text{-}60}}\right]^2 + \left[\frac{\sigma(C_{Cs\text{-}137})}{DCGL_{Cs\text{-}137}}\right]^2} = \sqrt{\left[\frac{32\ \text{Bq/kg}}{130\ \text{Bq/kg}}\right]^2 + \left[\frac{153\ \text{Bq/kg}}{410\ \text{Bq/kg}}\right]^2} = 0.45$$

The weighted sum would be reported as 0.77 ± 0.45 (1σ). This weighted sum and standard deviation can be used to determine the number of samples required for FSS based on the statistical tests chose by the design team. See the example in **Section 4.12.4.**

4.12.3 Required Number of Samples for a Single Radionuclide

See **Sections 5.3.3 and 5.3.4** for detailed discussions on determining the required number of data points for the WRS and Sign tests.

4.12.3.1 WRS Test

In this example the following data[8] were collected for the survey unit and reference area. Under consideration are a single radionuclide that is present in the background and a single survey unit. This process would be repeated for each survey unit and reference area combination. Because the actual activity units are irrelevant to the example, they will be omitted.

Data from a post-remediation survey are shown in **Table 4.3** below:

Table 4.3: Sample Data from a Post-Remediation Survey

	Reference Area	Survey Unit	Difference
Mean =	38.8	189.8	151.1
Median =	38.0	188.0	150.0
σ =	6.6	8.1	NA

The DCGL of concern is 160. The design team settled on alpha of 0.05 and beta of 0.10.

To determine the appropriate number of measurements, the relative shift must be calculated using **Equation (**4-17)**:**

$$\text{Relative Shift} = \frac{DCGL - LBGR}{\sigma} \tag{4-17}$$

The LBGR is often set at the expected median concentration of the radionuclide. However, in our example the mean is higher than the median. Because it is conservative to set the LBGR at

[8] This example is based on data presented in NRC (1998a).

the higher value[9] (i.e., the expected mean) and to choose the larger value for σ for the reference area or survey unit, that is what the design team does using **Equation (**4-17)**:**

$$\text{Relative Shift} = \frac{160 - 151.1}{8.1} = 1.1$$

Referring to **Table 5.2,** we see that the recommended number of measurements (N/2) is 22 (given an alpha of 0.05 and beta of 0.10).[10] This is the number of samples that must be collected in both the reference area and survey unit, for a total of 44 measurements. Also, this number accounts for missing or unusable data. The simplest approach is to assign half of those points to the survey unit and half to the reference area.

4.12.3.2 Sign Test

In this example, the following data were collected for the survey unit and reference area. Under consideration are a single radionuclide that is not present in the background or present an insignificant fraction of the $DCGL_W$ and a single survey unit. The activity levels are compared directly to the DCGL. This process would be repeated for each survey unit. Because the actual activity units are irrelevant to the example, they will be omitted.

Data from a post-remediation survey are shown in **Table 4.4** below:

Table 4.4: Sample Data from a Post-Remediation Survey

	Survey Unit
Mean =	10.9
Median =	11.5
σ =	3.3

The DCGL of concern is 16. The design team settled on alpha of 0.05 and beta of 0.05.

To determine the appropriate number of measurements, the relative shift must be calculated using **Equation (**4-17)**:**

$$\text{Relative Shift} = \frac{\text{DCGL} - \text{LBGR}}{\sigma}$$

The LBGR is often set at the expected median concentration of the radionuclide. Because it is conservative to set the LBGR at the higher of the mean or median, the median is used (see **Equation (**4-17)):

$$\text{Relative Shift} = \frac{16 - 11.5}{3.3} = 1.4$$

Referring to **Table 5.2,** we see that the required number of measurements (N) is 20 (given the alpha of 0.05 and beta of 0.05). This number accounts for missing or unusable data.

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[9] Larger vales for the LBGR and σ lead to a smaller relative shift that, in turn, leads to a larger number of required measurements.
[10] Using the median value results in a relative shift of 1.2 and an N/2 value of 19.

4.12.4 Required Number of Samples for the Multiple Radionuclides

See **Sections 5.3.3–5.3.4** for detailed discussions on determining the required number of data points for the WRS and Sign tests.

4.12.4.1 Applying the Unity Rule

A design team is tasked with classifying a survey unit according to the potential for contamination and determining the appropriate number of soil samples to take during the FSS. The contaminants are cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs). The $DCGL_W$ values are—

- $DCGL_{W,Co\text{-}60}$: 130 Bq/kg (3.5 pCi/g)
- $DCGL_{W,Cs\text{-}137}$: 410 Bq/kg (11 pCi/g)

During the DQO process and with approval of the regulator, the acceptable probability of a Type I error[11] (α) is set to 0.05, and the acceptable probability of a Type II error[12] (β) set to 0.10.

Because compliance must be demonstrated for more than one radionuclide, and each radionuclide will be measured separately, the unity rule will be used, wherein the concentration of each contaminant is normalized to (divided by) its $DCGL_W$. When this is done, the collective "concentration" of the multiple radionuclides is expressed as the weighted sum of ratios (T) or sum of the ratios (SOR). See **Section 4.5.3.5** for details on the SOR.

The following data, obtained earlier during the characterization survey, are assumed to be representative of the existing conditions in the survey unit. The data from the characterization survey are shown in **Table 4.5**.

<u>Sign test</u>

Although ^{137}Cs is in the background, it is present at such a low concentration[13] relative to the DCGL that the planning team decides to "swallow" background and use the Sign test.[14]

<u>Classification and General Observations</u>

Both the mean (0.78) and median[15] (0.66) of the SOR are less than 1. This indicates that the survey unit might comply with the release criteria without further remediation. That the mean and median differ indicates that the measurements might not be normally distributed. This supports our decision to analyze the FSS data with a nonparametric test (Sign test).

That the value of the SORs for several samples (1, 4, 5, and 9) exceed 1 indicates that this should be considered a Class 1 survey unit. Recall from the discussion of a Class 1 area that

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[11] This is the probability that the statistical test will indicate that the survey unit meets the release criteria when, in fact, it does not.
[12] This is the probability that the statistical test will indicate that the survey unit does not meet the release criteria when, in fact, it does.
[13] Cesium-137 appears in background soil at a concentration of about 37 Bq/kg (1 pCi/g).
[14] The Sign test is a statistical test to demonstrate compliance with the release criteria when the radionuclide of concern is not present in background.
[15] The median is the middle value of the data set when the number of data points is odd, and it is the average of the two middle values when the number of data points is even. Thus, 50 percent of the data points are above the median, and 50 percent are below the median.

Table 4.5: Sample Results for Unity Rule Example

Sample	Concentration (Bq/kg)		Normalized Concentration		T[a]
	$C_{Co\text{-}60}$	$C_{Cs\text{-}137}$	$(C/DCGL)_{Co\text{-}60}$	$(C/DCGL)_{Cs\text{-}137}$	
1	104	308	0.80	0.74	1.54
2	33	78	0.25	0.19	0.45
3	30	185	0.23	0.45	0.69
4	41	322	0.32	0.79	1.11
5	78	525	0.60	1.28	1.89
6	26	70	0.20	0.17	0.38
7	4	44	0.03	0.11	0.14
8	0	-11	0.00	-0.03	-0.03
9	59	229	0.45	0.56	1.02
10	37	137	0.28	0.33	0.62
Mean	41	188	0.32	0.46	0.78
Median	35	161	0.27	0.39	0.66
Sample	**Sigma (Bq/kg)**		**Normalized Sigma**		**T[a]**
	$C_{Co\text{-}60}$	$C_{Cs\text{-}137}$	$(\sigma/DCGL)_{Co\text{-}60}$	$(\sigma/DCGL)_{Cs\text{-}137}$	
N/A	32	162	0.25	0.39	N/A

Abbreviations: Bq = becquerel; kg = kilogram; DCGL = defined concentration guideline level; T = weighted sum of ratios (see **Equation 4-12**).
[a] To be conservative, all the ratios in the table have been rounded up.

"areas containing residual radioactive material in excess of the $DCGL_W$ prior to remediation should be classified as Class 1 areas." (See **Section 4.6.1.**) In this example, the survey unit has several individual locations where SOR exceeds 1, which is the unity rule DCGL. However, this does not mean that the survey unit fails to meet the release criteria.

<u>Determining the Appropriate Number of Systematic Samples</u>

To determine the appropriate number of soil samples, we must calculate the relative shift using **Equation (**4-17**):**

$$\text{Relative Shift} = \frac{\text{DCGL} - \text{LBGR}}{\sigma}$$

Because we have two radionuclides (^{60}Co and ^{137}Cs), the unity rule is used, wherein the concentration of each radionuclide is divided by its DCGL. When this is done, the DCGL for the combined radionuclides effectively becomes 1, as shown in **Equation (**4-18)**:**

$$\text{Relative Shift} = \frac{1 - \text{LBGR}}{\sigma} \qquad (4\text{-}18)$$

The LBGR is often set at the expected median concentration of the contaminant. However, in our example the mean is higher than the median. Because it is conservative to set the LBGR at the higher value (i.e., the expected mean), that is what we will do.

Given the fact that we have multiple contaminants, we divide the expected mean concentration of each radionuclide by its DCGL and use T or the SOR as our LBGR **(Equation (**4-12)**):**

$$\text{LBGR} = \left(\frac{\text{Expected Mean Concentration}}{\text{DCGL}}\right)_{\text{Co-60}} + \left(\frac{\text{Expected Mean Concentration}}{\text{DCGL}}\right)_{\text{Cs-137}}$$
$$= \frac{41\text{ Bq/kg}}{130\text{ Bq/kg}} + \frac{188\text{ Bq/kg}}{410\text{ Bq/kg}}$$
$$= 0.32 + 0.46$$
$$= 0.78$$

Using **Equation (**4-18)**,** the relative shift calculation then becomes

$$\text{Relative Shift} = \frac{1 - 0.78}{\sigma}$$

Using **Equation (**4-13)**,** The combined sigma (σ) for ^{60}Co and ^{137}Cs using data from **Table 4.5** on previous page is

$$\sigma = \sqrt{\left(\frac{\sigma}{\text{DCGL}}\right)^2_{\text{Co-60}} + \left(\frac{\sigma}{\text{DCGL}}\right)^2_{\text{Cs-137}}}$$
$$= \sqrt{(0.25)^2 + (0.39)^2}$$
$$= 0.47$$

The relative shift is then determined as follows, using **Equation (**4-18)**:**

$$\text{Relative Shift} = \frac{1 - 0.78}{0.47} = 0.47$$

Note that the relative shift and sigma have the same value (0.47), which is a coincidence.

Referring to **Table 5.3,** we see that the recommended number of samples is somewhere between 71 and 107 (given the alpha of 0.05 and beta of 0.10). When the relative shift falls between the values on two lines on **Table 5.3,** the number of samples can be conservatively estimated by using the number of samples corresponding to the smaller value of the relative shift. For this example, the number of required samples would be 107.

4.12.5 Instrument Efficiencies

The instrument efficiency (ε_i) is defined as the ratio of the net count rate of the instrument to the surface emission rate of a source for a specified geometry. The surface emission rate is defined as the number of particles of a given type above a given energy emerging from the front face of the source per unit time. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that effect the radiation emitted from the source. Thus, the instrument efficiency is determined by the ratio of the net count rate and the surface emission rate.

The source efficiency (ε_s) is defined as the ratio of the number of particles of a given type emerging from the front face of a source to the number of particles of the same type created or released within the source per unit time. The source efficiency takes into account the increased particle emission due to backscatter effects, as well as the decreased particle emission due to self-absorption losses. For an ideal source (i.e., no backscatter or self-absorption), the value of the source efficiency is 0.5. Many real sources will exhibit values less than 0.5, although values greater than 0.5 are possible, depending on the relative importance of the absorption and backscatter processes.

For surface activity measurements, the product of the instrument and surface efficiencies is the total efficiency of the instrument (ε_t). The total efficiency is the net count rate of the instrument divided by the total (4π) emission rate in a specified geometry. It is usually the efficiency of ultimate interest when planning FSSs.

4.12.5.1 Multiple Radionuclides

Whatever approach is used to assess multiple radionuclides, the FSS design team needs to account for different instrument responses to the radionuclides of concern. It is important to use an appropriately weighted total efficiency to convert from instrument counts to activity units. This most frequently arises when measuring surface activity. When multiple radionuclides are being measured with the same instrument, a weighted efficiency must be used. Starting with the unity rule in its most general form (**Equation (**4-1)), the total number of counts is simply sum of the counts from each radionuclide j present:

$$\text{Total Number of Counts} = A_{\text{Total}}\varepsilon_t = \sum_{j=1}^{n} A_j \varepsilon_{s,j} \varepsilon_{i,j} \qquad (4\text{-}19)$$

where

- A_{Total} is the total activity of the n radionuclides.
- A_j is the activity of the jth radionuclide.
- $\varepsilon_{s,j}$ is the source efficiency of the jth radionuclide.
- $\varepsilon_{i,j}$ is the instrument efficiency of the jth radionuclide.

If the fraction f_j of each radionuclide in the mix is known, then, as shown in **Equation (**4-20)**,**

$$A_{\text{Total}}\varepsilon_t = \sum_{j=1}^{n} (A_{\text{Total}} f_j) \varepsilon_{s,j} \varepsilon_{i,j} \qquad (4\text{-}20)$$

Dividing both sides by A_{Total} yields the total efficiency for the mixture, as shown in **Equation (**4-21)**:**

$$\varepsilon_t = \sum_{j=1}^{n} f_j \varepsilon_{s,j} \varepsilon_{i,j} \qquad (4\text{-}21)$$

The example below illustrates the calculation of a weighted total efficiency for two radionuclides with different instrument efficiencies.

Consider a site contaminated with cesium-137 (^{137}Cs) and strontium/yttrium-90 (^{90}Sr/Y), with ^{137}Cs representing 60 percent of the total activity. Therefore, the relative fractions are 0.6 for ^{137}Cs and 0.4 for ^{90}Sr/Y. The source efficiency for both ^{137}Cs and ^{90}Sr/Y is 0.5. The corresponding instrument efficiencies for ^{137}Cs and ^{90}Sr/Y are determined to be 0.38 and 0.45, respectively.

The total efficiency can be calculated using **Equation (**4-21)**:**

$$\begin{aligned}\varepsilon_t &= f_{\text{Cs}}\varepsilon_{s,\text{Cs}}\varepsilon_{i,\text{Cs}} + f_{\text{Sr/Y}}\varepsilon_{s,\text{Sr/Y}}\varepsilon_{i,\text{Sr/Y}} \\ &= (0.6)(0.5)(0.38) + (0.4)(0.5)(0.45) \\ &= 0.20\end{aligned}$$

Alternatively, the total efficiencies for each radionuclide can be calculated by multiplying the surface efficiency by the instrument efficiency, as shown in the equations below, modified from **Equation (**4-21)**:**

$$\varepsilon_{t,\text{Cs}} = \varepsilon_{s,\text{Cs}} \times \varepsilon_{i,\text{Cs}} = (0.5)(0.38) = 0.19$$
$$\varepsilon_{t,\text{Sr/Y}} = \varepsilon_{s,\text{Sr/Y}} \times \varepsilon_{i,\text{Sr/Y}} = (0.5)(0.45) = 0.22$$

The weighted total efficiency can then be calculated as follows using equations modified from **Equation (**4-21)**:**

$$\begin{aligned}\varepsilon_t &= f_{\text{Cs}}\varepsilon_{t,\text{Cs}} + f_{\text{Sr/Y}}\varepsilon_{t,\text{Sr/Y}} \\ &= (0.6)(0.19) + (0.4)(0.22) \\ &= 0.20\end{aligned}$$

The weighted total efficiency is 0.20, or 20 percent.

When calculating the weighted total efficiency, one must account for the assumptions underlying the corresponding DCGL, particularly the relative ratios of the radionuclides present. In this case, the relative ratio of ^{137}Cs and ^{90}Sr/Y is needed to calculate the weighted total efficiency. This can be important when dealing with the naturally occurring radionuclide chains (e.g., ^{226}Ra and progeny). The state of secular equilibrium (disequilibrium) would need to be accounted for in determining the weighted total efficiency. An example of calculating the total weighted efficiency for a mixture of radionuclides is shown in **Section 4.12.6.**

This weighted efficiency discussion addresses considerations for fractional activity. However, more complex situations may be encountered, which must consider things such as radiation emission intensities and branching ratios of decay chains. MARSAME and NUREG-1507 provide some additional examples of these more complex situations.

4.12.6 Data Conversion

This example illustrates the data conversion process along with another weighed total efficiency calculation. Additional details are provided in **Section 6.7.**

A radionuclide laboratory is being decommissioned. Options are being considered for the FSS of surfaces in the laboratory. The following radionuclide information is given in **Table 4.6:**

Table 4.6: Sample Radionuclide Information

Radionuclide	$DCGL_W$		Relative Fraction
	Bq m^{-2}	dpm $(100\ cm^2)^{-1}$	
^{14}C	5.77×10^6	3.46×10^6	0.12
^{63}Ni	2.72×10^6	1.63×10^6	0.18
^{99}Tc	1.95×10^6	1.17×10^6	0.40
^{204}Tl	1.33×10^4	8.00×10^3	0.02
$^{90}Sr/Y$	1.30×10^4	7.78×10^3	0.13
$^{106}Ru/Rh$	3.98×10^4	2.39×10^4	0.15

Abbreviations: $DCGL_W$ = derived concentration guideline level determined for a wide area; Bq = Becquerels; m = meters; dpm = decays per minute; cm = centimeters.

Because the relative ratios are well known, were determined through the DQO process, and were approved by the regulatory agency, gross beta activity measurements will be used to determine compliance with the release criterion for this survey. The gross activity $DCGL_W$ can be determined from **Equation (**4-10)**.**

$$DCGL_{gross} = \frac{1}{\left(\frac{0.18}{2.72\text{x}10^6} + \frac{0.12}{5.77\text{x}10^6} + \frac{0.40}{1.95\text{x}10^6} + \frac{0.02}{1.33\text{x}10^4} + \frac{0.13}{1.30\text{x}10^4} + \frac{0.15}{3.98\text{x}10^4}\right)}$$

$= 6.42 \text{ x}10^4$ Bq m^{-2} ($3.85 \text{ x}10^4$ dpm $(100\ cm^2)^{-1}$).

It has been decided to use a gas-flow proportional counter with a physical probe area of 126 cm^2 (0.0126 m^2) in β particle–only mode for the survey. The design team has determined the following total efficiencies for the detector (**Table 4.7**):

Table 4.7: Sample Efficiencies for a Detector

Radionuclide	Source Efficiency	Instrument Efficiency	Total Efficiency	Relative Fraction	Weighted Efficiency
^{14}C	0.25	0.16	0.04	0.12	0.0048
^{63}Ni	0.25	0.00	0.00	0.18	0.000
^{99}Tc	0.25	0.64	0.16	0.40	0.064
^{204}Tl	0.50	0.58	0.29	0.02	0.0058
$^{90}Sr/Y$	0.50	0.72	0.36	0.13	0.047
$^{106}Ru/Rh$	0.50	1.10	0.55	0.15	0.082
			Total =	**1.00**	**0.20**

In general, the output of the counter is a gross counting rate or integrated counts in a set counting interval. The relationship between the counter's output and surface activity (A_s) concentration is given by **Equation 6-19:**

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times W}$$

where C_s is the integrated net counts recorded by the instrument; t_s is the time period over which the counts were recorded; ε_t is the total efficiency of the instrument in counts per disintegration, effectively the product of the instrument efficiency (ε_i) and the source efficiency

(ε_s); and W is the physical probe area. To account for background, **Equation (**4-22) (a slightly modified form of **Equation 6-20**) is used:

$$A_s = \frac{C_{s+b}/t_s - C_b/t_b}{\varepsilon_t \times W} = \frac{C_s/t_s}{\varepsilon_t \times W} = \frac{R_{net}}{\varepsilon_t \times W} \qquad (4\text{-}22)$$

where C_b is the background counts[16] recorded by the instrument, t_b is the time period over which the background counts were recorded,[17] and R_{net} is the net counting rate. The units for t_s, t_b, and W depend on the desired units for the FSS.

For this example, surface activity measurements are being made on drywall. Consider the following data for one measurement location:

- C_b = 1,626 counts
- t_b = 5 minutes
- C_s = 1,210 counts
- t_s = 1 minute

The net counting rate is calculated using **Equation (**4-23)**:**

$$R_{net} = C_{s+b}/t_s - C_b/t_b \qquad (4\text{-}23)$$

$$= \frac{1{,}210 \text{ counts}}{1 \text{ minute}} - \frac{1{,}626 \text{ counts}}{5 \text{ minutes}}$$

$$= (1{,}210 - 325.2) \text{ cpm}$$

$$= 884.8 \text{ cpm}$$

The net counting rate can be converted to the surface activity concentration, as shown below, using **Equation (**4-22)**:**

$$A_s = \frac{R_{net}}{\varepsilon_T \times W}$$

$$= \frac{884.8 \text{ cpm}}{0.20 \text{ (c/d)} \times 0.0126 \text{ m}^2}$$

$$= 3.51 \times 10^5 \text{ dpm/m}^2$$

[16] Background measurements should be made on uncontaminated material similar in composition to the material at the measurement location.
[17] The sample and background counting intervals can be different, depending on the desired MDC. See **Section 6.3** and the professional literature for more discussion.

In general, either SI (Bq/m^2) or conventional (dpm/100 cm^2) units are desired. For SI units, the conversion is straightforward, because 60 dpm is equivalent to 1 Bq (see **Equation (**4-22)):

$$A_s = \left(3.51\times 10^5 \ {}^{dpm}/_{m^2}\right)\times\left(\frac{1\ \text{Bq}}{60\ \text{dpm}}\right)$$

$$= 5.83\times10^3\ \text{Bq/m}^2$$

The conversion to conventional units is shown below, using **Equation (**4-22)**:**

$$A_s = \left(3.51\times 10^5 \ {}^{dpm}/_{m^2}\right)\times\left(\frac{0.01\ \text{m}^2}{100\ \text{cm}^2}\right)$$

$$= 3.51\times10^3\ \text{dpm/100 cm}^2$$

The FSS design team should determine the desired units during the planning phase. After the desired units are chosen, the design team can create spreadsheets or other methods of analyzing the raw counting data to streamline the process. Similarly, any action or investigation levels chosen by the design team should be converted into the proper units. This process needs to be performed for each field measurement instrument and technique.

For example, if it is determined that units of dpm/100 cm^2 will be used, then the physical probe area should be measured in cm^2, and the following equation (**Equation (**4-24)) can be used for each instrument used:

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t\times\left({}^{W}/_{100}\right)} = \frac{R_{net}}{\varepsilon_t\times\left({}^{W}/_{100}\right)} \qquad (4\text{-}24)$$

where t_s and t_b are recorded in minutes (R_{net} is expressed in cpm), and W is recorded in square centimeters instead of square meters.

For this example, the equation is shown below (see **Equation (**4-22)):

$$A_s = \frac{884.8\ \text{cpm}}{0.20\ (\text{c/d})\times\left({}^{126}/_{100}\right)}$$

$$= 3.51\times10^3\ \text{dpm/100 cm}^2$$

The result is the same as in the earlier example, as expected.

Additionally, action and investigation levels and the DCGL can be converted to detector outputs to facilitate timely actions (i.e., expressing action levels in terms of net counting rate might allow the field survey team to alert supervisors about measurements exceeding action levels in near-real time). In this case, the net counting rate corresponding to an action level can be expressed by the following equation (**Equation (**4-25)):

$$R_{net}^{AL} = \varepsilon_t \times W \times A_s^{AL} \qquad (4\text{-}25)$$

Suppose the design team set an action level at 10 percent of the $DCGL_{gross}$. The net counting rate corresponding to this value is found as shown below, keeping in mind that 1 Bq is equivalent to 1 disintegration per second (dps), using (**Equation (**4-25)):

$$R_{net}^{AL} = 0.20 \times 0.0126 \text{ m}^2 \times \left(6.42 \times 10^3 \text{ Bq/m}^2\right) = 16.2 \text{ cps} = 971 \text{ cpm}$$

Thus, any net count exceeding about 970 counts per minute (cpm) would be flagged for investigation. If background rates are relatively constant, an action level can be expressed as a gross counting rate, as well.

4.12.7 Example of a Deviation from a Recommended Statistical Test

Consider the case of a survey unit that contains many different surfaces with potentially different backgrounds (e.g., drywall panels, concrete floor, glass windows, metal doors, wood trim, and plastic fixtures) and gross activity measurements are being considered. In this case, MARSSIM recommends the use of the WRS test when gross activity measurements are used; however, the use of the WRS test might require several survey and associated reference units, resulting in an inordinately large number of measurements. Furthermore, “it is not appropriate to make each material a separate survey unit because the dose modeling is based on the dose from the room as a whole and because a large number of survey units in a room would require an inappropriate number of samples” (NRC 2006). In this situation, the design team should use the DQO process and determine the best approach.

Instead of attempting to use the WRS test and multiple reference units, the design team might investigate the materials to determine if material-specific backgrounds are needed or whether materials with similar background could be grouped and considered as a unit. If this is done, it might be “acceptable to perform a one-sample test (Sign test) on the difference between the paired measurements from the survey unit and from the appropriate reference material” (NRC 2006). Chapter 2 of NUREG–1505 (NRC 1998a) contains details on this method.

In addition to the alternative statistical approach discussed above, the NRC (2006) discusses two additional approaches to resolve this issue. First, if the materials in the survey unit have substantially different backgrounds, then a reference unit containing a similar mix of material might be used, and the WRS test can then be applied. Second, if the materials in the survey unit have similar backgrounds, or if one material predominates, then a reference background from a single material might suffice. See NRC (2006) for more details.

The design team should use the DQO process to investigate any deviations from usual methods and get approval from the regulatory agency before executing the FSS.

4.12.8 Release Criteria for Discrete Radioactive Particles

With the installation in the mid- and late-1980s of very sensitive portal monitors, many nuclear power plants detected residual radioactive material on individuals and their clothing, present as small—usually microscopic—highly radioactive particles having relatively high specific activity. These particles became known as “discrete radioactive particles” and sometimes “hot particles.” Discrete radioactive particles are small (usually on the order of millimeters or micrometers), distinct, highly radioactive particles capable of delivering extremely high doses to a localized area in a short period of time.

To prove compliance with requirements for discrete radioactive particles, some surveys have used the MARSSIM EMC process (see **Section 8.6.1**); however, that process is not valid when instrumentation dose-to-rate conversion factor modeling assumes a “point source” as opposed to an “area source” or “plane source.” This violates the assumption inherent in the dose or risk model of an activity concentration averaged over some definable area. Therefore, it is not acceptable to use the MARSSIM EMC process when the distance to the detector is greater than three times the longest dimension of the area of elevated activity, as represented by **Equation (**4-26)**:**

$$d > 3L \tag{4-26}$$

where L is the estimated longest dimension of the area of elevated activity, and d is the distance to the detector.

To address discrete radioactive particles in surface soils or building surfaces—

- Include discrete radioactive particles as a consideration during the DQO process for MARSSIM surveys.
- When a regulatory agency sets requirements on the concentration of discrete radioactive particles in a survey unit, use the DQO process to develop a survey to assess whether requirements are met.
- When appropriate, apply ALARA by addressing discrete radioactive particles during the RAS survey.
- If discrete radioactive particles do not contribute significantly to dose or risk at a site, it is a reasonable assumption that they will not affect the outcome of a wide-area FSS. If an FSS fails due to discrete radioactive particles, investigate the reasons for survey failure (see **Section 8.6.3**).

4.12.9 Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) Sites

At UMTRCA sites, the U.S. Environmental Protection Agency’s Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (in 40 CFR 192) are applicable. However, the technical requirements in these standards are not always consistent with some of the recommendations in MARSSIM. Specifically, the soil cleanup standards for ^{226}Ra and ^{228}Ra are specified as averages over an area of 100 m^2. (In the 40 CFR 192 rulemaking, an averaging area of 100 m^2 was used as a reasonable footprint for a home. One goal of the 40 CFR 192 standards was to protect future homes from indoor radon, and the specified averaging area was a component implemented for the protection of health.) The rules at 40 CFR 192 do not establish specific requirements for small areas of elevated radioactive material. At sites where the uranium or thorium mill tailings standards are applicable, the following approach for FSSs is acceptable:

- A survey unit of no greater than 100 m^2 sections of land should be used, consistent with the regulatory standards.
- The systematic sampling for performance of statistical tests, normally required under the MARSSIM approach, is not required for each survey unit. Instead, compliance with the standard can be demonstrated through the analysis of soil samples or composite soil samples from each survey unit in conjunction with gamma radiation scanning or in situ

gamma radiation measurements of each survey unit. When appropriate, gamma radiation scanning or in situ measurements correlated to soil sampling may be used in place of soil sampling.

- Survey units may be classified, as appropriate, and the percentage of the survey unit that is scanned may be adjusted accordingly for Class 1, Class 2, or Class 3 survey units.
- EMC criteria for small elevated areas of activity may be developed but are not required for the purposes of MARSSIM.

These minor modifications to the standard MARSSIM radiological survey approach are acceptable for those sites to which the UMTRCA standards are applicable.

5 SURVEY PLANNING AND DESIGN

5.1 Introduction

This chapter is intended to assist the user in planning radiological surveys with a particular emphasis on conducting a final status survey (FSS), with the ultimate objective being to demonstrate compliance with the derived concentration guideline levels (DCGLs).[1] The survey types that make up the Radiation Survey and Site Investigation (RSSI) process include scoping, characterization, remedial action support (RAS), and FSSs; depending on the regulatory framework, the process may also include confirmatory or independent verification surveys. Although the scoping, characterization, and RAS surveys have multiple objectives, this manual focuses on those aspects related to supporting the FSS and demonstrating compliance with DCGLs. In general, each of these survey types expands upon the data collected during the previous survey (e.g., the characterization survey is planned with information collected during the scoping survey) up through the FSS. The conduct and extent of scoping and characterization surveys will depend on the available information from the Historical Site Assessment (HSA) and site-specific conditions. The purpose of the FSS is to demonstrate that the release criteria established by the regulatory agency have not been exceeded. This final release objective should be kept in mind throughout the design and planning phases for each of the other survey types. For example, scoping surveys may be designed to meet the objectives of the FSS such that the scoping survey report is also the FSS report. The survey and analytical procedures referenced in this chapter are described in **Chapters 6–7** and **Appendix H.** An example of an FSS, as described in **Section 5.3,** appears in **Appendix A.** In addition, example checklists are provided for each type of survey to assist the user in obtaining the necessary information for planning an FSS.

Scoping surveys—used to augment the HSA and provide input to future survey designs—and survey unit characterization and classification are described in **Section 5.2.1. Section 5.2.2** describes characterization surveys performed to determine the following: nature and extent of residual radioactive material; potential remediation alternatives and technologies; the inputs to pathway analysis and dose or risk assessment models; occupational and public health and safety impacts; and inputs to the FSS design. RAS surveys, performed to support remedial activities, update estimates of site-specific parameters used in FSS planning, and determine when a site or survey unit is ready for an FSS are described in **Section 5.2.3. Section 5.3** covers FSSs, which are performed to demonstrate that a site or survey unit meets the residual radioactive material release criteria.

A flowchart diagram illustrating the Survey Planning and Design Process, broken up by survey type, is provided in **Figures 5.1–5.3.**

[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

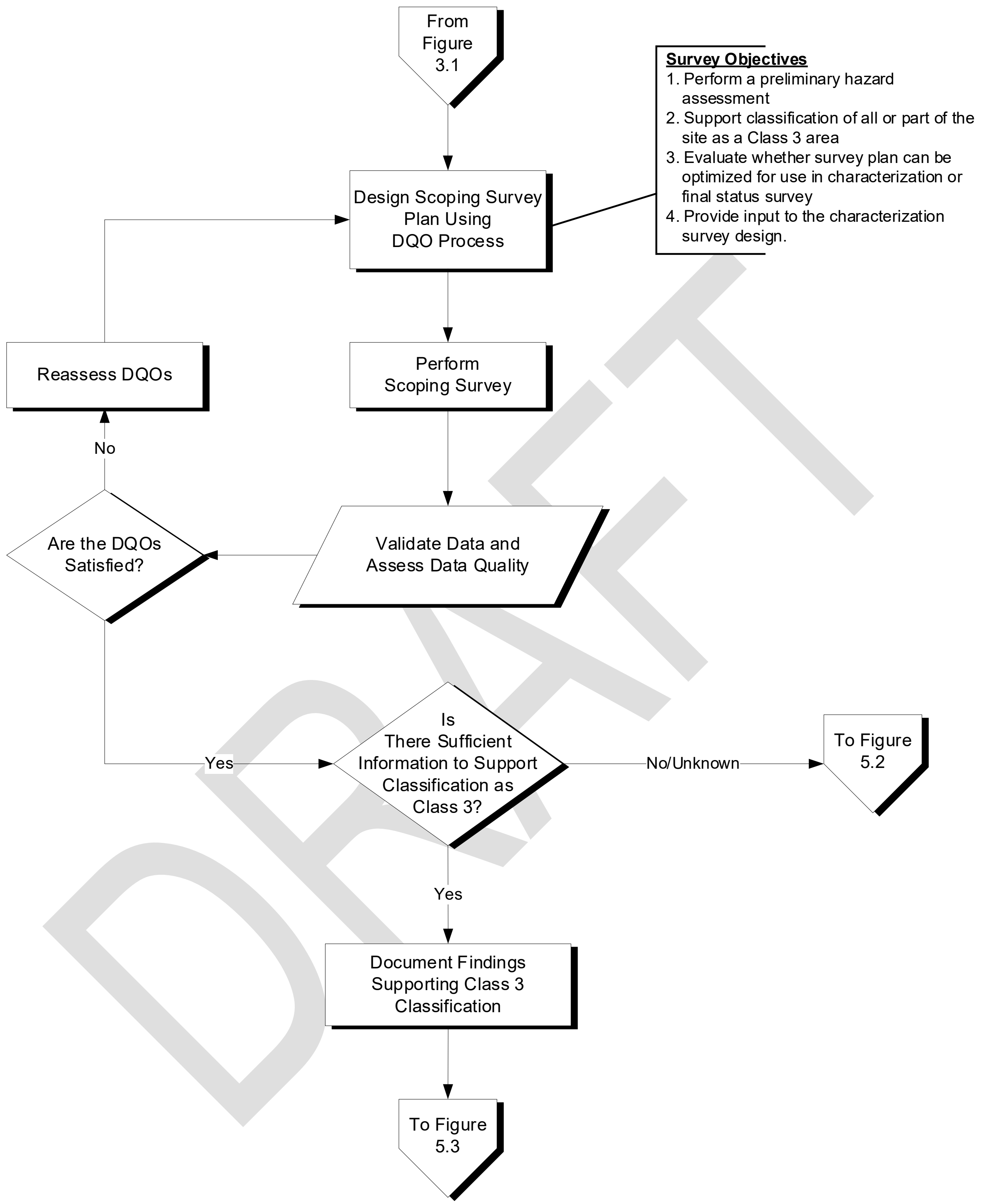
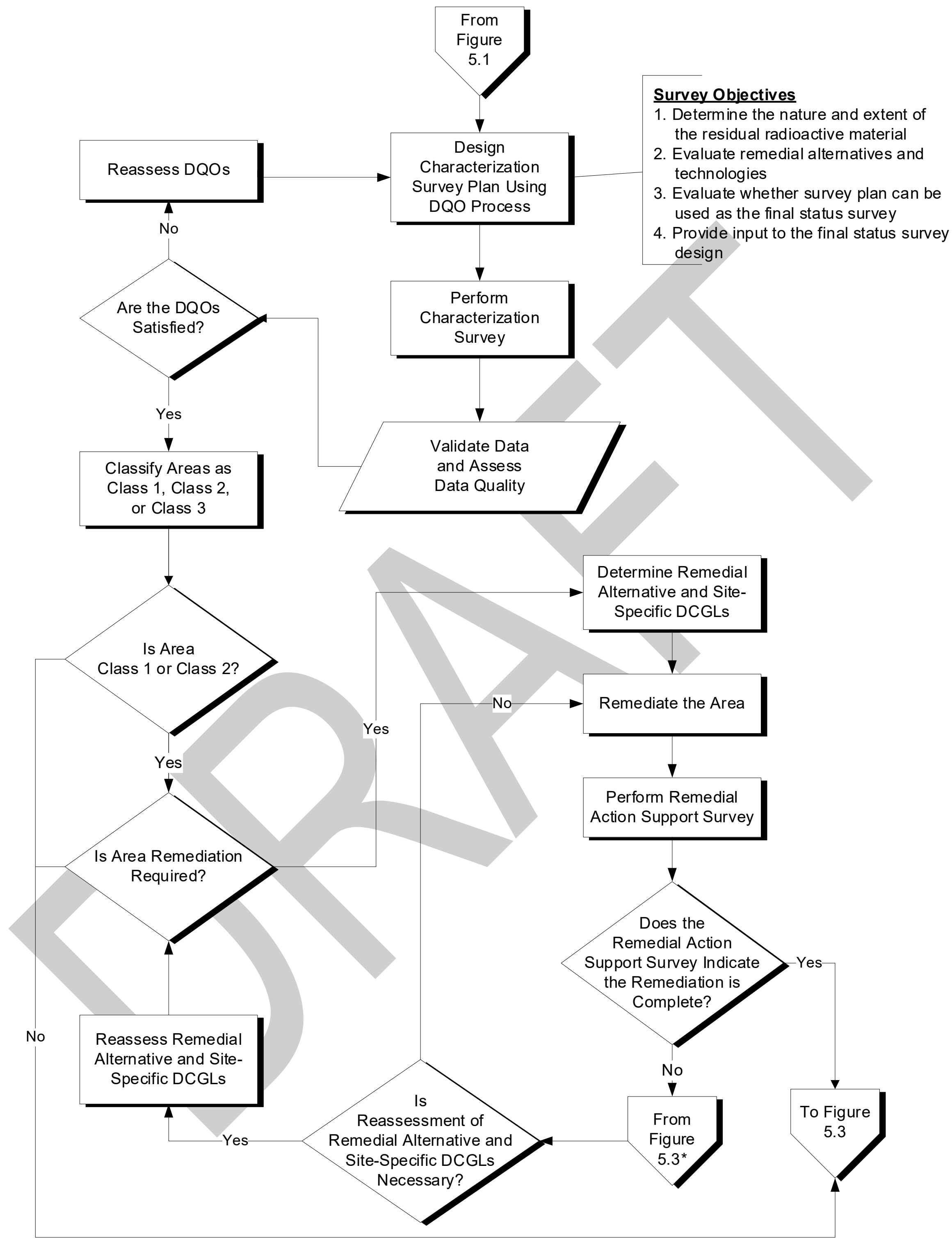
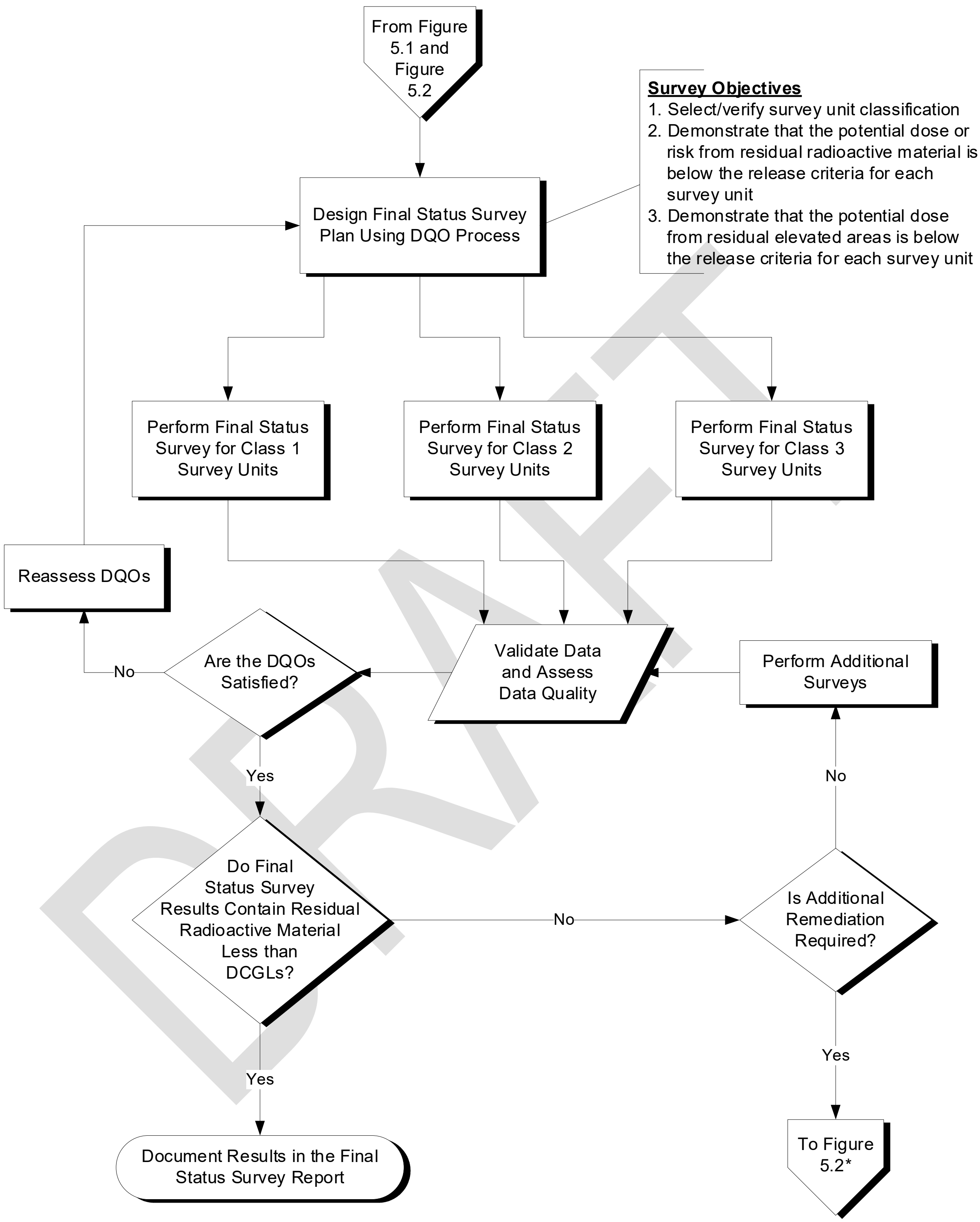


Figure 5.1: The Scoping Survey Portion of the Radiation Survey and Site Investigation Process



1 * The point where survey units that fail to demonstrate compliance in the final status survey in Figure 5.3 re-enter the process

2 **Figure 5.2: The Characterization and Remedial Action Support Survey Portions of the**
3 **Radiation Survey and Site Investigation Process**



* Connects with the Remedial Action Support Survey portion of the process in Figure 5.2

Figure 5.3: The Final Status Survey Portion of the Radiation Survey and Site Investigation Process

5.2 Preliminary Surveys

5.2.1 Scoping Surveys

If the data collected during the HSA indicate that a site or area is impacted, a scoping survey may be performed. The objective of this survey is to augment the HSA for sites with potential residual radioactive material. Specific objectives may include—

- performing a preliminary risk assessment and providing data to complete the site prioritization scoring process for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites only (EPA 1992c)
- providing input to the characterization survey design, if necessary
- supporting the classification of all or part of the site as a Class 3 area for planning the FSS
- obtaining an estimate of the variability in the residual radioactive material concentration for the site
- identifying non-impacted areas that may be appropriate for reference areas and estimating the variability in radionuclide concentrations when the radionuclide of interest is present in background

A scoping survey is not a requirement if HSA information meets the needs for designing subsequent surveys, including the FSS. Alternatively, scoping surveys and characterization surveys may be combined, if one survey can be designed to meet the requirements of both survey types. See **Section 5.2.2** for a description of characterization surveys.

Scoping survey information about the general radiation levels at the site, including gross levels of residual radioactive material on building surfaces and in environmental media, is needed when conducting a preliminary risk assessment (as noted above for CERCLA and RCRA sites). If unexpected conditions are identified that prevent the completion of the survey, the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) user should contact the regulatory agency for further guidance. Sites that meet the National Contingency Plan (NCP) criteria for a removal should be referred to the Superfund Removal program (EPA 1988b).

If the HSA indicates that residual radioactive material above release levels is likely, a scoping survey could be performed to provide initial estimates of the level of effort for remediation and information for planning a more detailed survey, such as a characterization survey. Not all radiological parameters need to be assessed when planning for additional characterization, because total surface activity or limited sample collection may be sufficient to meet the objectives of the scoping survey.

Once a review of pertinent site history indicates that an area is impacted, the minimum survey coverage at the site will include a Class 3 area FSS before the site's being released. For scoping surveys with this objective, identifying radiological decision levels is necessary for selecting instruments and procedures with the necessary instrument capabilities to demonstrate compliance with the release criteria. A methodology for planning, conducting, and documenting scoping surveys is described in the following sections.

5.2.1.1 Survey Design

Planning a scoping survey involves reviewing the HSA for a site (**Chapter 3**). This process considers available information concerning locations of spills or other releases of radioactive material. Reviewing the radioactive materials license or similar documentation provides information on the identity, locations, and general quantities of radioactive material used at the site. This information helps determine which areas are likely to contain residual radioactive material and, thus, areas where scoping survey activities will be concentrated. The information may also identify one or more non-impacted areas as potential reference areas when radionuclides of concern are present in background (**Section 4.5**). Following the review of the HSA, appropriate DCGLs for the site are selected. The DCGLs may be adjusted later if a determination is made to use site-specific information to support the development of DCGLs.

If residual radioactive material is identified during the scoping survey, the area may be classified as Class 1 or Class 2 for FSS planning (refer to **Section 4.6.1** for information on initial classification), and a characterization survey is subsequently performed. For scoping surveys that are designed to provide input for characterization surveys, measurements and sampling may not be as comprehensive or performed to the same level of sensitivity necessary for FSSs. The design of the scoping survey should be based on specific Data Quality Objectives (DQOs). See **Section 2.3.1** and **Appendix D** for the information to be collected.

For scoping surveys that potentially serve to release the site or portions of the site from further consideration, the scoping survey design for the Class 3 area should consist of sampling based on the HSA data, and professional judgment and must be consistent with the requirements for an FSS. If residual radioactive material is *not* identified, it may be appropriate to characterize the area as non-impacted. Refer to **Section 5.3** for a description of FSSs. However, collecting additional information during subsequent surveys (e.g., characterization surveys) may be necessary to make a final determination as to area classification.

5.2.1.2 Conducting Surveys

Scoping survey activities performed for preliminary risk assessment or to provide input for additional characterization include a limited amount of surface scanning, surface activity measurements, and sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials). In this case, scans, direct measurements, and samples are used to examine areas likely to contain residual radioactive material. These activities are conducted based on HSA data, preliminary investigation surveys, and professional judgment.

Background activity and radiation levels for the area should be determined, including direct radiation levels on building surfaces and radionuclide concentrations in media. Survey locations should be referenced to grid coordinates, if appropriate, or fixed site features. This may be accomplished by establishing a reference coordinate system in the event that residual radioactive material is detected above the DCGLs (**Section 4.8.5**). Samples collected as part of a scoping survey should be maintained under custody from collection through analysis and reporting to ensure the integrity of the results. Sample tracking may include use of a chain of custody, which is the unbroken trail of accountability that ensures the physical security of samples, data, and records (**Section 7.8**).

Scoping surveys that are expected to be used as Class 3 area FSSs should be designed following the procedure in **Section 5.3**. Scoping surveys should also include judgment measurements and sampling in areas likely to have accumulated residual radioactive material (**Section 5.3.9**). However, when performing a scoping survey as a Class 3 FSS, judgment samples should not be used as part of the statistical sampling population utilized to make a release decision on a site or survey unit.

5.2.1.3 Evaluating Survey Results

Survey data are converted to the same units as the DCGLs (**Section 6.6**). Identification of potential radionuclides of concern at the site is performed using direct measurements or laboratory analysis of samples. The data are compared to the appropriate regulatory DCGLs.

For scoping survey activities that provide an initial assessment of the radiological hazards at the site or input for additional characterization, the survey data are used to identify locations and the general extent of residual radioactive material. Scoping surveys that are expected to be used as Class 3 area FSSs should follow the methodology presented in **Chapter 8** to determine whether the release criteria have been exceeded.

5.2.1.4 Documentation

How the results of the scoping survey are documented depends on the specific objectives of the survey. For scoping surveys that provide additional information for characterization surveys, the documentation should provide general information on the radiological status of the site. Survey results should include identification of the potential radionuclides of concern (including the methods used for radionuclide identification), general extent of residual radioactive material (e.g., activity levels, area, and depth), and possibly even relative ratios of radionuclides to facilitate DCGL application. A narrative report or a report in the form of a letter may suffice for scoping survey data that is used to provide input for characterization surveys. Sites being released from further consideration should provide a level of documentation consistent with FSS reports (**Section 5.3.11**). **Example 1** includes an illustration of a scoping survey checklist, including survey design, conduct of the survey, and evaluation of survey results.

Example 1: Example Scoping Survey Checklist

Survey Design

_____ Enumerate Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs). State the objectives of the survey; survey instrumentation capabilities should be appropriate for the specified survey objectives. Document survey requirements in a project-specific Quality Assurance Project Plan (QAPP).

_____ Review the Historical Site Assessment (HSA) for the following:

- _____ Operational history (e.g., problems, spills, releases, or notices of violation) and available documentation (e.g., radioactive materials license)
- _____ Other available resources—site personnel, former workers, residents, etc.
- _____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, moved, relocated, and disposed
- _____ Release and migration pathways

- _____ Areas that are potentially affected and likely to contain residual radioactive material (Note: Survey activities will be concentrated in these areas.)
- _____ Types and quantities of materials likely to remain onsite—consider radioactive decay

_____ Select derived concentration guideline levels (DCGLs) for the site based on the HSA review. (It may be necessary to assume appropriate regulatory DCGLs in order to permit selection of survey methods and instrumentation for the expected radioactive material and quantities.)

Conducting Surveys

_____ Follow the survey design documented in the QAPP. Record deviations from the stated objectives or documented standard operating procedures, and document additional observations made when conducting the survey.

_____ Select instrumentation based on the specific DQOs and MQOs of the survey. Consider instrumentation capabilities for the expected residual radioactive material and quantities.

_____ Determine background activity and radiation levels for the area; include direct radiation levels on building surfaces, radionuclide concentrations in media, and exposure rates.

_____ Record measurement and sample locations referenced to grid coordinates or fixed site features.

_____ For scoping surveys that are conducted as Class 3 area final status surveys (FSSs), follow FSS procedure.

_____ Conduct scoping survey, which involves judgment measurements and sampling based on HSA results:

- _____ Perform investigatory surface scanning.
- _____ Conduct limited surface activity measurements.
- _____ Perform limited sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials).
- _____ Maintain sample tracking.

Evaluating Survey Results

_____ Compare survey results with the DQOs and MQOs.

_____ Identify radionuclides of concern.

_____ Identify impacted areas and the general extent of residual radioactive material.

_____ Estimate the variability in the residual radioactive material levels for the site.

______ Adjust DCGLs based on survey findings (the DCGLs initially selected may not be appropriate for the site).

______ Determine the need for additional action (e.g., none, remediate, more surveys)

______ Prepare report for regulatory agency (determine if letter report is sufficient).

5.2.2 Characterization Surveys

Characterization surveys may be performed to satisfy a number of specific objectives. Examples of characterization survey objectives include—

- determining the nature and extent of residual radioactive material
- evaluating remediation alternatives (e.g., unrestricted use, restricted use, onsite disposal, off-site disposal, etc.)
- input to pathway analysis/dose or risk assessment models for determining site-specific DCGLs (becquerel [Bq]/kilogram [kg], Bq/square meter [m^2])
- estimating the occupational and public health and safety impacts during decommissioning
- evaluating remediation technologies
- providing input to FSS design
- meeting Remedial Investigation/Feasibility Study (RI/FS) requirements (under a CERCLA program) or RCRA Facility Investigation/Corrective Measures Study (RFI/CMS) requirements (under an RCRA program).

A characterization survey is not a requirement if HSA and scoping survey information meets the needs for designing subsequent surveys, including FSSs. Alternatively, scoping surveys and characterization surveys may be combined if one survey can be designed to meet the requirements of both survey types. The scope of this manual precludes detailed discussions of characterization survey design for each of these objectives; therefore, the user should consult other references for specific characterization survey objectives not covered. For example, the *Decommissioning Handbook* (DOE 1994a) is a good reference for characterization objectives that are concerned with evaluating remediation technologies or unrestricted/restricted use alternatives. Other references (e.g., Abelquist 2014; EPA 1988b, 2006c; NRC 1994a) should be consulted for planning decommissioning actions, including remediation techniques, projected schedules, costs, waste volumes, and health and safety considerations during remedial action. Also, the types of characterization data needed to support risk or dose modeling should be determined from the specific modeling code documentation. This manual concentrates on providing information for the FSS design, with limited coverage on determining the specific nature and extent of residual radioactive material. The specific objectives for providing information to the FSS design include—

- estimating the projected radiological status at the time of the FSS, in terms of radionuclides present, concentration ranges and variances, spatial distribution, etc.

- evaluating potential reference areas to be used for background measurements, if necessary
- reevaluating the initial classification of survey units
- selecting instrumentation based on the necessary Measurement Quality Objectives (MQOs)
- establishing acceptable Type I and Type II errors with the regulatory agency (**Appendix D** provides information on establishing acceptable decision error rates.)

Many of these objectives are satisfied by determining the specific nature and extent of residual radioactive material in structures, residues, and environmental media. Additional detail on the performance of characterization surveys designed to determine the general extent of residual radioactive material can be found in the U.S. Nuclear Regulatory Commission's (NRC's) *Consolidated Decommissioning Guidance* (NUREG-1757) (NRC 2006), *Performance and Documentation of Radiological Surveys* (HPS/ANSI 13.49-2001) (HPS 2001), *Characterization in Support of Decommissioning Using the Data Quality Objectives Process* (HPS/ANSI N13.59) (HPS 2008), and the U.S. Environmental Protection Agency's (EPA's) RI/FS guidance (EPA 1988b; EPA 1993b).

Results of the characterization survey should include—

- the identification and distribution of residual radioactive material in buildings, structures, and other site facilities
- the concentration and distribution of radionuclides of concern in surface and subsurface soils
- the distribution and concentration of residual radioactive material in surface water, ground water, and sediments
- the distribution and concentration of radionuclides of concern in other impacted media, such as vegetation or paint

The characterization should include sufficient information on the physical characteristics of the site, including surface features, meteorology and climatology, surface water hydrology, geology, demography and land use, and hydrogeology. This survey should also address environmental conditions that could affect the rate and direction of radionuclide transport in the environment, depending on the extent of residual radioactive material identified above.

The following sections describe a method for planning, conducting, and documenting characterization surveys. Alternative methodologies may also be acceptable to the regulatory agencies.

5.2.2.1 Survey Design

The design of the site characterization survey is based on the specific DQOs for the information to be collected, and it is planned using the HSA and scoping survey results. The DQO process ensures that adequate data with sufficient quality are collected for the purpose of characterization. The site characterization process typically begins with a review of the HSA, which includes available information on site description, operational history, and the type and extent of residual radioactive material (from the scoping survey, if performed). The site description, or conceptual site model as first developed in **Section 3.6.4,** consists of the general area, dimensions, and locations of affected areas on the site. A site map should show site boundaries, roads, hydrogeological features, major structures, and other features that could affect decommissioning activities. When available, Global Positioning System (GPS) coordinates should be recorded for major features.

The operational history includes records of site conditions before operational activities, operational activities of the facility, effluents and on-site disposal, and significant incidents—including spills or other unusual occurrences—involving the spread of residual radioactive material around the site and on areas previously released from radiological controls. This review should include other available resources, such as site personnel, former workers, residents, etc. Historic aerial photographs and site location maps may be particularly useful in identifying potential areas of residual radioactive material.

The types and quantities of materials that were handled and the locations and disposition of radioactive materials should be reviewed using available documentation (e.g., the radioactive materials license). Release and migration pathways of radionuclides should be identified, as well as areas that are potentially affected and are likely to contain residual radioactive material. The types and quantities of materials likely to remain onsite, considering radioactive decay, should be determined.

The characterization survey should clearly identify those portions of the site (e.g., soil, structures, and water) that have been affected by site activities and potentially contain residual radioactive material. The survey should also identify the portions of the site that have not been affected by these activities. In some cases where no remediation is anticipated, results of the characterization survey may indicate compliance with DCGLs established by the regulatory agency. When planning for the potential use of characterization survey data as part of the FSS, the characterization data must be of sufficient quality and quantity for that use (see **Section 5.3**).

Several processes are likely to occur in conjunction with characterization. These include considering and evaluating remediation alternatives and calculating site-specific DCGLs.

The survey should also provide information on variability in the radionuclide distribution in the survey area. The radionuclide variability in each survey unit contributes to determining the number of data points based on the statistical tests used during the FSS (**Sections 5.3.3–5.3.4**) and the required scan coverage for Class 2 areas. Additionally, characterization data may be used to justify reclassification for some survey units (e.g., from Class 1 to Class 2).

In some cases, judgment sampling is the most appropriate for meeting the data needs. Judgment sampling includes measurements performed at locations selected using professional judgment based on unusual appearance, location relative to known contaminated areas, high potential for residual radioactive material, general supplemental information, etc. Examples of situations in which judgment sampling may be the most appropriate include those where residual radioactive material is isolated to locations that can be defined by individual measurements, or in which biased results will provide the data from the areas of highest suspected concentration of residual radioactive material. It should be understood, however, that use of a judgment characterization survey will produce data that is considered biased and which can generally only be used to draw conclusions about individual samples or specific locations rather than provide quantifiable estimates about a larger aggregate population. As a result, averages of judgment samples (i.e., biased) should not be used to determine the mean concentration of the residual radioactive material in the survey unit.

For those characterization survey objectives that require statistical evaluation of the data, the sampling plan should be designed to produce unbiased data. Unbiased sampling makes use of random sample selection, whereby each sample has an equal probability of being selected. Unbiased data can be used to provide a measure of the population characteristics, such as the average or mean radioactive material concentration and variance on that mean. One example of when unbiased sample data may be required is the use of a data set in assessing compliance with dose- or risk-based criteria. Most human health risk assessment protocols (e.g., EPA 1989d) require the computation of a mean and upper confidence limit (UCL) as the best measure of residual radioactive material in identifying excess lifetime cancer risk or radiation dose to a target population (EPA 2002b; 2006b).

The characterization survey may be used as an FSS for Class 3 areas under the following conditions:

- The characterization survey was planned as an FSS.
- Site or survey unit conditions warrant the use of the characterization survey as the FSS.
- Only randomly selected samples are utilized as part of the statistical evaluation of the site or survey unit. Any judgment samples collected may not be used as part of the statistical sample count or as part of the statistical evaluation of results.

It may be also appropriate to combine the principles of judgment and unbiased sampling strategies in designing a sample plan that provides the most representative data but also meets all of the DQOs.

Note that because of site-specific characteristics of residual radioactive material, performing all types of measurements described here may not be relevant at every site. For example, detailed characterization data may not be needed for areas with residual radioactive material well above the DCGLs that clearly require remediation. Judgment should be used in determining the types of characterization information needed to provide an appropriate basis for remediation decisions.

A number of software programs have been developed over the years to facilitate the design of surveys, an example of which is Visual Sample Plan, developed by the Pacific Northwest National Laboratory. These software programs can perform calculations to determine the number of locations where measurements should be made or where samples should be collected.

5.2.2.2 Conducting Surveys

Characterization survey activities often involve the detailed assessment of various types of building and environmental media, including building surfaces, surface and subsurface soil, surface water, and ground water. The HSA data should be used to identify the media onsite with a potential for residual radioactive material (see **Section 3.6.3**). Identifying the media that may contain residual radioactive material is useful for preliminary survey unit classification and for planning subsequent survey activities. Selection of survey instrumentation and analytical techniques are typically based on knowledge of the appropriate DCGLs, because remediation decisions are made based on the level of the residual radioactive material as compared to the

DCGL. Exposure rate measurements may be needed to assess occupational and public health and safety.

Structure Surveys

Surveys of building surfaces and structures can include surface scanning, surface activity measurements, exposure rate measurements, and sample collection (e.g., smears, subfloor soil, water, paint, and building materials). Both field survey instrumentation (**Chapter 6**) and analytical laboratory equipment and procedures (**Chapter 7**) are selected based on their instrumentation capabilities for the expected residual radioactive material and their quantities. Field and laboratory instruments are described in **Appendix H**.

Background activity and radiation levels for the area should be determined from appropriate background reference areas. Background assessments include surface activity measurements on building surfaces, exposure rates, and radionuclide concentrations in various media (refer to **Section 4.5**). Building reference area measurements should be collected in non-impacted areas within the same building, or in another similar building, provided that the reference area has been constructed with materials of the same type and age. This ensures that the reference area has the same inherent radioactive material and decay time, and therefore background radioactivity, as the impacted area.

Measurement locations should be documented using reference system coordinates, if appropriate, or fixed site features. A typical reference system spacing for building surfaces is 1 m. This is chosen to facilitate identifying survey locations and small areas of elevated activity.

Scans should be conducted in areas likely to contain residual radioactive material, based on the results of the HSA and scoping survey.

Both systematic and judgment surface activity measurements are performed. Judgment direct measurements are performed at locations of elevated direct radiation, as identified by surface scans, to provide data on the upper ranges of residual radioactive material levels. Judgment measurements may also be performed in sewers, air ducts, storage tanks, and septic systems and on roofs of buildings, if necessary. Each surface activity measurement location should be carefully recorded on the appropriate survey form.

Exposure rate measurements and media sampling are performed as necessary. For example, subfloor soil samples may provide information on the horizontal and vertical extent of residual radioactive material. Similarly, concrete core samples are necessary to evaluate the depth of activated concrete in a reactor facility. Note that one type of radiological measurement may be sufficient to determine the extent of residual radioactive material. For example, surface activity measurements alone may be all that is needed to demonstrate that remediation of an area is necessary; exposure rate measurements would add little to this determination.

Lastly, the measuring and sampling techniques should be commensurate with the intended use of the data, as characterization survey data may be used to guide the FSS survey design or supplement FSS data, provided that the data meet the selected DQOs and the FSS design requirements.

Land Area Surveys

Characterization surveys for surface and subsurface soils and media involve employing techniques to determine the lateral and vertical extent and radionuclide concentrations in the soil. This may be performed using either sampling and laboratory analyses or in situ gamma spectrometry analyses, depending on the instrumentation capabilities of each methodology for the expected radionuclides and concentrations. Note that in situ gamma spectrometry analyses or any direct surface measurement cannot easily be used to determine distributions of radionuclides as a function of depth. Sample collection followed by laboratory analysis introduces several additional sources of uncertainty that need to be considered during survey design. In many cases, a combination of direct measurements and samples is required to meet the objectives of the survey.

Radionuclide concentrations in background soil samples should be determined for a sufficient number of soil samples that are representative of the soil in terms of soil type, soil depth, etc. It is important that the background samples be collected in non-impacted areas. Consideration should be given to spatial variations in the background radionuclide concentrations as discussed in **Section 4.6** and NRC draft report NUREG-1501 (NRC 1994a).

Sample locations should be documented using GPS; reference system coordinates (see **Section 4.9.5**), if appropriate; or fixed site features. A typical reference system spacing for open land areas is 10 m (NRC 1992a). This spacing is somewhat arbitrary and is chosen to facilitate determining survey unit locations and identifying areas of elevated concentrations of radioactive material.

Surface scans for gamma activity should be conducted in areas likely to contain residual radioactive material. Selection of instrumentation should be appropriate to detect the radionuclide(s) of interest. Beta scans may be appropriate if the residual radioactive material is near the surface and beta is the dominant radiation emitted from the residual radioactive material. The detection capability and measurement uncertainty of the scanning technique should be appropriate to meet the DQOs and MQOs.

Both systematic and judgment surface activity measurements are performed. Judgment direct measurements are performed at locations of elevated direct radiation, as identified by surface scans, to provide data on upper ranges of residual radioactive material levels. Judgment measurements may also be performed in areas where radioactive materials might have accrued, such as in swales, under downspouts, near access roads, etc., if necessary. Each surface activity measurement location should be carefully recorded on the appropriate survey form.

Both surface and subsurface soil and media samples may be necessary. Subsurface soil samples should be collected where residual radioactive material is present on the surface and where residual radioactive material is known or suspected in the subsurface. Boreholes should be constructed to provide samples representing subsurface deposits.

Exposure rate measurements at 1 m (~3 feet) above the sampling location may also be appropriate. Each surface and subsurface soil sampling and measurement location should be carefully recorded.

Surface Water and Sediments

Surface water and sediment sampling may be necessary, depending on the potential for these media to contain residual radioactive material, which depends on several factors, including the proximity of surface water bodies to the site, size of the drainage area, total annual rainfall, and spatial and temporal variability in surface water flow rate and volume. Refer to **Section 3.6.3.3** for further criteria to determine the necessity for surface water and sediment sampling.

Characterizing surface water involves techniques that determine the extent and distribution of residual radioactive material. This may be performed by collecting grab samples of the surface water in a well-mixed zone. At certain sites, it may be necessary to collect stratified water samples to provide information on the vertical distribution of residual radioactive material. Sediment sampling should also be performed to assess the relationship between the composition of the suspended sediment and the bedload sediment fractions (i.e., suspended sediments compared to deposited sediments). When judgment sampling is used to find radionuclides in sediments, radioactive sediments are more likely to be accumulated on fine-grained deposits found in low-energy environments (e.g., deposited silt on inner curves of streams).

Radionuclide concentrations in background water samples should be determined for a sufficient number of water samples that are upstream of the site or in areas unaffected by site operations. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be documented using reference system coordinates, if appropriate, or scale drawings of the surface water bodies. Effects of variability of surface water flow rate should be considered. Surface scans for gamma activity may be conducted in areas likely to contain residual radioactive material (e.g., along the banks) based on the results of the document review or preliminary investigation surveys.

Surface water sampling should be performed in areas of runoff from active operations, at plant outfall locations, upstream and downstream of the outfall, and any other areas likely to contain residual radioactive material (see **Section 3.6.3.3**). Measurements of radionuclide concentrations in water should include gross alpha and gross beta radioactivity concentration assessments, as well as any necessary radionuclide-specific analyses. Non-radiological parameters—such as specific conductance, pH, and total organic carbon—may be used as surrogate indicators of potential radioactive material, if a specific relationship exists between the radionuclide concentration and the level of the indicator (e.g., if a linear relationship between pH and the radionuclide concentration in water is found to exist, then the pH may be measured such that the radionuclide concentration can be calculated based on the known relationship rather than performing an expensive nuclide-specific analysis). The use of surrogate measurements is discussed in **Section 4.5.3.**

Each surface water and sediment sampling location should be carefully recorded on the appropriate survey form. Additionally, surface water flow models may be used to illustrate radionuclide concentrations and migration rates.

<u>Ground Water</u>

Ground water sampling may be necessary, depending on the local geology, potential for residual radioactive material in the subsurface, and the regulatory framework. Because different agencies handle ground water compliance in different ways (e.g., EPA's Superfund program and some States require compliance with maximum contaminant levels specified in the Safe Drinking Water Act), the regulatory agency should be contacted if residual radioactive material in ground water is expected. The need for ground water sampling is described in **Section 3.6.3.4.**

If residual radioactive material in ground water is identified, the regulatory agency should be contacted at once, because (1) ground water release criteria and DCGLs should be established by the appropriate agency (**Section 4.5.2**), and (2) the default DCGLs for soil may be inappropriate, because they are usually based on ground water without any residual radioactive material.

Characterization of residual radioactive material in ground water should determine the extent and distribution of residual radioactive material, rates and direction of ground water migration, and the assessment of potential effects of ground water withdrawal on the migration of residual radioactive material in ground water. This may be performed by designing a suitable monitoring well network. The actual number and location of monitoring wells depends on the size of the affected area, the type and extent of the residual radioactive material, the hydrogeological system, and the objectives of the monitoring program.

When ground water samples are taken, background radiation levels should be determined by collecting samples from the same aquifer upgradient of the site and then analyzing them. Any tidal effects and effects of additional wells in the upgradient zone on ground water flow should be evaluated to aid in selecting the proper location of upgradient background samples. The background samples should not be affected by site operations and should be representative of the quality of the ground water that would exist if the site had not been affected by the residual radioactive material. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be referenced to grid coordinates, if appropriate, or to scale drawings of the ground water monitoring wells. Construction specifications on the monitoring wells should also be provided, including elevation, internal and external dimensions, types of casings, type of screen and its location, borehole diameter, and other necessary information about the wells.

In addition to organic and inorganic constituents, ground water sampling and analyses should include all significant radiological constituents. Measurements in potential sources of drinking water should include gross alpha and gross beta assessments, as well as any other radionuclide-specific analyses deemed appropriate based on the HSA. Non-radiological parameters—such as specific conductance, pH, and total organic carbon—may be used as surrogate indicators of the potential presence of certain radionuclides, provided that a specific relationship exists between the radionuclide concentration and the level of the indicator.

Each ground water monitoring well location should be carefully recorded on the appropriate survey form. Additionally, radionuclide concentrations and sources should be plotted on a map to illustrate the relationship among radionuclides, sources, hydrogeological features and boundary conditions, and property boundaries (EPA 1993f).

<u>Other Media</u>

Air sampling may be necessary at some sites, depending on the local geology and the radionuclides of potential concern. This may include collecting air samples or filtering the air to collect resuspended particulates. Air sampling is often restricted to monitoring activities for occupational and public health and safety, and it is not required to demonstrate compliance with risk- or dose-based regulations. **Section 3.6.3.5** describes examples of sites where air sampling may provide information useful to designing an FSS. At some sites, radon measurements may be used to indicate the presence of radium, thorium, or uranium in the soil. **Section 6.8** and **Appendix H** provide information on this type of sampling.

In rare cases, vegetation samples may be collected as part of a characterization survey to provide information in preparation for an FSS. Because most risk- and dose-based regulations are concerned with potential future land use that may differ from the current land use, vegetation samples are unsuitable for demonstrating compliance with regulations. There is a relationship between radionuclide concentrations in plants and those in soil (the soil-to-plant transfer factor is used in many models to develop DCGLs), and the plant concentration could be used as a surrogate measurement of the soil concentration. In most cases, a measurement of the soil itself as the parameter of interest is more appropriate and introduces less uncertainty in the result.

5.2.2.3 Evaluating Survey Results

Survey data are converted to the same units as those in which DCGLs are expressed (**Section 6.7**). Laboratory and in situ analyses are performed to identify potential residual radioactive material at the site. Appropriate regulatory DCGLs for the site are selected, and the data are then compared to the DCGLs. For characterization data that are used to supplement FSS data, the statistical methodology in **Chapter 8** should be followed to determine if a survey unit satisfies the release criteria.

For characterization data that are used to help guide remediation efforts, the survey data are used to identify locations and the general extent of residual radioactivity. The survey results are first compared with DCGLs. Surfaces and environmental media are then differentiated as exceeding DCGLs, not exceeding DCGLs, or not affected, depending on the measurement results relative to the DCGL value. Direct measurements indicating areas of elevated activity are further evaluated, and the need for additional measurements is determined.

5.2.2.4 Documentation

Documentation of the site characterization survey should provide a complete and unambiguous record of the radiological status of the site. In addition, sufficient information to characterize the extent of residual radioactive material, including all possible affected environmental media, should be provided in the report. This report should also provide sufficient information to support reasonable approaches or alternatives to site remediation. **Example 2** includes an example of a characterization survey checklist.

Example 2: Example Characterization Survey Checklist

Survey Design

_____ Enumerate Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs): State the objective of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.

_____ Review the Historical Site Assessment (HSA) and scoping survey results, if performed, for—

_____ Operational history (*e.g.*, any problems, spills, or releases) and available documentation (*e.g.*, radioactive materials license).

_____ Other available resources—site personnel, former workers, residents, etc.

_____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, and disposed of.

_____ Release and migration pathways.

_____ Information on the potential for residual radioactive material that may be useful during area classification for final status survey (FSS) design. Note: Survey activities will be concentrated in Class 1 and Class 2 areas.

_____ Types and quantities of materials likely to remain onsite—consider radioactive decay and ingrowth of decay products.

_____ Document the survey plan (*e.g.*, Quality Assurance Project Plan, standard operating procedures, etc.)

Conducting Surveys

______ Select instrumentation based on its capabilities for the expected residual radioactive material and quantities and knowledge of the appropriate derived concentration guideline levels (DCGLs).

______ Define background locations and determine background activity and radiation levels for the area; include surface activity levels on building surfaces, radionuclide concentrations in environmental media, and exposure rates.

______ Establish a reference coordinate system. Prepare scale drawings for surface water and ground water monitoring well locations.

______ Perform thorough surface scans of all areas potentially containing residual radioactive material. Examples of indoor areas include expansion joints, stress cracks, penetrations into floors and walls for piping, conduits, anchor bolts, and wall/floor interfaces. Examples of outdoor areas include radioactive material storage areas, areas downwind of stack release points, dripline and downspout areas, surface drainage pathways, and roadways that may have been used for transport of radioactive materials.

______ Perform systematic surface activity measurements.

______ Perform systematic smear, surface and subsurface soil and media, sediment, surface water, and ground water sampling, if appropriate for the site.

______ Perform judgment direct measurements and sampling of elevated areas to provide data on the upper ranges of levels of the concentration of radioactive material.

______ Document survey and sampling locations.

______ Maintain chain of custody of samples when necessary.

Note: One category of radiological data (e.g., radionuclide concentration, direct radiation level, or surface radioactivity) may be sufficient to determine the extent of residual radioactive material; other measurements may not be necessary (e.g., removable surface radioactive material or exposure rate measurements).

Note: Measuring and sampling techniques should be commensurate with the intended use of the data, because characterization survey data may be used to supplement FSS data.

Evaluating Survey Results

_____ Compare survey results with DCGLs. Differentiate surfaces or areas as exceeding DCGLs, not exceeding DCGLs, or not affected.

_____ Evaluate all locations of elevated direct measurements, and determine the need for additional measurements or samples.

_____ Prepare site characterization survey report.

5.2.3 Remedial Action Support Surveys

RAS surveys are conducted to (1) support remediation activities, (2) determine when a site or survey unit is ready for the FSS, and (3) provide updated estimates of site-specific parameters to use for planning the FSS. This manual does not discuss the routine operational surveys (e.g., air sampling, dose rate measurements, environmental sampling) conducted for health and safety purposes to support remediation activities.

A RAS survey serves to monitor the effectiveness of remediation efforts to reduce residual radioactive material to acceptable levels. The RAS survey also ensures that remediation is targeted to only those areas requiring remediation, which in turn ensures a cost-effective remediation. This type of survey guides the cleanup in a real-time mode. The RAS survey typically relies on a simple radiological parameter, such as direct radiation near the surface, as an indicator of effectiveness. The investigation level for the RAS survey (established as the DCGL) is determined and used for immediate, in-field decisions (**Section 5.3.8**).

Such a survey is intended for expediency and cost-effectiveness and does not provide thorough or accurate data describing the radiological status of the site. Note that this survey typically does not provide information that can be used to demonstrate compliance with the DCGLs; rather, it is an interim step in the compliance demonstration process. Areas that are determined to likely satisfy the DCGLs on the basis of the RAS survey will then be surveyed in detail by the FSS. Alternatively, the RAS survey can be designed to meet the objectives of an FSS as described in **Section 5.3.**

Remedial activities result in changes to the distribution of residual radioactive material within a survey unit. The site-specific parameters used during FSS planning (e.g., variability in the radionuclide concentration within a survey unit or the probability of small areas of elevated activity) will change during remediation. For most survey units, values for these parameters will need to be re-established following remediation. Obtaining updated values for these critical planning parameters should be considered when designing a RAS survey.

5.2.3.1 Survey Design

The objective of the RAS survey is to determine whether remediation was adequate to remove radioactive material to levels at or below the DCGL criteria. Although the presence of small areas of elevated concentrations of radioactive material may satisfy the elevated measurement criteria, it may be more efficient to design the RAS survey to identify residual radioactive material at the radionuclide-specific release limit based on the spatial distribution of the radionuclide within a survey unit ($DCGL_W$) and to remediate small areas of elevated activity that may potentially satisfy the release criteria. Survey instrumentation and techniques are therefore selected based on the instrumentation capabilities for the known or suspected radionuclides and DCGLs to be achieved.

There will be radionuclides and media that cannot be evaluated at the $DCGL_W$ using field monitoring techniques. For these cases, it may be feasible to collect and analyze samples by methods that are quicker and less costly than radionuclide-specific laboratory procedures. Field laboratories and screening techniques may be acceptable alternatives to more expensive analyses. Reviewing remediation plans may be required to get an indication of the location and amount of residual radioactive material remaining following remediation.

5.2.3.2 Conducting Surveys

Field survey instruments and procedures are selected based on their ability to detect and quantify the expected radionuclides. Survey methods typically include scans of surfaces followed by direct measurements to identify residual radioactive material. The surface activity levels are compared to the investigation levels, and a determination is made on the need for further remediation efforts.

Survey activities for soil excavations include surface scans using field instrumentation sensitive to beta and gamma activity. Because it can be difficult to correlate scanning results to radionuclide concentrations in soil, judgment should be exercised carefully when using scan results to guide the cleanup efforts. Field laboratories and screening techniques may provide a better approach for determining whether further soil remediation is necessary.

5.2.3.3 Evaluating Survey Results

Survey data (e.g., surface activity levels and radionuclide concentrations in various media) are converted to standard units and compared to the DCGLs (**Section 6.7**). If results of these survey activities indicate that remediation has been successful in meeting the DCGLs, remedial actions are ceased, and FSS activities are initiated. Alternatively, further remediation may be needed if results indicate the presence of residual radioactive material in excess of the DCGLs.

DCGLs may be recalculated based on the results of the remediation process as the regulatory program allows or permits.

5.2.3.4 Documentation

The RAS survey should guide the cleanup and alert those performing remedial activities that (1) additional remediation is needed or (2) the site may be ready to initiate an FSS. Data that indicate an area has been successfully remediated could be used to estimate the variance for the survey units in that area. Information identifying areas of elevated activity that existed before remediation may be useful for planning FSSs. **Example 3** includes an example of a RAS survey checklist, including survey design, conduct of surveys, and evaluation of survey results.

Example 3: Example Remedial Action Support Survey Checklist

Survey Design

_____ Enumerate Data Quality Objectives and Measurement Quality Objectives: State the objectives of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.

_____ Document the survey plan (e.g., Quality Assurance Project Plan, standard operating procedures, *etc.*)

_____ Review the remediation plans.

_____ Determine applicability of monitoring surfaces/soils for the radionuclides of concern.

Note: RAS surveys may not be feasible for residual radioactive materials with very low-energy beta emitters or for soils or media containing pure alpha emitters.

_____ Select simple radiological parameters (e.g., surface activity) that can be used to make immediate in-field decisions on the effectiveness of the remedial action.

Conducting Surveys

_____ Select instrumentation based on its capabilities for measuring the expected radionuclides.

_____ Perform scanning and surface activity measurements near the surface being remediated.

_____ Survey soil excavations and perform field evaluation of samples (e.g., gamma spectrometry of undried/non-homogenized soil) as remedial actions progress.

Evaluating Survey Results

_____ Compare survey results with DCGLs using survey data as a field decision tool to guide the remedial actions in a real-time mode.

_____ Document survey results.

5.3 Final Status Surveys

An FSS is performed to demonstrate that residual radioactive material in each survey unit satisfies the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations. The survey provides data to demonstrate that all radiological parameters do not exceed the established DCGLs. For these reasons, more detailed information is provided for this category of survey. For the FSS, survey units represent the fundamental elements for demonstrating that the property is less than the $DCGL_W$ by using a combination of direct measurements or sampling and scanning (see **Sections 5.3.3–5.3.5**) or by a scan-only survey of the property (if warranted by the scanning instrumentation detection capability and measurement uncertainty; see **Section 5.3.6**). The percentage of the area scanned is dependent upon the classification of the property or survey units within the property as well as the relative shift for the site. The documentation specified in the following sections helps ensure a consistent approach among different organizations and regulatory agencies. This allows for comparisons of survey results between sites or facilities.

The MARSSIM approach recognizes that alternative methods may be acceptable to different regulatory agencies. Flow diagrams and a checklist to assist the user in planning a survey are included in this section.

Figures 5.4–5.6 illustrate the process of designing an FSS. This process begins with development of DQOs and MQOs. The first decision after developing the DQOs and MQOs is to establish whether a scan-only or traditional MARSSIM approach (scanning with direct measurements and/or samples) will be used. Based on these objectives and the known or anticipated radiological conditions at the site, the numbers and locations of measurement and sampling points used and amount of scanning to demonstrate compliance with the release criteria are then determined. Finally, survey techniques appropriate to develop adequate data (see **Chapters 6 and 7**) are selected and implemented.

The elements of an FSS discussed in **Section 5.3** consist of the following subsections:

- selecting either Scenario A or Scenario B as a basis of the survey design (**Section 5.3.1**)
- determining the appropriate release criteria based on whether radionuclides of concern are present in the background (**Section 5.3.2**)
- determining the appropriate number of data points for statistical tests when residual radioactive materials are present in the background (**Section 5.3.3**)
- determining the appropriate number of data points for statistical tests when residual radioactive materials are not present in the background (**Section 5.3.4**)
- establishing procedures for determining data points for small areas of elevated activity (**Section 5.3.5**)
- determining the scan area (**Section 5.3.6**)
- determining the survey locations (**Section 5.3.7**)
- establishing the appropriate investigation level for a survey (**Section 5.3.8**)
- developing an integrated survey design (**Section 5.3.9**)
- evaluating the survey results (**Section 5.3.10**)
- documenting the results (**Section 5.3.11**)

Another important consideration during planning for an FSS is the performance of confirmatory surveys. Planning for the FSS should include early discussions with the regulatory agency concerning logistics for confirmatory or verification surveys. A confirmatory survey (also known as an independent verification survey) may be performed by the regulatory agency or by an independent third party (e.g., a party contracted by the regulatory agency) to provide data to substantiate results of the FSS. Actual field measurements and sampling may be performed.

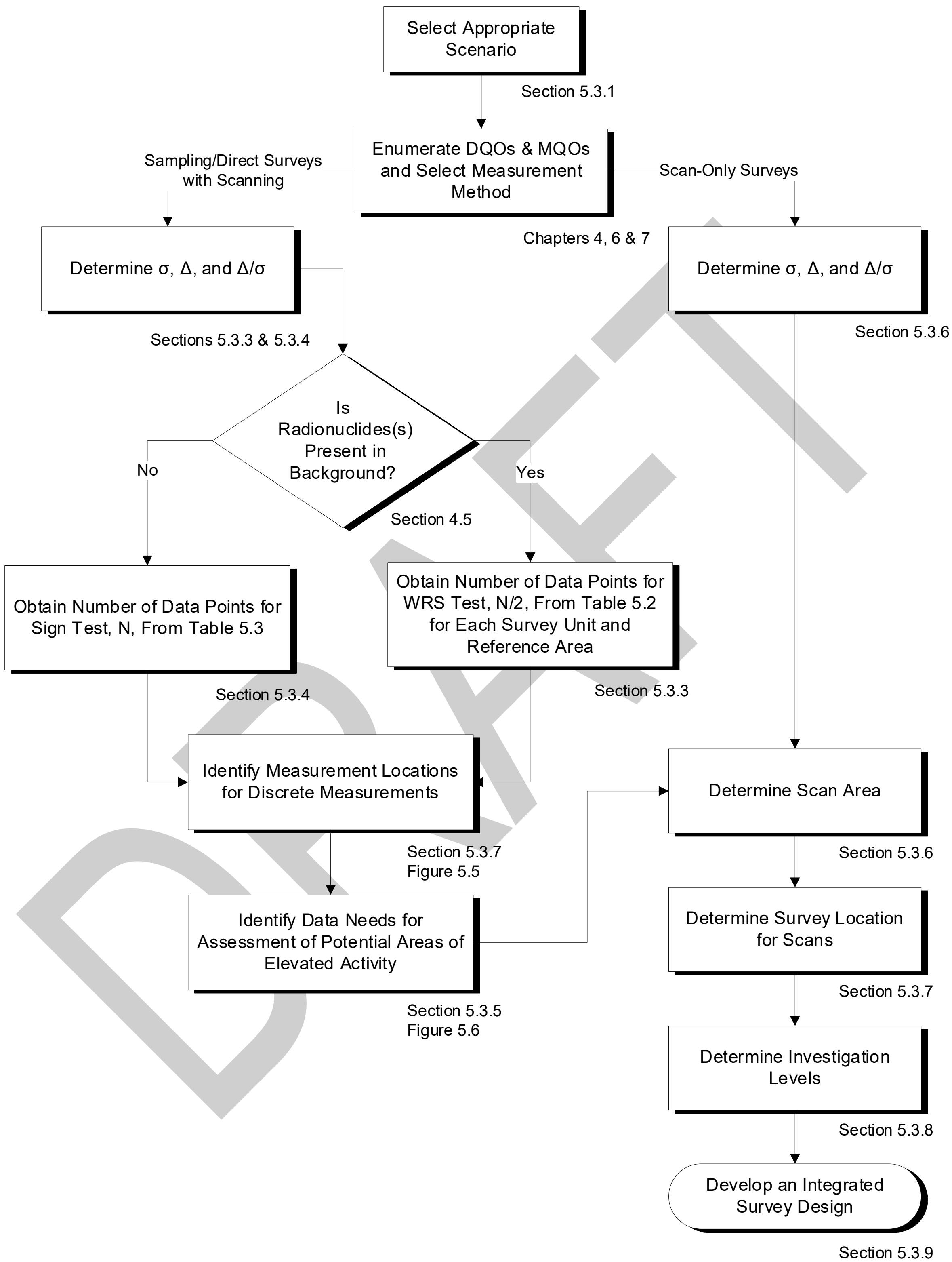


Figure 5.4: Process for Designing an Integrated Survey Plan for a Final Status Survey

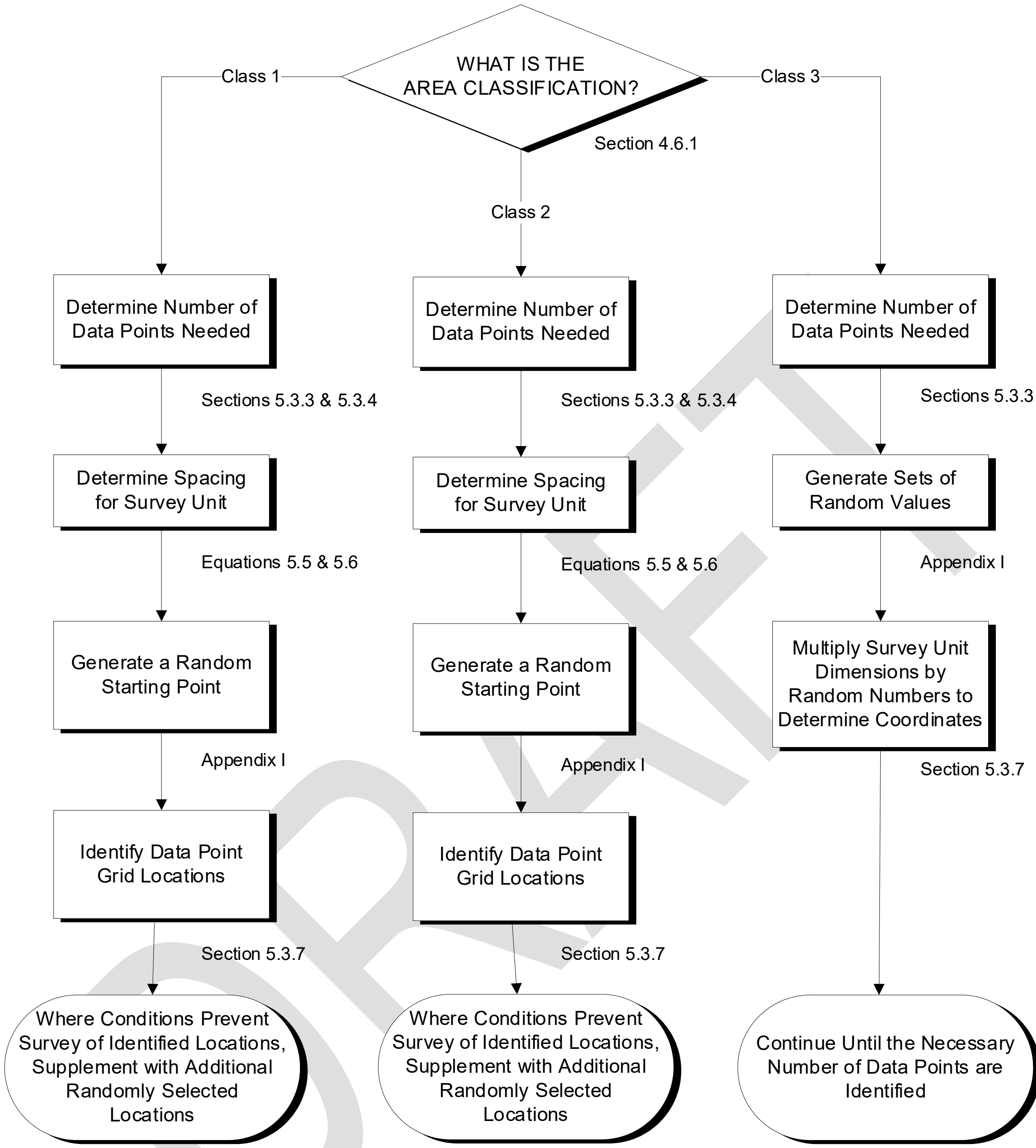


Figure 5.5: Process for Identifying Discrete Measurement Locations

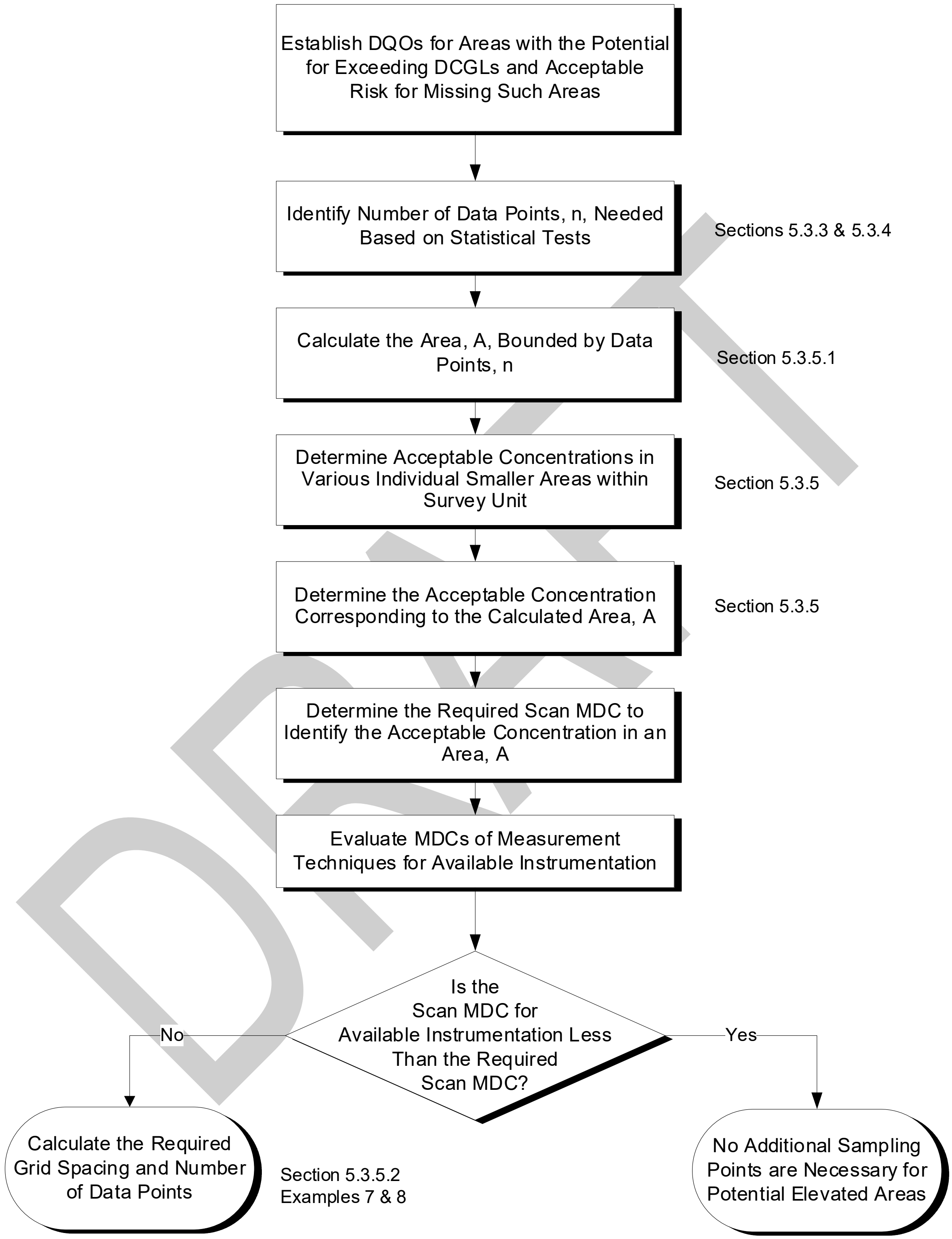


Figure 5.6: Identifying Data Needs for Assessment of Potential Areas of Elevated Activity in Class 1 Survey Units

Independent confirmatory survey activities are usually limited in scope to spot-checking conditions at selected locations, comparing findings with those of the FSS and performing independent statistical evaluations of the data developed from the confirmatory survey and the FSS. Another purpose of the confirmatory activities may be to identify any deficiencies in the FSS documentation based on a thorough review of survey procedures and results. Finally, reviewing the results of confirmatory surveys performed on other sites may provide insight into possible survey deficiencies, which can then be corrected before the FSS is performed (Roberts 2008).

5.3.1 Selecting the Appropriate Scenario

The DQO process, as it is applied to FSSs, is described in more detail in **Appendix D** of this manual and in EPA and NRC guidance documents (EPA 1987b, 1987c, 2006c; NRC 1998a). As part of this process, the objective of the survey and the null and alternative hypotheses should be clearly stated. The objective of FSSs is typically to demonstrate that residual radioactive material levels meet the release criteria. One of two approaches is used to demonstrate that this objective is met; the two approaches differ in the selection of the null hypothesis (i.e., what is assumed to be the true state of nature), as summarized in **Table 5.1.**

Table 5.1: Null and Alternative Hypothesis for Scenarios A and B

Scenario	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
A	The concentration of residual radioactive material is equal to or exceeds the release criteria.	The concentration of residual radioactive material is less than the release criteria.
B	The concentration of residual radioactive material is equal to or less than the release criteria.	The concentration of residual radioactive material exceeds the release criteria.

Historically, MARSSIM recommended the use of Scenario A, which put the burden of proof that the survey unit met the release criteria on the individuals designing the survey. However, Scenario A requires that survey designers choose a discrimination limit (DL), the lower bound of the gray region (LBGR), at some radioactive material concentration less than the DCGL. This is effectively impossible when the AL corresponding to the release criteria is "zero residual radioactive material" or "zero residual radioactive material above background." The only way to design a survey for these kinds of release criteria is to establish a DL at some radioactive material concentration greater than the AL.

In Scenario B, the burden of proof is no longer on the individuals designing the survey and, thus, should be used with caution and only in those situations where Scenario A is not an effective alternative. The consequence of inadequate power is an increased Type II decision error (β) rate. For Scenario A, this means that a survey unit that does meet the release criteria has a higher probability of being incorrectly determined not to meet the release criteria. For Scenario B, this means that a survey unit that does not meet the release criteria has a higher probability of being incorrectly determined to meet the release criteria. For this reason, individuals designing a MARSSIM Survey using Scenario B should make conservative assumptions for the estimate of the standard deviation (σ) (see **Section 5.3.3.2**) so that even if the variability in the survey unit is higher than expected, the power of the resulting survey ($1-\beta$) (see **Section 5.3.2**) will still be sufficient to ensure that survey units with residual radioactive material in excess of the AL will be discovered $1-\beta$ percent of the time. As a result, a retrospective power analysis needs to be performed following the completion of Scenario B

MARSSIM surveys indicating that regulatory agency requirements on β at the DL were met. See **Chapter 8** and **Appendix M** for more information on performing a retrospective power analysis.

5.3.2 Application of Release Criteria

The statistical test used to evaluate data for FSSs where direct measurements or sampling and analysis is performed depend on the scenario selected. For radionuclides that are present in background, the Wilcoxon Rank Sum (WRS) test is typically used in Scenario A. In Scenario B two nonparametric statistical tests are performed: the WRS test and the Quantile test. The WRS and Quantile tests are both used because each test detects different residual radioactive material patterns in the survey unit. When radionuclides of concern are not present in background, the Sign test is used for both scenarios. For scan-only surveys, a comparison to an upper confidence level (UCL) is performed. The Sign, WRS, UCL, and Quantile tests are discussed in **Chapter 8.**

To determine data needs for these tests, the acceptable probability of making Type I decision errors (α) and Type II decision errors (β) should be established (see **Appendix D, Section D.1.6**). The acceptable decision error rates are defined at the LBGR and the $DCGL_W$ for Scenario A and the action level (AL) and the DL for Scenario B. Acceptable decision error rates are determined during survey planning using the DQO process.

The final step of the DQO process includes selecting a survey design that satisfies the DQOs. For some sites or survey units, the information provided in this section may result in a survey design that cannot be accomplished with the available resources. For these situations, the planning team may be able to relax one or more of the constraints used to develop the survey design as described in **Appendix D.** For example—

- increasing the decision error rates, considering the risks associated with making an incorrect decision
- increasing the width of the gray region, as long as the LBGR is not set lower than the estimate of the residual radioactive material remaining in the survey unit in Scenario A
- changing the boundaries—it may be possible to reduce measurement costs by changing or eliminating survey units that may require different decisions

5.3.3 Determining Numbers of Data Points for Statistical Tests for Residual Radioactive Material Present in Background

The comparison of measurements from the reference area and survey unit is made using the WRS test, which is usually conducted for each survey unit. In addition, the Elevated Measurement Comparison (EMC) may need to be performed against each measurement to ensure that the measurement result does not exceed a specified investigation level. If any measurement in the remediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactive material is uniformly present throughout a survey unit. The test is designed to detect whether the median concentration exceeds the $DCGL_W$. The advantage of this nonparametric test is that it does not assume the data are normally or log-normally distributed. The WRS test also allows for "less than" measurements to be present in the reference area and the survey units. This test can generally be used with up to 40 percent "less than" measurements in either the reference area or the survey unit. However, the use of "less than" values in data reporting is not recommended (NRC 2004). Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

This section introduces several terms and statistical parameters that will be used to determine the number of data points needed to apply the nonparametric tests. An example is provided below to better illustrate the application of these statistical concepts.

5.3.3.1 Define the Gray Region

In Scenario A, the upper bound of the gray region (UBGR) is equal to the $DCGL_W$. The gray region is defined as the interval between the LBGR and the $DCGL_W$ (**Figure 5.7**). For Scenario A, the LBGR is typically chosen to represent a conservative (slightly higher) estimate of the mean concentration of residual radioactive material remaining in the survey unit at the beginning of the FSS. If there is no information with which to estimate the residual radioactive material concentration remaining, the LBGR may be initially set to equal one-half of the $DCGL_W$.

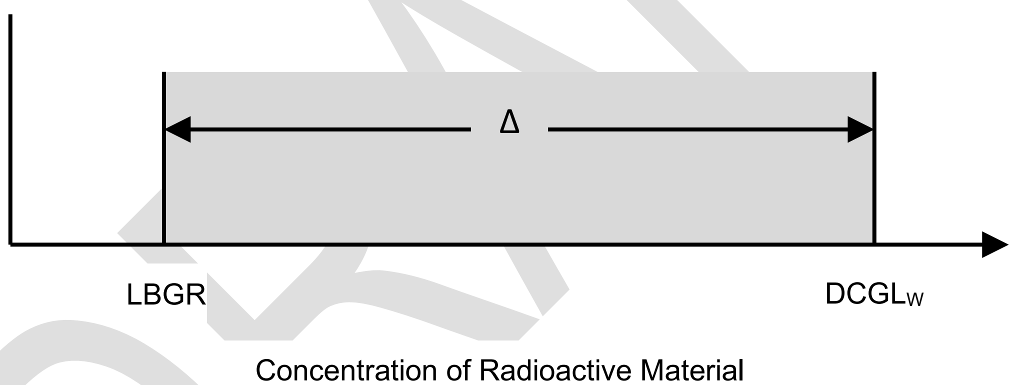


Figure 5.7: Gray Region for Scenario A

In Scenario B, the UBGR is equal to the DL, and the LBGR is equal to the AL. The gray region is defined as the interval between the AL and the DL (**Figure 5.8**).[2] The AL is the concentration of radioactive material that causes a decision maker to choose one of the alternative actions, such as releasing a survey unit or requiring additional investigation. The planning team also chooses the DL. The DL is the concentration of radioactive material or level of radioactivity that can be reliably distinguished from the action level by performing measurements with the devices selected for the survey (i.e., direct measurements, scans, in situ measurements, samples with laboratory analyses) and defines the rigor of the survey. It is determined through negotiations with the regulator, and, in some cases, the DL will be set equal to a regulatory limit (e.g., 10 CFR 36.57 and DOE 2011c). The DL and the AL should be reported in the same units. The selection of the appropriate null hypothesis is further discussed in **Chapter 8** and **Appendix D.**

[2] This description of Scenario B is based on information contained in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) Manual and the Multi-Agency Radiation Laboratory Analytical Protocols and is fundamentally different from the description of Scenario B found in NUREG-1505 (NRC 1998a).

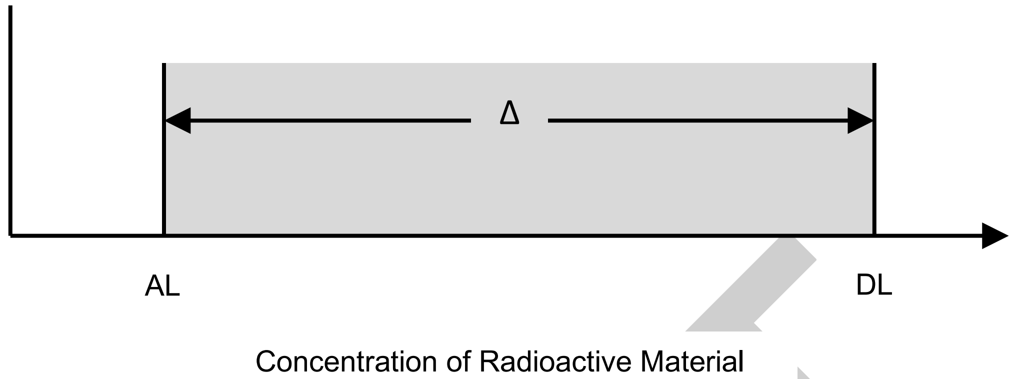


Figure 5.8: Gray Region for Scenario B

When Scenario B is being used, the variability in the data may be such that a decision may be "too close to call" when the true but unknown value of the residual radioactivity concentration is very near the DL. In this situation, consultation with the appropriate regulator may be required to determine the AL and DL. As an example, the U.S. NRC discusses methods in NUREG-1505 (NRC 1998a), Chapter 13, to establish the gray region and a concentration level that is considered indistinguishable from background when the WRS test is used[3].

5.3.3.2 Calculate the Relative Shift

The width of the gray region is a parameter that is essential for planning all statistical tests; it is also referred to as the shift, Δ. In Scenario A, the shift is the difference between the LBGR and the $DCGL_W$ ($\Delta = DCGL_W - LBGR$). In Scenario B, the shift is the difference between the AL and the DL ($\Delta = DL - AL$). The absolute size of the shift is less important than the relative shift, Δ/σ, where σ is an estimate of the standard deviation of the measured values in the survey unit. This estimate of σ includes both the real spatial variability in the quantity being measured and the uncertainty of the chosen measurement method. The relative shift is an expression of the resolution of the measurements in units of measurement uncertainty.

The shift and the estimated standard deviation in the measurements of the radioactive material in the survey unit (σ_s) and reference area (σ_r) are used to calculate the relative shift (Δ/σ) (see **Appendix D, Section D.1.7.3**). The standard deviations in the radionuclide level will likely be available from previous systematic and non-judgment survey data (e.g., scoping or characterization survey data for un-remediated survey units or RAS surveys for remediated survey units). If they are not available, it may be necessary to (1) perform some limited preliminary measurements (about 5–20) to estimate the distributions or (2) to make a reasonable estimate based on available site knowledge. If the first approach above is used, the scoping or characterization survey data or preliminary measurements used to estimate the standard deviation should use the same technique as the FSS will. When preliminary data are not obtained, it may be reasonable to assume a coefficient of variation (CV) on the order of

[3] Chapter 8 in NUREG-1505 [NRC 1998] provides additional information on the WRS test.

30 percent, based on experience. The CV is a measure of the dispersion of the data and is defined by the ratio of the standard deviation to the mean.

The value selected as an estimate of σ for a survey unit may be based on data collected only from within that survey unit or from data collected from a much larger area of the site. Note that survey units are not finalized until the planning stage of the FSS. This means that there may be some difficulty in determining which individual measurements from a preliminary survey may later represent a particular survey unit. For many sites, the most practical solution is to estimate σ for each area classification (i.e., Class 1, Class 2, and Class 3) for both interior and exterior survey units. This will result in all exterior Class 3 survey units using the same estimate of σ, all exterior Class 2 survey units using a second estimate for σ, and all exterior Class 1 survey units using a third estimate for σ. If there are multiple types of surfaces within an area classification, additional estimates of σ may be required. For example, a Class 2 concrete floor may require a different estimate of σ than a Class 2 cinder block wall, or a Class 3 unpaved parking area may require a different estimate of σ than a Class 3 lawn. In addition, a separate estimate of σ should be obtained for every reference area.

The importance of choosing appropriate values for σ_r and σ_s must be emphasized. If the value is grossly underestimated, the number of data points will be too few to obtain the desired power level for the test, and a resurvey may be recommended (see **Chapter 8**). If, on the other hand, the value is overestimated, the number of data points determined will be unnecessarily large.

Values for the relative shift that are less than 1 will result in a large number of measurements needed to demonstrate compliance. The number of data points will also increase as Δ becomes smaller. Because the DCGL is fixed, this means that the LBGR also has a significant effect on the estimated number of measurements needed to demonstrate compliance in Scenario A. The DL selected during the DQO process will have a similar effect in Scenario B. When the estimated standard deviations in the reference area and survey units are different, the larger value should be used to calculate the relative shift (Δ/σ). There is little benefit, in terms of reduced number of measurements, for relative shift values greater than 3. Because of this and the large number of measurements resulting from relative shift values less than 1, in Scenario A, the LBGR may be adjusted to ensure the relative shift is greater than 1, as long as the LBGR is not set lower than the estimate of the residual radioactive material remaining in the survey unit. For Scenario B, the planning team may wish to adjust the DL to achieve a similar effect with approval from the regulator. However, it is extremely important that such adjustments be supported by data. Additional considerations related to adjusting the relative shift are provided in **Appendix D, Section D.1.7.3.**

In practice, the DQO process is used to obtain a proper balance among the use of various measurement techniques. In general, there is an inverse correlation between the cost of a specific measurement method and the detection levels being sought. Depending on the survey objectives, there are many important considerations when selecting a measurement method that will ultimately affect both the survey costs and the statistical power of the sampling design. Statistical power is defined as the probability that a statistical test will correctly reject the null hypothesis (i.e., under Scenario A, accepting that a site that meets the release criteria truly does, and under Scenario B, accepting that a site that does not meet the release criteria truly does not). A general example approach that might be undertaken for a Scenario A planning session is discussed below.

N is the total number of data points for each survey unit/reference area combination. The N data points are divided between the survey unit, n, and the reference area, m. The simplest method for distributing the N data points is to assign half the data points to the survey unit and half to the reference area, so $n = m = N/2$. This means that $N/2$ measurements are performed in each survey unit, and $N/2$ measurements are performed in each reference area. If more than one survey unit is associated with a particular reference area, $N/2$ measurements should be performed in each survey unit, and $N/2$ measurements should be performed in the reference area.

Table 5.2 provides a list of the number of data points needed to demonstrate compliance using the WRS test for selected values of α, β, and Δ/σ. The values listed in **Table 5.2** represent the number of measurements to be performed in each survey unit and in the corresponding reference area. **Example 4** illustrates the use of the WRS Test under Scenario A.

Example 4: Use of WRS Test under Scenario A

A site has 14 survey units and 1 reference area in a building, and the same measurement method is used to perform measurements in each survey unit and the reference area. The radionuclide has a wide-area derived concentration guideline level of 400 becquerels/square meter (Bq/m^2) (240 decays per minute [dpm]/100 square centimeters [cm^2]). The radionuclide is present in background at a level of 100 ± 15 Bq/m^2 (1σ). The standard deviation of the radionuclide in the survey area is ± 40 Bq/m^2 (24 dpm/100 cm^2), based on previous survey results for the same or similar radionuclide distribution. When the estimated standard deviation in the reference area and the survey units are different, the larger value, 40 Bq/m^2 in this example, is used to calculate the relative shift. During the Data Quality Objective process, Scenario A is selected. The LBGR is selected to be 240 Bq/m^2. This is based on a conservative estimate of the concentration of residual radioactive material in the survey unit. Type I and Type II error values (α and β) of 0.05 are selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.

The value of the relative shift for the survey unit, Δ/σ, is $(400 - 240)/40$, or 4.0. The number of data points can be obtained directly from **Table 5.2.** For $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 4.0$, a value of 9 is obtained for $N/2$. The table value has already been increased by 20 percent to account for missing or unusable data.

Table 5.2: Values of $N/2$ for Use with the Wilcoxon Rank Sum Test[4,5]

Δ/σ	$\alpha = 0.01$					$\alpha = 0.025$					$\alpha = 0.05$					$\alpha = 0.10$					$\alpha = 0.25$				
	β					β					β					β					β				
	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	5,452	4,627	3,972	3,278	2,268	4,627	3,870	3,273	2,646	1,748	3,972	3,273	2,726	2,157	1,355	3,278	2,646	2,157	1,655	964	2,268	1,748	1,355	964	459
0.2	1,370	1,163	998	824	570	1,163	973	823	665	440	998	823	685	542	341	824	665	542	416	243	570	440	341	243	116
0.3	614	521	448	370	256	521	436	369	298	197	448	369	307	243	153	370	298	243	187	109	256	197	153	109	52
0.4	350	297	255	211	146	297	248	210	170	112	255	210	175	139	87	211	170	139	106	62	146	112	87	62	30
0.5	227	193	166	137	95	193	162	137	111	73	166	137	114	90	57	137	111	90	69	41	95	73	57	41	20
0.6	161	137	117	97	67	137	114	97	78	52	117	97	81	64	40	97	78	64	49	29	67	52	40	29	14
0.7	121	103	88	73	51	103	86	73	59	39	88	73	61	48	30	73	59	48	37	22	51	39	30	22	11
0.8	95	81	69	57	40	81	68	57	46	31	69	57	48	38	24	57	46	38	29	17	40	31	24	17	8
0.9	77	66	56	47	32	66	55	46	38	25	56	46	39	31	20	47	38	31	24	14	32	25	20	14	7
1.0	64	55	47	39	27	55	46	39	32	21	47	39	32	26	16	39	32	26	20	12	27	21	16	12	6
1.1	55	47	40	33	23	47	39	33	27	18	40	33	28	22	14	33	27	22	17	10	23	18	14	10	5
1.2	48	41	35	29	20	41	34	29	24	16	35	29	24	19	12	29	24	19	15	9	20	16	12	9	4
1.3	43	36	31	26	18	36	30	26	21	14	31	26	22	17	11	26	21	17	13	8	18	14	11	8	4
1.4	38	32	28	23	16	32	27	23	19	13	28	23	19	15	10	23	19	15	12	7	16	13	10	7	4
1.5	35	30	25	21	15	30	25	21	17	11	25	21	18	14	9	21	17	14	11	7	15	11	9	7	3
1.6	32	27	23	19	14	27	23	19	16	11	23	19	16	13	8	19	16	13	10	6	14	11	8	6	3
1.7	30	25	22	18	13	25	21	18	15	10	22	18	15	12	8	18	15	12	9	6	13	10	8	6	3
1.8	28	24	20	17	12	24	20	17	14	9	20	17	14	11	7	17	14	11	9	5	12	9	7	5	3
1.9	26	22	19	16	11	22	19	16	13	9	19	16	13	11	7	16	13	11	8	5	11	9	7	5	3
2.0	25	21	18	15	11	21	18	15	12	8	18	15	13	10	7	15	12	10	8	5	11	8	7	5	3
2.25	22	19	16	14	10	19	16	14	11	8	16	14	11	9	6	14	11	9	7	4	10	8	6	4	2
2.5	21	18	15	13	9	18	15	13	10	7	15	13	11	9	6	13	10	9	7	4	9	7	6	4	2
2.75	20	17	15	12	9	17	14	12	10	7	15	12	10	8	5	12	10	8	6	4	9	7	5	4	2
3.0	19	16	14	12	8	16	14	12	10	6	14	12	10	8	5	12	10	8	6	4	8	6	5	4	2
3.5	18	16	13	11	8	16	13	11	9	6	13	11	9	8	5	11	9	8	6	4	8	6	5	4	2
4.0	18	15	13	11	8	15	13	11	9	6	13	11	9	7	5	11	9	7	6	4	8	6	5	4	2

[4] In Scenario B the sample size for the WRS test is also used for the Quantile test.

[5] The values were calculated using Equation O-1 and increased by 20 percent for the reasons discussed in Appendix O.

Example 5 illustrates the use of the WRS Test under Scenario B.

Example 5: Use of WRS Test under Scenario B

A site has 14 survey units and 1 reference area in a building, and the same measurement method is used to perform measurements in each survey unit and the reference area. The radionuclide is present in background at a level of 100 ± 15 becquerels/meter squared (Bq/m^2) (1σ). The standard deviation of the radionuclide in the survey area is 40 Bq/m^2, based on previous survey results for the same or similar radionuclide distribution. When the estimated standard deviation in the reference area and the survey units are different, the larger value, 40 Bq/m^2 in this example, should be used to calculate the relative shift. During the Data Quality Objective process, Scenario B is selected because the release criterion for the site is no residual radioactive material above background. The discrimination limit is selected to be 220 Bq/m^2 as a stakeholder agreed-upon starting point for developing an acceptable survey design, and Type I and Type II error values (α and β) of 0.05 are selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.

The value of the relative shift for the reference area, Δ/σ, is $(220 - 100)/40$, or 3.0. The number of data points can be obtained directly from **Table 5.2.** For $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 3.0$, a value of 10 is obtained for $N/2$. The table value has already been increased by 20 percent to account for missing or unusable data.

5.3.4 Determining Numbers of Data Points for Statistical Tests for Residual Radioactive Material Not Present in Background

For the situation where the residual radioactive material is not present in background or is present at such a small fraction of the $DCGL_W$ as to be considered insignificant, a background reference area is not necessary. Instead, the radionuclide levels are compared directly with the DCGL value. The general approach closely parallels that used for the situation when the radionuclide is present in background as described in **Section 5.3.3.** However, the statistical tests differ slightly. The Sign test replaces the WRS test described above.

5.3.4.1 Define the Gray Region

In Scenario A, the UBGR is equal to the $DCGL_W$ (**Figure 5.7**). The LBGR is typically chosen to represent a conservative (slightly higher) estimate of the residual radioactive material concentration remaining in the survey unit at the beginning of the FSS. If there is no information with which to estimate the residual radioactive material concentration remaining, the LBGR may be initially set to equal one-half of the $DCGL_W$. In Scenario B, the LBGR is equal to zero or the $DCGL_W$, and the UBGR is defined as the DL (**Figure 5.8**). The DL is a concentration or level of radioactive material that can be reliably distinguished from the LBGR by performing measurements with the devices selected for the survey. The DL defines the rigor of the survey and is determined through negotiations with the regulator. The selection of the appropriate null hypothesis is further discussed in **Chapter 8** and **Appendix D.**

5.3.4.2 Calculate the Relative Shift

In Scenario A, the shift is the distance between the LBGR and the $DCGL_W$ ($\Delta = DCGL_W - LBGR$). In Scenario B, the shift is the distance between the AL and the DL ($\Delta = DL - AL$). The absolute size of the shift is less important than the relative shift, Δ/σ, where σ is an estimate of the variability in the survey unit. The value of σ may be obtained from earlier surveys, limited preliminary measurements, or a reasonable estimate. This estimate of σ includes both the real spatial variability in the quantity being measured and the uncertainty of the measurement method. The relative shift, Δ/σ, is an expression of the resolution of the measurements in units of measurement uncertainty. Values of the relative shift that are less than 1 will result in a large number of measurements needed to demonstrate compliance. **Section 5.3.3.2** provides more detail on the relative shift.

Table 5.3 provides a list of the number of data points used to demonstrate compliance using the Sign test for selected values of α, β, and Δ/σ. The values listed in **Table 5.3** represent the number of measurements to be performed in each survey unit. These values were calculated using **Equation O-1** in **Appendix O** and increased by 20 percent to account for missing or unusable data and uncertainty in the calculated value of N. **Example 6** illustrates the use of the Sign Test under Scenario A.

Example 6: Use of Sign Test Under Scenario A

A site has one survey unit. The wide-area derived concentration guideline level for the radionuclide of interest is 140 becquerels/kilogram (Bq/kg) (3.9 picocuries/gram [pCi/g]) in soil. The radionuclide is not present in background; data from previous investigations indicate average residual radioactive material at the survey unit of 110 ± 3.7 (1 σ) Bq/kg (3.7 ± 0.1 pCi/g). Using Scenario A, the lower bound of the gray region was selected to be 110 Bq/kg. A value of 0.05 is next selected for the probability of Type I decision errors (α), and a value of 0.01 is selected for the probability of Type II decision errors (β) based on the survey objectives. Determine the number of data points to be obtained from the survey unit for the statistical tests.

The value of the relative shift, Δ/σ, is $(140 - 110)/3.7$, or 8.1. The number of data points can be obtained directly from **Table 5.3.** For $\alpha = 0.05$, $\beta = 0.01$, and $\Delta/\sigma > 3.0$, a value of 20 is obtained for N. The table value has already been increased by 20 percent to account for missing or unusable data and uncertainty in the calculated value of N.

Table 5.3: Values of N for Use with the Sign Test[6]

Δ/σ	α = 0.01					α = 0.025					α = 0.05					α = 0.10					α = 0.25				
	β					β					β					β					β				
	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	4,095	3,476	2,984	2,463	1,704	3,476	2,907	2,459	1,989	1,313	2,984	2,459	2,048	1,620	1,018	2,463	1,989	1,620	1,244	725	1,704	1,313	1,018	725	345
0.2	1,035	879	754	623	431	879	735	622	503	333	754	622	518	410	258	623	503	410	315	184	431	333	258	184	88
0.3	468	398	341	282	195	398	333	281	227	150	341	281	234	185	117	282	227	185	143	83	195	150	117	83	40
0.4	270	230	197	162	113	230	1921	162	131	87	197	162	136	107	68	162	131	107	82	48	113	87	68	48	23
0.5	178	152	130	107	75	152	126	107	87	58	130	107	89	71	45	107	87	71	54	33	75	58	45	33	16
0.6	129	110	94	77	54	110	92	77	63	42	94	77	65	52	33	77	63	52	40	23	54	42	33	23	11
0.7	99	83	72	59	41	83	70	59	48	33	72	59	50	40	26	59	48	40	30	18	41	33	26	18	9
0.8	80	68	58	48	34	68	57	48	39	26	58	48	40	32	21	48	39	32	24	15	34	26	21	15	8
0.9	66	57	48	40	28	57	47	40	33	22	48	40	34	27	17	40	33	27	21	12	28	22	17	12	6
1.0	57	48	41	34	24	48	40	34	28	18	41	34	29	23	15	34	28	23	18	11	24	18	15	11	5
1.1	50	42	36	30	21	42	35	30	24	17	36	30	26	21	14	30	24	21	16	10	21	17	14	10	5
1.2	45	38	33	27	20	38	32	27	22	15	33	27	23	18	12	27	22	18	15	9	20	15	12	9	5
1.3	41	35	30	26	17	35	29	24	21	14	30	24	21	17	11	26	21	17	14	8	17	14	11	8	4
1.4	38	33	28	23	16	33	27	23	18	12	28	23	20	16	10	23	18	16	12	8	16	12	10	8	4
1.5	35	30	27	22	15	30	26	22	17	12	27	22	18	15	10	22	17	15	11	8	15	12	10	8	4
1.6	34	29	24	21	15	29	24	21	17	11	24	21	17	14	9	21	17	14	11	6	15	11	9	6	4
1.7	33	28	24	20	14	28	23	20	16	11	24	20	17	14	9	20	16	14	10	6	14	11	9	6	4
1.8	32	27	23	20	14	27	22	20	16	11	23	20	16	12	9	20	16	12	10	6	14	11	9	6	4
1.9	30	26	22	18	14	26	22	18	15	10	22	18	16	12	9	18	15	12	10	6	14	10	9	6	4
2.0	29	26	22	18	12	26	21	18	15	10	22	18	15	12	8	18	15	12	10	6	12	10	8	6	3
2.5	28	23	21	17	12	23	20	17	14	10	21	17	15	11	8	17	14	11	9	5	12	10	8	5	3
3.0	27	23	20	17	12	23	20	17	14	9	20	17	14	11	8	17	14	11	9	5	12	9	8	5	3

[6] The values were calculated using Equation O-2 and increased by 20 percent for the reasons discussed in Appendix O.

5.3.5 Determining the Number of Discrete Data Points for Small Areas of Elevated Activity

As described in **Section 4.2.5,** the treatment of elevated areas of radioactive material is determined strictly through requirements of regulatory agencies and is beyond the scope of MARSSIM. A technically sound approach should be used for the derivation of the DCGL for the Elevated Measurement Comparison ($DCGL_{EMC}$) values. The methodology presented in MARSSIM of using the unity rule to consider the combined impact of each elevated area is one conservative approach to assess areas of elevated radioactive materials. See **Figure 5.6** for a summary of data needs for areas of elevated activity.

The statistical tests described throughout **Sections 5.3.3 and 5.3.4** (see also **Chapter 8**) evaluate whether the residual radioactive material in an area exceeds the $DCGL_W$ for radionuclide concentrations that are approximately uniform across the survey unit. In addition, there should be a reasonable level of assurance that any small areas of elevated concentrations of residual radioactive material that could be significant relative to the $DCGL_{EMC}$ are not missed during the FSS. The statistical tests introduced in the previous sections may not successfully detect small areas of elevated concentrations of radioactive material. Instead, systematic measurements or samples are made at locations defined by a systematic grid, in conjunction with surface scanning. These results are used to obtain adequate assurance that small areas of elevated concentrations of radioactive material are below the $DCGL_{EMC}$ and the release criteria are met. The procedure is applicable for all radionuclides, regardless of whether they are present in background and is implemented for Class 1 survey units.

5.3.5.1 Determine if Additional Data Points are Needed

Identify the number of survey data points needed for the statistical tests discussed in **Sections 5.3.3 or 5.3.4** (the appropriate section is determined by whether the radionuclide is present in background). These data points are then positioned throughout the survey unit by randomly selecting a start point and establishing a systematic pattern. This systematic sampling grid may be either triangular or rectangular. The triangular grid is generally more efficient for locating small areas of elevated activity. **Appendix D** includes a brief discussion on the efficiency of triangular and rectangular grids for locating areas of elevated activity. A more detailed discussion is provided by EPA (EPA 1994b).

The number of calculated survey locations, *n*, and the total area of the survey unit, A, are used to determine the grid spacing, L, of the systematic sampling pattern, using **Equations 5-1 and 5-2.**

$$L = \sqrt{\frac{A\ \text{(survey unit)}}{0.866\,n}} \quad \text{for a triangular grid} \tag{5-1}$$

$$L = \sqrt{\frac{A\ \text{(survey unit)}}{n}} \quad \text{for a rectangular grid} \tag{5-2}$$

The grid area that is bounded by these survey locations is given by **Equations 5-3 and 5-4.** The risk of not sampling a circular area—equal to *A* (grid area)—of elevated activity by use of a random-start grid pattern is illustrated in **Figure D.7** in **Appendix D.**

$$A \text{ (grid area)} = 0.866\, L^2 \text{ for a triangular grid} \quad (5\text{-}3)$$

$$A \text{ (grid area)} = L^2 \text{ for a rectangular grid} \quad (5\text{-}4)$$

The $DCGL_{EMC}$ that corresponds to this size of the area of elevated activity (A_{EA}) is obtained from specific regulatory agency guidance. After using the grid area calculated in **Equation 5-3 or 5-4** to determine the $DCGL_{EMC}$ for a specific radionuclide, the required minimum detectable concentration (MDC) of the scan procedure needed to detect an area of elevated activity is given by **Equation 5-5.**

$$\text{Scan MDC (required)} = DCGL_{EMC} \quad (5\text{-}5)$$

The actual scan MDCs of scanning techniques are then determined for the available instrumentation (see **Sections 6.3.2 and 6.6**). The actual scan MDC of the selected scanning technique is compared to the required scan MDC. If the actual scan MDC is less than the required scan MDC, no additional sampling points are necessary for assessment of small areas of elevated activity. In other words, the scanning technique exhibits adequate detection capability to detect small areas of elevated activity.

Revisions 0 and 1 of MARSSIM (published in 1998 and 2000, respectively) included the calculation of an area factor[7] as an intermediate step in the determination of the required scan MDC. The use of an area factor is not necessary if $DCGL_{EMC}$ is tabulated directly as a function of the area of radioactive material. To simplify the determination of the required scan MDC, the use of the area factor as an intermediate calculation is not included in this revision of MARSSIM. The area factor can still be used if the ratio of the $DCGL_{EMC}$ to the $DCGL_W$ is known and will produce the same results as the approach described in the current revision of MARSSIM.

5.3.5.2 Calculate the Required Grid Spacing and Number of Data Points

If the actual scan MDC is greater than the required scan MDC (i.e., the available scan detection capability is not sufficient to detect small areas of elevated activity), then it is necessary to calculate the $DCGL_{EMC}$ that corresponds to the actual scan MDC using **Equation 5-6.**

$$DCGL_{EMC} = \text{Scan MDC (actual)} \quad (5\text{-}6)$$

The size of the area of elevated activity (A_{EA}) that corresponds to this $DCGL_{EMC}$ is then obtained from specific regulatory agency guidance. The required number of data points for assessing

[7] The area factor, A_m, is defined as the ratio of the $DCGL_{EMC}$ to the $DCGL_W$ as a function of the grid area and relates the required scan MDC to the $DCGL_W$ using the equation: Scan MDC (required) $= A_m \times DCGL_W$.

small areas of elevated activity (n_{EA}) can then be determined by dividing the area of elevated activity (A_{EA}) into the survey unit area using **Equation 5-7.**

$$n_{EA} = \frac{A \text{ (survey unit)}}{A_{EA} \text{ (grid unit)}} \tag{5-7}$$

The calculated number of measurement or sampling locations, n_{EA}, is used to determine a revised spacing, L_{EA}, of the systematic pattern, using **Equations 5-8 and 5-9.**

$$L_{EA} = \sqrt{\frac{A \text{ (survey unit)}}{0.866\, n_{EA}}} \text{ for a triangular grid} \tag{5-8}$$

$$L_{EA} = \sqrt{\frac{A \text{ (survey unit)}}{n_{EA}}} \text{ for a rectangular grid} \tag{5-9}$$

The distance between measurement/sampling locations should generally be rounded *down* to the nearest distance that can be conveniently measured in the field. This value of L_{EA} is then used to determine the measurement locations as described in **Section 5.3.7.** The Sign, WRS, and quantile tests are performed using the larger number of data points, n_{EA}. **Figure 5.6** provides a concise overview of the procedure used to identify data needs for the assessment of small areas of elevated activity.

If residual radioactive material is found in an isolated area of elevated activity in addition to residual radioactive material distributed relatively uniformly across the survey unit, the information in **Section 8.6.2** can be used to ensure that the total dose or risk does not exceed the release criteria. If there is more than one area of elevated activity, a conservative method is to include a separate term in the formula for each; however, this method may violate assumptions used in the pathway modeling process if adjustments are not made to the modeling. Specifically, if a receptor is assumed to be located directly above one area of elevated activity for the full occupancy period, that same receptor cannot realistically also be assumed to be located directly above a separate area of elevated activity for the full occupancy period associated with the exposure scenario[8]. As an alternative, the dose or risk due to the actual residual radioactive material can be modeled if there is an appropriate exposure pathway model available. Note that these considerations generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical tests may become unreasonably large. In this situation, evaluate the survey objectives and considerations. These considerations may include the survey design and measurement methodology, exposure

[8] By default, RESRAD assumes that the receptor spends 50 percent of the time indoors and 25 percent of his time outdoors; without further adjustment, and if two areas are considered, the receptor would spent 100 percent of the time indoors and another 50 percent of the time outdoors for a total time of 150 percent of what would typically be assumed for the exposure scenario.

pathway modeling assumptions and parameter values used to determine the DCGLs, HSA conclusions concerning source terms and radionuclide distributions, and the results of scoping and characterization surveys. In most cases, the result of this evaluation is not expected to justify an unreasonably large number of measurements. **Example 7** provides an example of how to determine whether additional data points are required to ensure the actual scan MDC is less than or equal to the required scan MDC.

Example 7: Example Determination Whether Additional Data Points Are Required

A Class 1 land area survey unit of 1,500 square meters (m^2) is potentially affected by residual radioactive material consisting of cobalt-60 (^{60}Co). The wide-area derived concentration guideline level value for ^{60}Co is 110 becquerels/kilogram (Bq/kg; 3 picocuries/gram [pCi/g]), and the scan detection capability for this radionuclide has been determined to be 150 Bq/kg (4 pCi/g). The table below provides the derived concentration guideline level obtained using the Elevated Measurement Comparison for different grid areas:

Grid Area (m^2)	$DCGL_{EMC}$ (Bq/kg)
1	1,070
3	480
10	230
30	160
100	130
300	120
1,000	120
3,000	110
10,000	110

Abbreviations: m = meter; $DCGL_{EMC}$ = derived concentration guideline level obtained using the Elevated Minimum Comparison; Bq = becquerel; kg = kilogram.

Calculations indicate the number of data points needed for statistical testing is 27. The distance between measurement locations for this number of data points and the given land area is 8 m, as illustrated in the application of **Equation 5-1:**

$$L = \sqrt{\frac{A \text{ (survey unit)}}{0.866\, n}} = \sqrt{\frac{1{,}500 \text{ m}^2}{0.866 \times 27}} = 8.0 \text{ m for a triangular grid}$$

The grid area encompassed by a triangular sampling pattern of 8 m is approximately 55.4 m^2 as calculated using **Equation 5-3:**

$$A \text{ (grid area)} = 0.866\, L^2 = 0.866\, (8.0 \text{ m})^2 = 55.4 \text{ m}^2$$

The $DCGL_{EMC}$ for a grid area of 55.4 m^2 is determined by interpolation to be 150 Bq/kg:

$$160\ \text{Bq/kg} + \left(\frac{55.4\ \text{m}^2 - 30\ \text{m}^2}{100\ \text{m}^2 - 30\ \text{m}^2}\right)(130\ \text{Bq/kg} - 160\ \text{Bq/kg}) = 150\ \text{Bq/kg}$$

The acceptable minimum detectable concentration (MDC) of the scan procedure needed to detect an area of elevated activity in a 55.4 m^2 area is therefore given by **Equation 5-5:**

$$\text{Scan MDC (required)} = \text{DCGL}_{\text{EMC}} = 150\ \text{Bq/kg}$$

Because the detection capability of the procedure to be used (150 Bq/kg) is equal to or less than the required Scan MDC, no additional data points are needed to demonstrate compliance with the elevated measurement comparison criteria.

Example 8 provides another example of how to determine if additional data points are required to ensure the actual scan MDC is less than or equal to the required scan MDC, including how to calculate the number of required data points when the actual scan MDC is greater than the required scan MDC.

Example 8: Example Determination Whether Additional Data Points Are Required

A Class 1 land area survey unit of 1,500 square meters (m^2) is potentially affected by residual radioactive material consisting of ^{60}Co. The wide-area derived concentration guideline level for cobalt-60 (^{60}Co) is 110 becquerels/kilogram (Bq/kg; 3 picocuries/gram [pCi/g]). The table below provides the derived concentration guideline level obtained using the Elevated Measurement Comparison for different grid areas:

Grid Area (m^2)	$DCGL_{EMC}$ (Bq/kg)
1	1,070
3	480
10	230
30	160
100	130
300	120
1,000	120
3,000	110
10,000	110

Abbreviations: m = meter; $DCGL_{EMC}$ = derived concentration guideline level obtained using the Elevated Minimum Comparison; Bq = becquerel; kg = kilogram.

In contrast to **Example 7,** the scan detection capability for this radionuclide has been determined to be 170 Bq/kg (4.6 pCi/g). Calculations indicate the number of data points needed for statistical testing is 15. The distance between measurement locations for this number of data points and the given land area is 10 m, as illustrated in the application of **Equation 5-1:**

$$L = \sqrt{\frac{A\ \text{(survey unit)}}{0.866\ n}} = \sqrt{\frac{1{,}500\ \text{m}^2}{0.866 \times 15}} = 10.7\ \text{m for a triangular grid}$$

The grid area encompassed by a triangular sampling pattern of 10 m is approximately 86.6 m^2, as calculated using **Equation 5-3:**

$$A\ \text{(grid area)} = 0.866\ L^2 = 0.866\ (10.7\ \text{m})^2 = 99.1\ \text{m}^2$$

The $DCGL_{EMC}$ for a grid area of 99.1 m^2 is determined by interpolation to be 130 Bq/kg:

$$160\ \text{Bq/kg} + \frac{99.1\ \text{m}^2 - 30\ \text{m}^2}{100\ \text{m}^2 - 30\ \text{m}^2}(130\ \text{Bq/kg} - 160\ \text{Bq/kg}) = 130\ \text{Bq/kg}$$

The required scan minimum detectable concentration (MDC) for that grid area is therefore also 130 Bq/kg:

$$\text{Scan MDC (required)} = \text{DCGL}_{\text{EMC}} = 130\ \text{Bq/kg}$$

Because the actual scan MDC of the procedure to be used (170 Bq/kg) is greater than the required scan MDC, the data points obtained for the statistical testing may not be sufficient to demonstrate compliance using the elevated measurement comparison. The grid area corresponding to a $DCGL_{EMC}$ of 170 Bq/kg is determined by interpolation to be 27 m^2:

$$30\ \text{m}^2 + \left(\frac{170\ \text{Bq/kg} - 160\ \text{Bq/kg}}{230\ \text{Bq/kg} - 160\ \text{Bq/kg}}\right)\left(10\ \text{m}^2 - 30\ \text{m}^2\right) = 27\ \text{m}^2$$

The number of samples required to account for areas of elevated activity (n_{EA}) is calculated using **Equation 5-7:**

$$n_{EA} = \frac{A\text{ (survey unit)}}{A_{EA}\text{ (grid unit)}} = \frac{1{,}500\text{ m}^2}{27\text{ m}^2} = 56\text{ measurements}$$

The triangular grid spacing required to account for areas of elevated activity (L_{EA}) is calculated using **Equation 5-8:**

$$L_{EA} = \sqrt{\frac{A\text{ (survey unit)}}{0.866\, n_{EA}}} = \sqrt{\frac{1500\text{ m}^2}{0.866 \times 56}} = 5.5\text{ m for a triangular grid}$$

The number of data points required increased from 15 to 56, and the grid spacing decreased from 10.7 m to 5.5 m.

5.3.6 Determining the Scan Area

The use of direct measurements or sampling in combination with separate scans of the area is necessary when the scanning instrument and technique have sufficient detection capability to identify areas of elevated concentrations of radioactive material, but insufficient detection capability to quantify the average concentration of radioactive material in the survey unit. In instances where the measurement method has sufficient detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material, a scan-only survey can be considered. Similar in principle to a scan-only survey is a series of direct measurements that have the detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material.

5.3.6.1 Scan-Only Surveys

During scan-only surveys, a large number of discrete scan measurements are taken and analyzed; this approach is greatly facilitated by the use of scan systems that automatically record scan measurements and location. These systems typically utilize GPS or other position determinations in conjunction with radiological measurements, with both the radiological and locational data being automatically recorded. These techniques permit the convenient accumulation, storage, and display of hundreds or thousands of scan data points for a survey unit.

Scan-only surveys will likely require site-specific validation samples to ensure that the method can reliably detect concentrations at the $DCGL_W$ under the conditions expected at the site. This validation can be accomplished at any point in the RSSI process (post-remediation, if remediation is performed). Consult with your regulator for guidance on the level of effort needed to validate scan-only surveys.

Scan-only surveys generally cover a much larger portion of the survey unit than traditional discrete sampling or measurement. A similar concept is found in a series of direct measurements, where the field of view of the direct measurements covers a statistically significant portion of the survey unit (i.e., 10 percent or more).[9]

However, a scan-only approach should be used only for circumstances where the measurement method has sufficient detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material. To ensure that this is the case, the scan MDC (for the scan system) should be less than 50 percent of the $DCGL_W$. The scan-only methodology will require validation, which likely requires collecting some percentage of samples for laboratory analysis to compare with results from the same location. Other MQOs should be met as well, including the MQO for measurement method uncertainty at the $DCGL_W$.

In general, when utilizing a scan-only survey approach, the anticipated measurement method uncertainty is expected to be higher than traditional scan and sampling procedures. Therefore, a maximum scan coverage (e.g., 100 percent) should always be achieved in Class 1 areas when utilizing this approach. The percentages of Class 2 or Class 3 areas that should be scanned is 10 percent or the result using **Equation 5-10,** whichever is larger:

$$\text{Scan Area} = \frac{(10 - \Delta/\sigma)}{10} \times 100\% \tag{5-10}$$

Scanning a greater percentage than that calculated above is always acceptable. When performing scan-only surveys, the following must be considered and addressed in survey plans:

- Perform quality control procedures, such as evaluating measurement method uncertainty by performing replicate scans over a prescribed portion of the site and performing reference standard checks at a prescribed frequency.
- Evaluate the extent to which alpha and beta radiation in the surface may impact scan-only survey results.
- Determine the number and type of validation samples to establish a correlation between scan-only and laboratory results.

5.3.6.2 Scanning and Sampling

When scanning is done in combination with direct measurements or sampling, the scanning instrument and technique must have detection capabilities to meet the MQOs to identify areas of elevated concentrations of radioactive material. This differs from the requirements for scan-only surveys that must have detection capabilities to both identify areas of elevated concentrations of radioactive material and quantify the average concentration of radioactive material in the survey unit.

[9] In the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) Manual, a direct measurement survey covering a statistically significant portion of the survey unit was referred to as an “in situ” survey type; in MARSSIM, this survey type is incorporated into scan-only surveys.

The percentage of the area that needs to be scanned depends on the classification of the survey unit. For Class 1 survey units, 100 percent of the area should be scanned. The percentages of Class 2 or Class 3 areas are scanned according to **Equation 5-10.** Scanning a greater percentage than that calculated above for Class 2 or Class 3 areas is always acceptable.

The detection capability for scanning techniques used in Class 2 and Class 3 areas is not tied to the area between measurement locations like they are in a Class 1 area (see **Section 5.3.5**). The scanning techniques selected should represent the best reasonable effort based on the survey objectives. Structure surfaces are generally scanned for alpha-, beta-, and gamma-emitting radionuclides. In contrast, scanning for alpha or beta emitters for land area survey units is generally not considered effective because of problems with attenuation and media interferences. If one can reasonably expect to find any residual radioactive material, it is prudent to perform a judgment scanning survey.

5.3.7 Determining Survey Locations

Like the required scanning percentages, the determination of discrete survey locations for the direct measurements or the collection of samples depends on the classification of the survey unit. The method for determining survey locations for land areas and structure surfaces is described below.

5.3.7.1 Survey Locations for Discrete Measurements and Samples

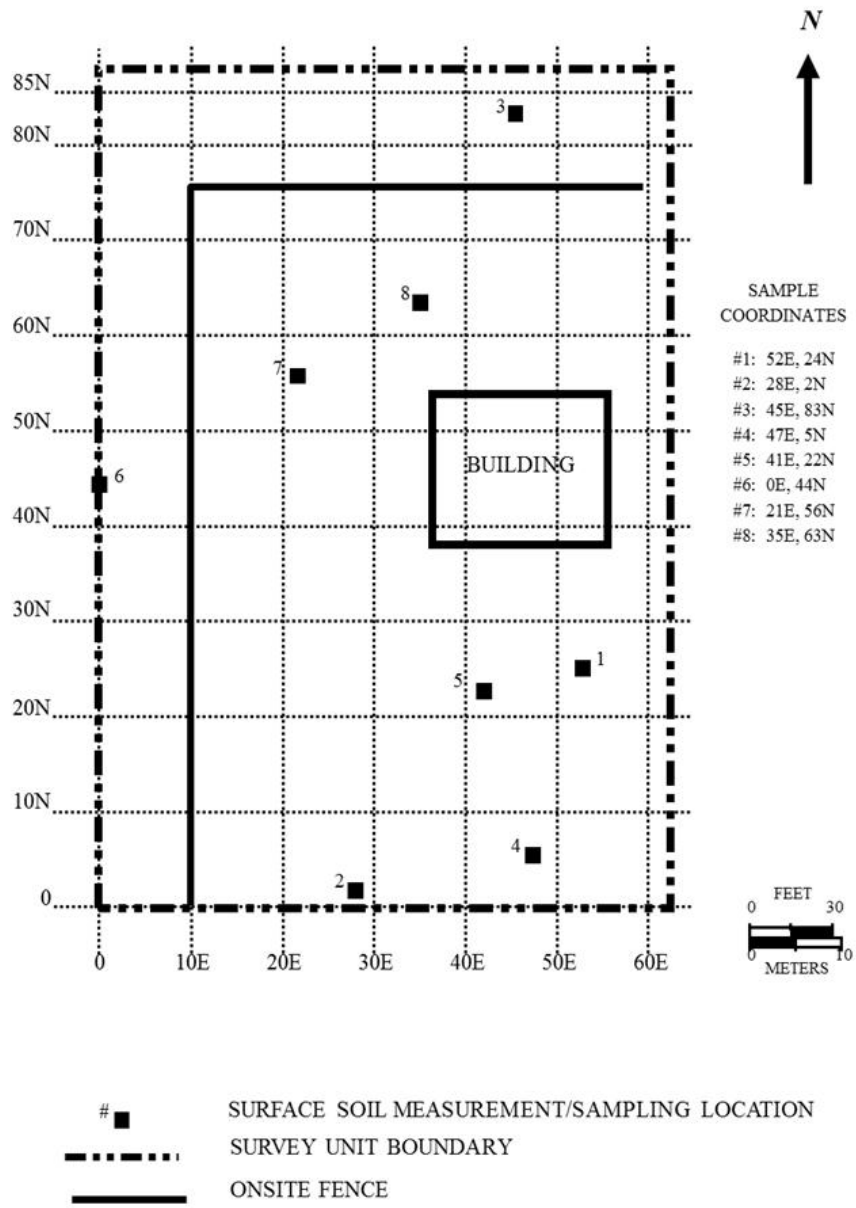
A scale drawing of the survey unit is prepared, along with the overlying planar reference coordinate system or grid system. Any location within the survey area is thus identifiable by a unique set of coordinates. The maximum length, X, and width, Y, dimensions of the survey unit are then determined. Identifying and documenting a specific location for each measurement performed is an important part of an FSS to ensure that measurements can be reproduced if necessary. The reference coordinate system described in **Section 4.9.5** provides a method for relating measurements to a specific location within a survey unit. Systems utilizing GPS technology and data logging software are widely available to identify and track survey dimensions, sampling locations, and locations associated with specific scan results.

<u>Land Areas</u>

Measurements and samples in Class 3 survey units and reference areas are usually taken at random locations. These locations are determined by generating sets of random numbers (two values, representing the X axis and Y axis distances). Random numbers can be obtained from mathematical tables, including **Table I.11** in **Appendix I,** or generated by calculator or computer. Sufficient sets of numbers will be needed to identify the total number of survey locations established for the survey unit. Each set of random numbers is multiplied by the appropriate survey unit dimension to provide coordinates, relative to the origin of the survey unit reference grid pattern. Coordinates identified in this manner that do not fall within the survey unit area or that cannot be surveyed because of site conditions are replaced with other survey points determined in the same manner. **Example 9** provides an example of a random sampling pattern.

Example 9: Random Sampling Pattern

In this example, eight data points were identified using the appropriate table (Table 5.2 or Table 5.3). The locations of these points were determined using the table of random numbers found in **Appendix I, Table I.11.**



Class 2 areas are surveyed on a random-start systematic pattern. The number of calculated survey locations, n, based on the statistical tests, is used to determine the spacing, L, of a systematic pattern as specified in **Equations 5-1 and 5-2.**

After L is determined, a random start location is identified, as described previously, for a survey pattern starting location. Beginning at the random start location, a row of points is identified parallel to the X-axis at intervals of L.

For a triangular grid, a second row of points is then developed, parallel to the first row, at a distance of $0.866 \times L$ from the first row. Survey points along that second row are midway (on the X-axis) between the points on the first row. This process is repeated to identify a pattern of survey locations throughout the affected survey unit. If identified points fall outside the survey unit or at locations that cannot be surveyed, additional points are determined using the random process described above until the desired total number of points is identified.

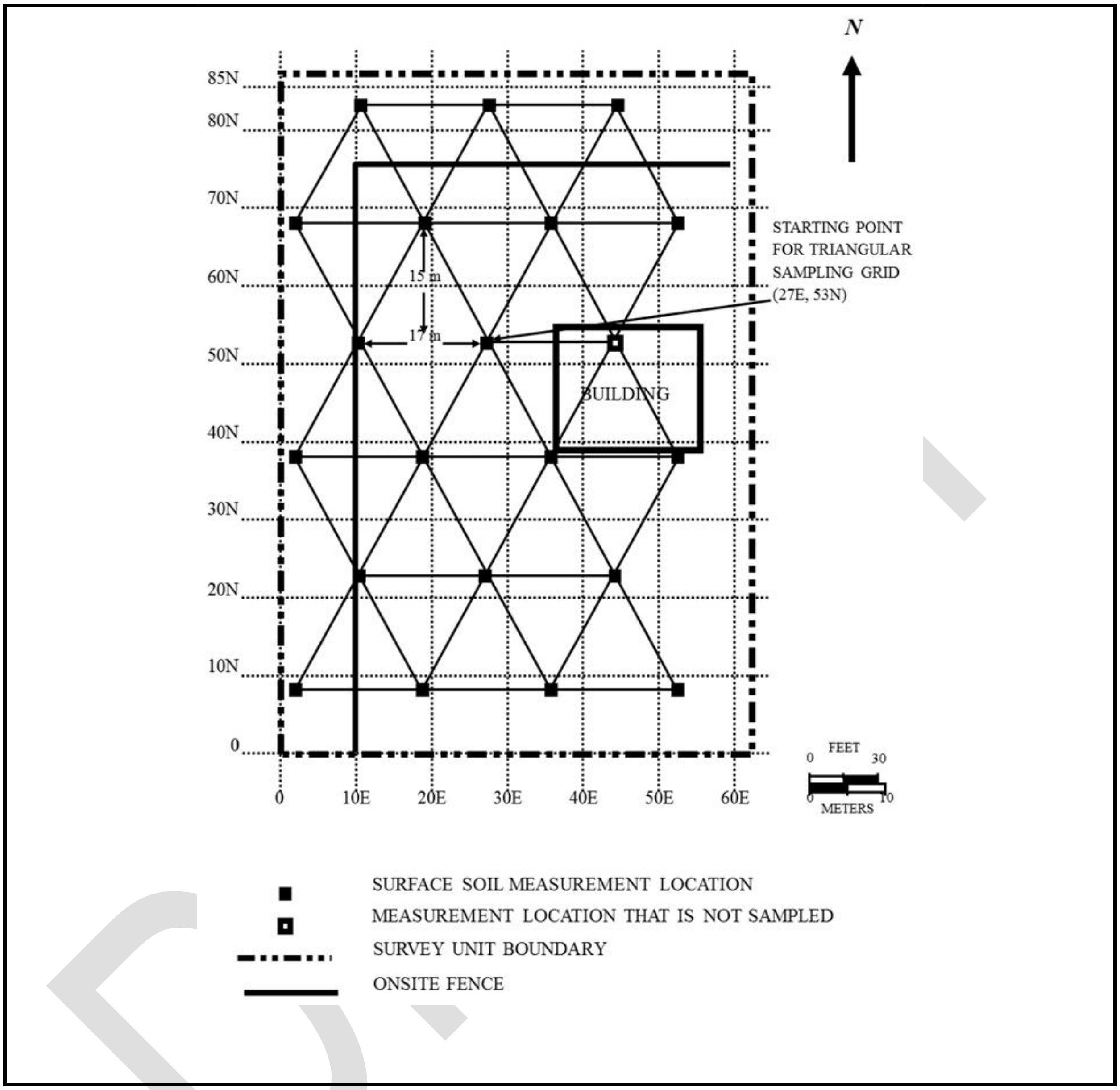
For Class 1 areas, a systematic pattern having dimensions determined in **Section 5.3.6** is installed on the survey unit. The starting point for this pattern is selected at random, as described above for Class 2 areas. The same process as described above for Class 2 areas applies to Class 1. **Example 10** provides an illustration of a triangular systematic pattern in an outdoor Class 2 survey unit.

Example 10: Illustration of a Triangular Systematic Pattern in an Outdoor Class 2 Survey Unit

An example of a triangular survey pattern is shown below. In this example, the statistical test calculations estimate 20 samples (**Table 5.3,** $\alpha = 0.01$, $\beta = 0.05$, $\Delta/\sigma > 3.0$). The random-start coordinates were 27E, 53N. The grid spacing (L) was calculated using **Equation 5-3.**

$$L = \sqrt{\frac{5{,}100\ \text{m}^2}{0.866 \times 20}} = 17\ \text{m}$$

Two points were identified on a row parallel to the X-axis, each 17 meters (m) from the starting point. The subsequent rows were positioned $0.866 \times L$, or 15 m, from the initial row. This random-start triangular sampling process resulted in 21 sampling locations, one of which was difficult to assess because of the building location, which yields the desired number of data points.



Structure Surfaces

All structure surfaces for a specific survey unit are included on a single reference grid system for purposes of identifying survey locations. The same methods as described above for land areas are then used to locate survey points for all classifications of areas.

In addition to the survey locations identified for statistical evaluations and elevated measurement comparisons, data may be obtained from judgment locations that are selected because of unusual appearance, location relative to areas affected by residual radioactive material, high potential for residual radioactive material, general supplemental information, etc.

Data points selected based on professional judgment are not included with the data points from the random-start triangular grid for statistical evaluations; instead they are compared individually with the established DCGLs and conditions. Measurement locations selected on the basis of professional judgment cannot be considered representative of the survey unit, a necessary condition if the statistical tests described in **Chapter 8** are used.

5.3.7.2 Survey Locations for Scans

Like the determination of the location of discrete measurements or samples, the determination of survey locations for scans depends on the classification of the survey unit.

Class 1 Areas

For Class 1 areas, scans are intended to detect small areas of elevated activity that are not detected by the measurements using the systematic pattern (**Section 5.3.5**). This is the reason for recommending 100 percent coverage for the scanning survey. One-hundred percent coverage means that the entire accessible surface area of the survey unit is covered by the field of view of the scanning instrument. If the field of view is 2 m wide, the survey instrument can be moved along parallel paths 2 m apart to provide 100 percent coverage. If the field of view of the detector is 5 centimeters (cm), the parallel paths should be 5 cm apart.

Class 2 Areas

Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgment scanning surveys focus on the portions of the survey unit with the highest probability for areas of elevated activity. If the entire survey unit has an equal probability for areas of elevated activity, or the judgment scans don’t cover at the required scanning percentage of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 Areas

Class 3 areas may be uniformly scanned for radiation emitted from the radionuclides of interest, or the scanning may be performed in areas with the greatest potential for residual radioactive material (e.g., corners, ditches, and drains) based on professional judgment and the objectives of the survey. Such recommendations are typically provided by a health physics professional with radiation survey experience. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area. In some cases, a combination of these approaches may be the most appropriate.

5.3.8 Determining Investigation Levels

An important aspect of the FSS is the design and implementation of investigation levels. Investigation levels are radionuclide-specific levels of radioactive material used to indicate when additional investigations may be necessary. Investigation levels also serve as a quality control check to determine when a measurement process begins to get out of control. For example, a measurement that exceeds the investigation level may indicate that the survey unit has been improperly classified (see **Section 4.6**), or it may indicate a failing instrument. Typically, investigation levels are set as part of the DQO process.

When an investigation level is exceeded, the first step is to confirm that the initial measurement or sample actually exceeds the particular investigation level. This may involve taking further measurements to determine that the area and level of the elevated residual radioactive material are such that the resulting dose or risk meets the release criteria. Rather than—or in addition to—taking further measurements, the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs and area factors, as well as the consistency of the results obtained with the HSA and the scoping, characterization, and RAS surveys. Depending on the results of the investigation actions, the survey unit may require reclassification, remediation, or resurvey. **Table 5.4** illustrates an example of how investigation levels can be developed.

Table 5.4: Example FSS Investigation Levels

Survey Unit Classification	Flag Direct Measurement or Sample Result When…	Flag Scanning Measurement Result When…
Class 1	> $DCGL_{EMC}$ or > $DCGL_W$ and > a statistical parameter-based value	> $DCGL_{EMC}$ for the area bounded by four adjacent systematic grid measurement points to determine the $DCGL_{EMC}$ (when a traditional MARSSIM approach is utilized), or for the area bounded by an acceptable elevated area size (when a scan-only approach is utilized)
Class 2	> $DCGL_W$	> $DCGL_W$ or > scan MDC
Class 3	> fraction of $DCGL_W$	> $DCGL_W$ or > scan MDC

Abbreviations: $DCGL_{EMC}$ is the derived concentration guideline level (DCGL) determined with the Elevated Measurement Comparison; $DCGL_W$ is the wide-area DCGL.

When determining an investigation level using a statistical-based parameter (e.g., standard deviation) one should consider survey objectives, underlying radionuclide distributions, and an understanding of corresponding types (e.g., normal, lognormal, non-parametric), descriptors (e.g., standard deviation, mean, median), population stratifications (i.e., subgroups), and other prior survey and historical information. For example, a level might be arbitrarily established at the mean + 3*s*, where *s* is the standard deviation of the survey unit, assuming a normal distribution. A higher value might be used if locating discrete sources of higher activity was a primary survey objective. By the time the FSS is conducted, survey units should be defined. Estimates of the mean, variance, and standard deviation of the radionuclide activity levels within the survey units should also be available.

For a Class 1 survey unit, measurements above the $DCGL_W$ are not necessarily unexpected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all of the other discrete measurements. Thus, any discrete measurement that is both above the $DCGL_W$ and above the statistical-based parameter for the measurements should be investigated further. Any measurement, either at a discrete location or from a scan that is above the $DCGL_{EMC}$ should also be flagged for further investigation. When a traditional MARSSIM approach (scanning with direct measurements and/or samples) is utilized, the $DCGL_{EMC}$ should be established for the largest (worst case) potential elevated measurement area (the area bounded by four sampling grid measurement points). This largest potential elevated area is also the survey unit area divided by the number of measurements or samples (for the systematic sampling grid). When a scan-only approach is utilized, it is important that an appropriate size for a potential elevated area and associated $DCGL_{EMC}$ be established as a part of the DQO process and in agreement with the regulator.

In Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the survey design for Class 2 and Class 3 survey units is not driven by the EMC, the scan MDC might exceed the $DCGL_W$. In this case, any indication of residual radioactive material during the scan would warrant further investigation.

When it is not feasible to obtain a scan MDC below the $DCGL_W$, the basis for using the $DCGL_{EMC}$ or an investigation level above the $DCGL_W$ in **Table 5.4** for Class 2 and Class 3 areas may be necessary but should be justified in survey planning documents. For example, where there is high uncertainty in the reported scan MDC, more conservative criteria would be warranted.

Similarly, data quality assessment (DQA) for scanning may warrant a more conservative flag, as would greater uncertainty from HSA or other surveys on the size of potential areas of elevated activity. In some cases, it may even be necessary to agree in advance with the regulatory agency on which site-specific investigation will be used if other than those presented in **Table 5.4.**

Because there is a low expectation for residual radioactive material in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The level selected in these situations should be commensurate with the potential exposures at the site, the radionuclides of concern, and the measurement and scanning methods chosen. This level should be set using the DQO Process during the survey design phase of the Data Life Cycle. In some cases, the user may also wish to follow this procedure for Class 2 and even Class 1 survey units.

5.3.9 Developing an Integrated Survey Strategy

The final step in survey design is to integrate the survey techniques (**Chapter 6**) with the number of measurements and measurement spacing, with the amount of scanning determined earlier in this chapter. This integration, along with the information provided in other portions of this manual, produce an overall strategy for performing the survey. The survey design may consist of scan-only, or a combination of scans with sampling or direct measurements. **Table 5.5** provides a summary of the recommended survey coverage for structures and land areas. This survey coverage for different areas is the subject of this section.

Table 5.5: Recommended Survey Coverage for Structures and Land Areas

Area Classification	Scanning and Direct Measurements and/or Sampling Survey		Scan-Only Survey
	Scanning	Direct Measurements or Samples)	Scanning
Class 1	100%	Number of data points from statistical tests (**Sections 5.3.3 and 5.3.4**); additional measurements may be necessary for small areas of elevated activity (**Section 5.3.5**)	100%
Class 2	10–100% Systematic and Judgment "Scan Area"= $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$	Number of data points from statistical tests (**Sections 5.3.3 and 5.3.4**)	10–100% Systematic and Judgment "Scan Area"= $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$
Class 3	Judgment	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4)	"Scan Area"= $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$ Judgment

Abbreviation: Δ/σ represents the relative shift.

For surveys in which discrete measurements or samples are taken, random measurement patterns are generally used for Class 3 survey units to ensure that the measurements are independent and support the assumptions of the statistical tests. Systematic grids are used for Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision maker to draw conclusions about the size of the potential areas of elevated activity based on the area between measurement locations. The random starting point of the grid provides an unbiased method for obtaining measurement locations to be used in the statistical tests. Class 1 survey units have the highest potential for small areas of elevated activity, so the areas between measurement locations might need to be adjusted to ensure that these areas can be detected by scanning techniques.

MARSSIM allows the use of both sampling (where a sample is collected and sent to an analytical laboratory, on-site or off-site) and direct measurements (fixed measurement taken in the field by an *in situ* gamma spectroscopy or beta scintillation meter, for example.) It is important to consider the required MQOs for the survey and ensure that the measurement method chosen meets those criteria. Some direct measurement methods may not be appropriate for some radionuclides in land areas.

The objectives of the scanning surveys are different. Scanning is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and/or receive additional investigations to determine the concentration, area, and extent of the residual radioactive material.

Scanning measurements can also be used in place of the sampling or direct measurements when the detection capability is sufficient and a large number of discrete scan measurements are taken and analyzed; this approach is greatly facilitated by the use of scan systems that automatically record scan measurements and location. These systems typically utilize GPS or other position determinations in conjunction with radiological measurements, with both the radiological and locational data being automatically recorded. These techniques permit the convenient accumulation, storage, and display of hundreds or thousands of scan data points for a survey unit. However, a scan-only approach should only be used for circumstances where the scan MDC (for the scan system) is less than 50 percent of the $DCGL_W$ and other MQOs, such as requirements for measurement method uncertainty, can be met. For scan-only surveys of Class 2 or Class 3 survey units where the percentage of the area scanned is less than 100 percent, the survey must be designed so that average concentration of radioactive material calculated from the survey data is an unbiased representative estimate of the true mean concentration in the survey unit. In the event the scan-only survey option is feasible for a site or survey unit, the sampling function of the FSS would not be applicable.

In addition to the building and land surface areas described above, there are numerous other locations where measurements and/or sampling may be necessary independent from the FSS. Examples include items of equipment and furnishings, building fixtures, drains, ducts, and piping. Many of these items or locations have both internal and external surfaces with potential residual radioactive material. An approach on conducting or evaluating these types of surveys is contained in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) Manual (NRC 2009), which is a supplement to MARSSIM. Subsurface measurements or sampling may also be necessary.

Special situations may be evaluated by judgment sampling and measurements. Data from such surveys should be compared directly with a limit developed for the specific situation and approved by the regulator.

Quality control measurements are recommended for all surveys, as described in **Sections 4.8, 6.2, and 7.2.** Also, some regulatory programs require removable activity measurements (e.g., DOE requirements in DOE Order 458.1 [DOE 2011c], 10 CFR 835). These additional measurements should be considered during survey planning.

5.3.9.1 Class 1 Areas

For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity above the $DCGL_W$ that are not detected by the measurements using the systematic pattern (**Section 5.3.7**). For this reason, the measurement locations and the number of measurements may need to be adjusted based on the sensitivity of the scanning technique (**Section 5.3.5.1**). This is also the reason for recommending 100 percent coverage for the scanning survey.

As discussed in **Section 5.3.6.1,** scanning techniques can be used in lieu of discrete samples or direct measurements when the scan MDC is less than 50 percent of the $DCGL_W$, and the scan coverage is 100 percent. Note that, in a statistical sense, a scan of 100 percent of a survey unit constitutes a sample of 100 percent of the survey unit. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty.

Locations of direct radiation above an investigation level are identified and evaluated. Results of initial and followup direct measurements and sampling at these locations are recorded and documented in the FSS report. For structure surfaces, measurements of total and (when applicable) removable radioactive material are performed at locations identified by scans and at previously determined locations (**Section 5.3.7**). Soil sampling or direct measurements are performed at locations identified by scans and at previously determined locations (**Section 5.3.7**).

The development of direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that exceed the investigation level. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that both is above the $DCGL_W$ and exceeds a statistical based parameter (e.g., three standard deviations above the mean) should be investigated further (**Section 5.3.8**). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation.

The results of the investigation and any additional remediation that was performed should be included in the FSS report. Data are reviewed as described in **Section 8.2.2,** additional data are collected as necessary, and the final complete data set evaluated as described in **Section 8.3** and **Section 8.4.**

5.3.9.2 Class 2 Areas

Scanning surveys in Class 2 areas are also primarily performed to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the number and location of measurements are not adjusted based on sensitivity of the scanning technique, and scanning is performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity based on the conceptual site model developed and refined from **Section 3.6.4.** In other words, the farther the expected residual radioactive material in the survey unit is from the $DCGL_W$ in units of uncertainty (the larger the Δ/σ), the less scanning is needed. Surface scans are performed over 10–100 percent of structure surfaces or open land surfaces, as calculated in **Equation 5-10.** A larger portion of the survey unit would be scanned in Class 2 survey units that have residual radioactive material close to the release criteria, but for survey units that are closer to background scanning, a smaller portion of the survey unit may be appropriate.

As discussed in **Section 5.3.6.1,** scanning techniques for Class 2 survey units might be used in lieu of discrete samples or direct measurements when the scan MDC is less than 50 percent of the $DCGL_W$ and the scan coverage is between 10 and 100 percent. Note that, in a statistical sense, a scan of 10–100 percent of a survey unit constitutes a sample of 10–100 percent of the survey unit. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty. The area scanned should be selected in an unbiased manner.

Locations of scanning survey results greater than the investigation level are identified and investigated. If small areas of elevated activity are confirmed by this investigation, all or part of the survey unit should be reclassified as Class 1 and the survey strategy for that survey unit redesigned accordingly. Investigation levels for Class 2 areas should establish levels for investigation of individual measurements close to but less than the $DCGL_W$. Investigation levels for Class 2 areas should also establish a course of action for individual measurements that exceed or approach the $DCGL_W$. The results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1 should be included in the FSS report.

The results of the investigation should be included in the FSS report. Data are reviewed as described in **Section 8.2.2,** additional data are collected as necessary, and the final complete data set evaluated as described in **Section 8.3** and **Section 8.4.**

5.3.9.3 Class 3 Areas

Class 3 areas have the lowest potential for areas of elevated activity. Locations exceeding the scanning survey investigation level should be flagged for further investigation. If the presence of residual radioactive material occurring at concentrations greater than a small fraction of the $DCGL_W$ is identified, reevaluation of the classification of the survey unit should be performed.

As discussed in **Section 5.3.6.1,** scanning techniques for Class 3 survey units can be used in lieu of sampling and statistical testing when the scan MDC is less than 50 percent of the $DCGL_W$. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty.

Sampling or direct measurements are performed at randomly selected locations (**Section 5.3.7**). Survey results are tested for compliance with DCGLs, and additional data are collected and tested as necessary. For structure surfaces, measurements of total and (when applicable) removable radioactive material are performed at the locations identified by the scans and at the randomly selected locations that are chosen in accordance with **Section 5.3.7.**

Investigation levels for Class 3 areas should be established to identify areas of elevated activity that may indicate the presence of residual radioactive material. Because there is a low expectation for residual radioactive material in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The investigation level selected will depend on the site, the radionuclides of concern, and the measurement and scanning methods chosen. This level should be commensurate with the potential exposures and should be determined using the DQO Process during survey planning. In some cases, the user may wish to follow this procedure for Class 2 survey units.

The data are tested relative to the preestablished criteria. If additional data are needed, they should be collected and evaluated as part of the entire data set. Identification of residual radioactive material suggests that the area may be incorrectly classified. If so, a reevaluation of the Class 3 area classification should be performed and, if appropriate, all or part of the survey unit should be resurveyed as a Class 1 or Class 2 area.

The results of the investigation of the measurements that exceed the investigation level and the basis for reclassifying all or part of the survey unit as Class 1 or Class 2 should be included in the FSS report.

As discussed in **Section 5.3.8,** investigation levels are determined and used to indicate when additional investigations may be necessary or when a measurement process begins to get out of control. The results of all investigations should be documented in the FSS report, including the results of scan surveys that may have potentially identified areas of elevated direct radiation.

5.3.10 Evaluating Survey Results

Chapter 8 describes detailed procedures for evaluating survey results. After data are converted to the same units as the DCGL, the process of comparing the results to the DCGLs and objectives begins. Individual measurements and sample concentrations are first compared to DCGL levels for evidence of small areas of elevated activity and not to determine if reclassification is necessary. Additional data or additional remediation and resurveying may be necessary. Data are then evaluated using statistical methods to determine if they exceed the release criteria. If the release criteria have been exceeded or if results indicate the need for additional data points, appropriate further actions will be determined by the site management and the regulatory agency. The scope of further actions should be agreed upon and developed as part of the DQO Process before the survey begins (**Appendix D**). Finally, the results of the survey are compared with the DQOs established during the planning phase of the project. Note that DQOs may identify a need for a report of the evaluation of removable radioactive material resulting from the analysis of smears. These results may be used to satisfy regulatory requirements or to evaluate the need for additional ALARA procedures.

5.3.11 Documentation

Documentation of the FSS should provide a complete and unambiguous record of the radiological status of the survey unit relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent re-creation and evaluation at some future time. Much of the information in the FSS report will be available from other site remediation documents; however, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. The report should be independently reviewed (see **Section 8.7**) and should be approved by a designated person (or persons) who are capable of evaluating all aspects of the report before release, publication, or distribution. **Example 11** includes an example of a final status survey checklist, including survey preparations, survey design, conduct of surveys, and evaluation of survey results.

Example 11: Example Final Status Survey Checklist

Survey Preparations

_____ Ensure that residual radioactive material limits have been determined for the radionuclides present at the site, typically performed during earlier surveys associated with the release process.

_____ Identify the radionuclides of concern. Determine whether the radionuclides of concern exist in background.

_____ Segregate the site into Class 1, Class 2, and Class 3 areas, based on the presence of potential residual radioactive material.

_____ Identify the survey units.

_____ Select representative reference (background) areas for both indoor and outdoor survey areas. Reference areas are selected from non-impacted areas and—

    _____ are free of residual radioactive material from site operations

    _____ exhibit similar physical, chemical, and biological characteristics of the survey area

    _____ have similar construction, but have no history of radioactive operations

_____ Select measurement method, based on the required Measurement Quality Objectives (MQOs).

    _____ Determine minimum detectable concentrations (MDCs; select instrumentation based on the radionuclides present) and match between instrumentation and derived concentration guideline levels (DCGLs)—the selected instruments should be capable of detecting the radionuclides of concern at less than 50 percent of the DCGLs.

    _____ Determine measurement method uncertainty and compared to required measurement method uncertainty.

    _____ Determine ruggedness, specificity, and range and compare to requirements.

_____ Prepare the area if necessary—clear and provide access to areas to be surveyed.

_____ Establish reference coordinate systems (as appropriate).

Survey Design

_____ Enumerate Data Quality Objectives (DQOs) and MQOs: State the objective of the survey, state the null and alternative hypotheses, specify the acceptable decision error rates (Type I [α] and Type II [β]) and requirements for MDC, measurement method uncertainty, ruggedness, specificity, and range.

_____ Specify sample collection and analysis procedures.

_____ Determine numbers of data points for statistical tests, depending on whether the radionuclide is present in background. Alternatively, design a scan-only survey using automated equipment recording both data and location.

- _____ Specify the number of samples/measurements to be obtained, if applicable.
- _____ Evaluate the power of the statistical tests to determine whether the number of samples is appropriate.
- _____ Ensure that the sample size is sufficient for detecting areas of elevated activity.
- _____ Add additional samples/measurements for quality control and to allow for possible loss.
- _____ Establish the percentage of the survey unit to be surveyed by scanning.

_____ Specify sampling locations, if appropriate.

_____ Specify areas and percentage of areas subject to scanning survey.

_____ Provide information on the survey measurement method.

_____ Specify methods of data reduction and comparison of survey units to reference areas.

_____ Provide quality control procedures and Quality Assurance Project Plan (QAPP) for ensuring validity of survey data:

- _____ properly calibrated instrumentation
- _____ necessary replicate, reference, and blank measurements
- _____ comparison of field measurement results to laboratory sample analyses

_____ Document the survey plan (e.g., QAPP, standard operating procedures [SOPs], etc.)

Conducting Surveys

_____ Perform reference (background) area measurements and sampling.

_____ Conduct survey activities:

- _____ Perform surface scans of the Class 1, Class 2, and Class 3 areas.

    ______ Conduct surface activity measurements and sampling at previously selected sampling locations, if applicable.

    ______ Conduct additional direct measurements and sampling at locations based on professional judgment.

______ Perform and document any necessary investigation activities, including survey unit reclassification, remediation, and resurvey.

______ Document measurement and sample locations; provide information on measurement system MDC and measurement method uncertainty.

______ Document any observations, abnormalities, and deviations from the QAPP or SOPs.

Evaluating Survey Results

______ Review DQOs and MQOs.

______ Perform data reduction on the survey results.

______ Conduct a preliminary data review.

______ Select the statistical test(s).

______ Verify the assumptions of statistical tests.

______ Compare survey results with regulatory DCGLs:

    ______ Conduct an elevated measurement comparison, if appropriate.

    ______ Determine the area-weighted average, if appropriate.

    ______ Conduct Wilcoxon Rank Sum or Sign tests, if appropriate.

    ______ Conduct quantile test or retrospective power analysis, if appropriate.

    ______ Conduct Upper Level Comparison, if appropriate.

______ Prepare FSS report.

______ Obtain an independent review of the report.

6 FIELD MEASUREMENT METHODS AND INSTRUMENTATION

6.1 Introduction

“Measurement” is used in the Multi-Agency Radiation Survey and Investigation Manual (MARSSIM) to mean (1) the act of using a detector to determine the level or quantity of radioactive material on a surface or in a sample of material removed from a medium being evaluated, or (2) the quantity obtained by the act of measuring.[1] Three methods are available for collecting radiation data while performing a survey: direct measurements, scanning, and sampling. This chapter discusses direct measurement methods, scanning, and instrumentation. The collection and analysis of media samples are presented in **Chapter 7.** Information on the operation and use of individual field and laboratory instruments is provided in **Appendix H.**

Total surface activities, removable surface activities, and radionuclide concentrations in various environmental media are the radiological parameters typically determined using field measurements and laboratory analyses. Certain radionuclides or radionuclide mixtures may necessitate the measurement of alpha, beta, and gamma radiations. In addition to assessing each survey unit as a whole, any small areas of elevated activity should be identified to the extent practicable and their extent and activities determined. Due to numerous detector requirements, multiple measurement methods (survey technique and instrument combination) may be needed to adequately measure all of the parameters required to satisfy the release criteria or meet all the objectives of a survey.

Selecting an appropriate measurement method requires evaluation of both Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs). Instruments should be stable and reliable under the environmental and physical conditions where they are used, and their physical characteristics (size and weight) should be compatible with the intended application. Numerous commercial firms offer a wide variety of instruments appropriate for the radiation measurements described in this manual. These firms can provide thorough information regarding capabilities, operating characteristics, limitations, etc., of specific equipment.

If the available field measurement methods do not achieve the MQOs, laboratory methods discussed in **Chapter 7** are typically used. There are certain radionuclides that are difficult to measure at some derived concentration guideline levels (DCGLs) typically encountered *in situ* using current state-of-the-art instrumentation and techniques because of the types, energies, and abundances of their radiations. Examples of such radionuclides include such very low-energy, pure beta emitters as tritium (^{3}H) and nickel-63 (^{63}Ni) and low-energy photon emitters as iron-55 (^{55}Fe) and iodine-125 (^{125}I). Pure alpha emitters dispersed in soil or covered with some absorbing layer may not be measurable, because alpha radiation will not penetrate through the media or covering to reach the detector. A common example of such a condition would be thorium-230 (^{230}Th) surface contamination covered by paint, dust, oil, or moisture. The U.S. Nuclear Regulatory Commission (NRC) report NUREG-1507 (NRC 1997a) provides information on the extent to which these surface conditions may affect detection capability. In

[1] MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

such circumstances, the survey design will usually rely on sampling and laboratory analysis to measure residual activity levels. **Appendix E** provides information on using a ranked set sampling procedure to reduce sampling requirements for hard-to-detect radionuclides.

Section 6.2 includes a discussion of DQOs and MQOs. Two important MQOs, detection capability and measurement uncertainty, are covered in more detail in **Sections 6.3 and 6.4,** respectively. **Section 6.5** discusses the selection of a service provider to perform field data collection activities. The selection of a measurement method is discussed in **Section 6.6. Section 6.7** includes information on the data conversion needed to make comparisons with the applicable DCGLs. Radon measurements are covered in **Section 6.8. Section 6.9** includes information about special equipment.

6.2 Data Quality Objectives

The third step of the DQO Process (EPA 2006c) involves identifying the data needs for a survey. One decision that can be made at this step is the selection of field measurement methods that meet the MQOs or determining that sample collection and subsequent laboratory analysis is required.

6.2.1 Identifying Data Needs for Field Measurement Methods

The decision maker and the survey planning team need to identify the data needs for the survey being performed, including the following:

- type of measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.5**)
- number of direct measurements to be performed (**Sections 5.3.3–5.3.4**)
- area of survey coverage for surface scans based on survey unit classification (**Section 5.3.6**)
- type and frequency of field QC measurements to be performed (**Section 4.8**)
- standard operating procedures (SOPs) to be followed or developed (**Chapter 6**)
- measurement method uncertainties (**Section 6.4**)
- detection capabilities for each radionuclide of interest (**Section 6.3**)
- cost of the measurement methods being evaluated (both cost per measurement and total cost) (**Appendix H**)
- necessary turnaround time (a potential health and safety concern for situations involving excavations)
- specific background for the radionuclide(s) of interest (**Section 4.5**)

- DCGL for each radionuclide of interest (**Section 4.10**)
- measurement documentation requirements
- measurement tracking requirements

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process may be needed to identify all of the data needs. Consulting with a health physicist or radiochemist may be necessary to properly evaluate the information before deciding between field measurement methods or sampling followed by laboratory analytical methods to perform the survey. Many surveys will involve a combination of field measurements and sampling methods to demonstrate compliance with the release criteria.

6.2.2 Measurement Performance Indicators

Measurement performance indicators are used to evaluate the performance of the measurement method. These indicators describe how the measurement method is performing to ensure the survey results are of sufficient quality to meet the survey objectives.

6.2.2.1 Background Measurements/Blanks

Background measurements are direct measurements or scans of materials with little or no radioactive material, other than that present in the natural background of the material; or the response of the instrument to ambient radiation when the instrument is moved away from the surface being surveyed. These measurements are performed to determine whether the measurement process introduces any increase in instrument signal rate that could impact the measurement method detection capability. Background measurements should be representative of all measurements performed using a specific measurement method (i.e., combination of instrumentation and measurement technique). When practical, the background measurements should consist of the same or equivalent material(s) as the area being surveyed.

Background measurements typically are performed before and after a series of measurements to demonstrate the measurement method was performing adequately throughout the survey. At a minimum, background measurements should be performed at the beginning and end of each shift. When large quantities of data are collected (e.g., scanning measurements) or there is an increased potential for radionuclide contamination of the instrument (e.g., removable or airborne radionuclides), background measurements may be performed more frequently. In general, background measurements should be performed before too many measurements have been performed such that it is not practical to repeat those measurements if a problem is identified.

A sudden change in the measured background indicates a condition requiring immediate attention. Sudden changes can be caused by the introduction of a radionuclide, a change in ambient background, instrument instability, or contamination of the detector. Gradual changes in the measured background indicate a need to inspect all survey areas for sources of radioactive material. Gradual buildup of removable radionuclides over time or instrument drift and deterioration can result in slowly increasing background measurements. High variability in background measurements can result from instrument instability or improper classification (i.e., high-activity and low-activity areas combined into a single survey unit). It is important to correct any problems with blanks to ensure that the detection capability (see **Section 6.3**) is not compromised.

If smears or swipes, described in more detail in **Section 6.6.1.4**, are used to estimate the amount of removable radioactive material on the surface, measurement of an unused smear, or blank, provides a background measurement of the instrument used to test the smears

6.2.2.2 Replicate Measurements

Replicate measurements are two or more measurements performed at the same location or on the same sample that are performed primarily to provide an estimate of the random uncertainty for the measurement method. The reproducibility of measurement results should be evaluated by replicates to establish this component of measurement uncertainty (see **Section 6.4**).

Replicates typically are performed at specified intervals during a survey (e.g., 5 percent of all measurements or once per day) and should be employed to evaluate each batch of data used to support a decision (e.g., one replicate per survey unit). For scan-only surveys, where decisions are made based on logged and geolocated measurements, typically 5 percent of all measurements are replicated (e.g., 5 percent of the scanned area is scanned twice).

Estimates of random uncertainty exhibit a range of values and depend in part on the surface being measured and the activity level. Small changes in the random uncertainty are expected, and the acceptable range of variability should be established before initiating data collection activities. The main causes for high random uncertainty include problems with repeating measurements on irregular surfaces, the surface being measured, counting statistics when the activity levels are low, and instrument contamination.

6.2.2.3 Spikes and Standards

Spikes and standards are materials with known composition and amounts of radioactive material; they are used to evaluate bias in the measurement method and typically performed periodically during a survey (e.g., 5 percent of all measurements or once per day). When spikes and standards are available, they should be used to evaluate each batch of data used to support a release decision (i.e., at least one spike or standard per survey unit).

Tracking results of measurements with known activity can provide an indication of the magnitude of the systematic uncertainty or drift of the measurement system. In general, activity levels near the DCGLs (or discrimination limits in Scenario B) will provide adequate information on the performance of the measurement system.

6.2.3 Instrument Performance Indicators

Evaluating instrument performance indicators provides information on the operation of the instruments and how they are performing.

6.2.3.1 Performance Tests

Performance tests should be carried out periodically and after any maintenance to ensure that the instruments continue to meet performance requirements for measurements. An example of a performance test is a test for response time. Performance requirements should be met as specified in the applicable sections of the American National Standards Institute (ANSI) publications ANSI N323AB (ANSI 2013), ANSI N42.17A (ANSI 2004), and ANSI N42.17C (ANSI 1990). These tests may be conducted as part of the calibration procedure.

6.2.3.2 Functional Tests

Functional tests should be performed before initial use of an instrument and after periods when the instrument was stored for a relatively long time or transported over a long distance. These functional tests should include—

- general condition
- battery condition
- verification of current calibration (i.e., check to see that the date due for calibration has not passed)
- source and background response checks (and other tests as applicable to the instrument)
- constancy check

The effects of environmental conditions (temperature, humidity, etc.) and interfering radiation on an instrument should be established before use. The performance of functional tests should be appropriately documented. This may be as simple as a checklist on a survey sheet, or it may include more detailed statistical evaluation, such as a chi-square test (Gilbert 1987).

6.2.3.3 Instrument Background

All radiation detection instruments have a background response, even in the absence of a sample or radiation source. Inappropriate background correction will result in measurement error and increase the uncertainty of data interpretation.

6.2.3.4 Efficiency Calibrations

Knowing the detector efficiency is critical for converting the instrument response to activity (see MARSSIM **Section 6.7,** Multi-Agency Radiation Survey and Assessment of Materials and Equipment [MARSAME] Section 7.8.2.2, and Multi-Agency Radiological Laboratory Analytical Protocols [MARLAP] Chapter 16). Routine performance checks may be used to demonstrate that the system's operational parameters are within acceptable limits, and these measurements typically are included in the assessment of systematic uncertainty. The system's operational parameters may be tracked using control charts.

6.2.3.5 Energy Calibrations (Spectrometry Systems)

Spectrometry systems identify radionuclides based on the energy of the detected radiations. A correct energy calibration is critical to accurately identify radionuclides. An incorrect energy calibration may result in misidentification of peaks or failure to identify radionuclides present.

6.2.3.6 Peak Resolution and Tailing (Spectrometry Systems)

The shape of the full energy peak is important for identifying radionuclides and quantifying their activity with spectrometry systems. Poor peak resolution and peak tailing may result in larger measurement uncertainty or in failure to identify the presence of peaks based on shape. Consistent problems with peak resolution indicate the presence of an analytical bias.

6.2.3.7 Voltage Plateaus (Proportional Counters, Geiger-Mueller Detectors)

The accuracy of results using a proportional counter or Geiger-Mueller (GM) detector can be affected if the system is not operated with its detector's high voltage adjusted such that it is on a stable portion of the operating plateau.

6.2.3.8 Self-Absorption, Backscatter, and Crosstalk

Alpha and beta measurement results can be affected through self-absorption and backscatter. Measurement systems using an electronic discriminator (e.g., gas flow proportional detectors) that simultaneously detect alpha and beta particles can be affected by crosstalk (i.e., identification of alpha particles as beta particles and vice versa). Accurate differentiation between alpha and beta activity depends on the assessment and maintenance of information on self-absorption and crosstalk.

6.3 Detection Capability

The detection capability (sometimes referred to as sensitivity) of a measurement system refers to a radiation level or quantity of radioactive material that can be measured or detected with some known or estimated level of confidence. This quantity is a factor of both the instrumentation and the technique or procedure being used.

The primary parameters that affect a measurement system's detection capability are the background count rate, the instrument's detection efficiency, and the counting time interval. When making field measurements, the detection capability will usually be less than what can be achieved in a laboratory due to increased background and, often, significantly lower detection efficiency. It is often impossible to guarantee that pure alpha emitters can be detected in situ, because the weathering of aged surfaces will often completely absorb the alpha emissions. NUREG-1507 (NRC 1997a) contains data on many of the parameters that affect detection efficiencies in situ, such as absorption, surface smoothness, and particulate radiation energy.

6.3.1 Detection Capability for Direct Measurements

Prior to performing field measurements using scalers, an investigator must evaluate the detection capability of the equipment proposed for use to ensure that levels below the DCGL can be detected. After a direct measurement has been made, it is then necessary to determine whether the result can be distinguished from the instrument background response of the measurement system. The terms that are used in this manual to define detection capability for fixed point counts and sample analyses are—

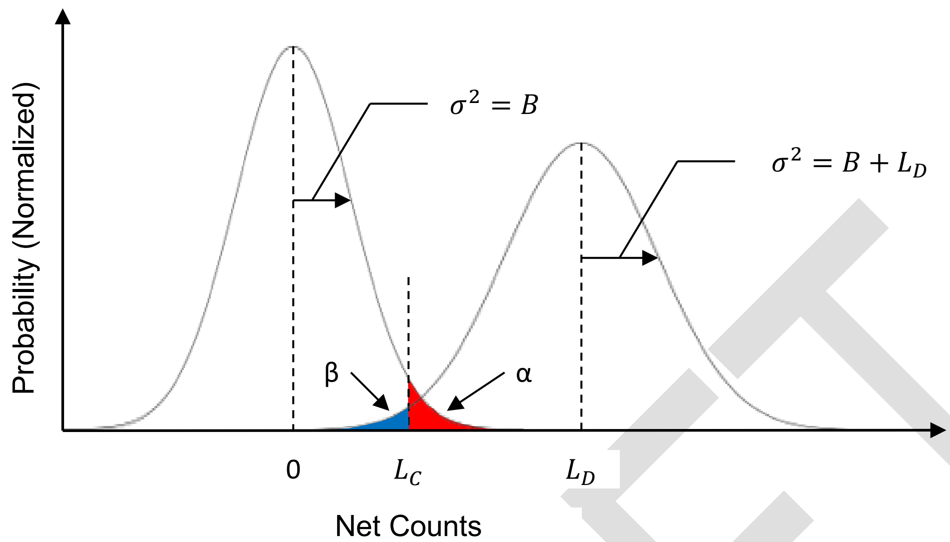
- *Critical level:* The critical level (L_C) is the level at which there is a statistical probability (with a predetermined confidence) of correctly identifying a measurement as greater than background.
- *Detection limit:* The detection limit (L_D) is the net response level that can be expected to be seen with a detector with a fixed level of confidence.
- *Minimum detectable concentration:* The minimum detectable concentration (MDC) is the a priori activity concentration that a specific instrument and technique that has a specified probability (typically 95 percent) of producing a net count (or count rate) above the critical level. When stating the detection limit of an instrument, this value should be used. The MDC is the detection limit multiplied by an appropriate conversion factor to give units of activity.

The following discussion provides an overview of the derivation contained in the well-known publication by Currie (1968) followed by a description of how the resulting formulas should be used. Publications by Currie (1968) and Altshuler and Pasternack (1963) provide details of the derivations involved. The two parameters of interest for a detector system with a background response greater than zero are—

1. The critical level is the lower bound on the 95 percent detection interval defined for L_D and is the level at which there is a 5 percent chance of calling a background value “greater than background.” This value should be used when counting samples or making direct radiation measurements. Any response above this level should be considered as above background (i.e., a net positive result). This will ensure 95 percent detection capability for L_D.
2. The detection limit is the net response level, in counts, that can be expected to be seen with a detector with a fixed level of confidence, which is assumed to be 95 percent.

Assuming that a system has a background response, and that random uncertainties and systematic uncertainties are accounted for separately, these parameters can be calculated using Poisson statistics. For these calculations, two types of decision errors should be considered. A Type I error occurs when a detector response is considered to be above background when, in fact, only background radiation is present. A Type II error occurs when a detector response is considered to be background when, in fact, radiation is present at levels above background. The probability of a Type I error is referred to as α (alpha) and is associated with L_C; the probability of a Type II error is referred to as β (beta) and is associated with L_D. **Figure 6.1** graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution.[2]

[2] Note that the values of α and β chosen here are for the detection hypothesis test and are always chosen to be 5% for comparability purposes. These α and β values are separate and distinct from the values of α and β chosen by the planning team for use in designing site surveys.



B = Background Counts (mean)
L_C = Critical Level (net counts above background)
L_D = Detection Limit (net counts above background)
α = Probability of Type I Error
β = Probability of Type II Error

Figure 6.1: Graphically Represented Probabilities for Type I and Type II Errors in Detection Capability for Instrumentation with a Background Response

If α and β are assumed to be equal, the variance (σ^2) of all measurement values is assumed to be equal to the values themselves. If the background of the detection system is not well known, then the critical level and the detection limit can be calculated by using the following formulas:

$$L_C = k\sqrt{2B} \quad (6\text{-}1)$$

$$L_D = k^2 = 2k\sqrt{2B} \quad (6\text{-}2)$$

where L_C is the critical level (counts), L_D is the detection limit (counts), k is the Poisson probability sum for α and β (assuming α and β are equal), and B is the number of background counts that are expected to occur while performing an actual measurement.

The curve to the left in **Figure 6.1** is the background distribution. The result is a Poisson distribution with a mean equal to the number of background counts, B, and a variance, σ^2, equal to B. Note that the distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay. Currie assumed “paired blanks” when deriving the above stated relationships (Currie 1968), which is interpreted to mean that the sample and background count times are the same.

If values of 0.05 for both α and β are selected as acceptable, then $k = 1.645$ (from **Appendix I, Table I.1**), and **Equations 6-1 and 6-2** can be written as—

$$L_C = 2.33\sqrt{B} \tag{6-3}$$

$$L_D = 3 + 4.65\sqrt{B} \tag{6-4}$$

Note: In Currie's derivation, the constant factor of 3 in the L_D formula was stated as being 2.71, but since that time it has been shown (Brodsky 1992) and generally accepted that a constant of 3 is more appropriate. If the sample count times and background count times are different, a slightly different formulation is used.

The MDC value should be used when stating the detection capability of an instrument. Again, this value is used before any measurements are made and is used to estimate the level of activity that can be detected using a given measurement method.

For an integrated measurement over a preset time, the MDC can be obtained from **Equation 6-4** by multiplying by the factor C. This factor is used to convert from counts to concentration, as shown in **Equation 6-5:**

$$\text{MDC} = C \times \left(3+4.65\sqrt{B}\right) \tag{6-5}$$

The total detection efficiency and other constants or factors represented by the variable C are usually not truly constants, as shown in **Equation 6-5.** It is likely that at least one of these factors will have a certain amount of variability associated with it, which may or may not be significant. These varying factors are gathered together into the single constant, C, by which the net count result will be multiplied when converting the final data. If C varies significantly between measurements, then it might be best to select a value, C', from the observed distribution of C values that represents a conservative estimate. For example, a value of C might be selected to ensure that at least 95 percent of the possible values of C are less than the chosen value, C'. The MDC calculated in this way helps assure that the survey results will meet the DQOs. This approach for including uncertainties into the MDC calculation is recommended in both NUREG/CR-4007 (NRC 1984) and Appendix A to ANSI N13.30 (ANSI 1996). Underestimating an MDC can have adverse consequences, especially if activity is later detected at a level above the stated MDC.

From a conservative point of view, it is better to overestimate the MDC for a measurement method. Therefore, when calculating MDC and L_C values, a measurement system background value should be selected that represents the high end of what is expected for a particular measurement method. For direct measurements, probes will be moved from point to point; as a result, it is expected that the background will most likely vary significantly because of variations in background, source materials, and changes in geometry and shielding. Ideally, the MDC values should be calculated for each type of area, but it may be more economical to simply select a background value from the highest distribution expected and use this for all calculations. For the same reasons, realistic values of detection efficiencies and other process parameters should be used when possible and should be reflective of the actual conditions, as adopting an overly conservative MDC may sometimes lead to difficulties in implementation. To a great degree, the selection of these parameters will be based on judgment and will require evaluation of site-specific conditions. **Example 1** illustrates the calculation of an MDC in becquerels per square meter (Bq/m^2) for an instrument with a 15 cm^2 probe area when the measurement and background counting times are each 1 minute.

Example 1: Calculation of a Minimum Detectable Concentration (MDC)

This example illustrates the calculation of an MDC in becquerels per square meter (Bq/m^2) for an instrument with a 15 square centimeter (cm^2) probe area when the measurement and background counting times are each 1 minute. Note that the count rate is reported in units of disintegrations per minute (dpm). The background counts, B, is 40 counts.

If the total efficiency of the probe is 20 percent, then 1 count will be recorded during a 1-minute timeframe for every 5 dpm. The concentration $C =$

$$C = \left(\frac{5\text{ dpm}}{\text{count}}\right)\left(\frac{\text{Bq}}{60\text{ dpm}}\right)\left(\frac{1}{15\text{ cm}^2}\right)\left(\frac{10{,}000\text{ cm}^2}{\text{m}^2}\right) = 55.6\ \text{Bq/m}^2$$

The MDC is calculated using **Equation 6-5:**

$$\text{MDC} = \left(55.6\ \text{Bq/m}^2\right) \times \left(3 + 4.65\sqrt{40}\right) = 1{,}800\ \text{Bq/m}^2\left(1{,}100\text{ dpm/100 cm}^2\right)$$

The critical level, L_C, for this example is calculated from **Equation 6-3:**

$$L_C = 2.33\sqrt{B} = 2.33\sqrt{40} = 15\text{ counts}$$

Given the above scenario, if a person asked what level of residual radioactive material could be detected 95 percent of the time using this method, the answer would be 1,800 Bq/m^2 (1,100 dpm/100 cm^2). When performing measurements using this method, any count yielding greater than 55 total counts, or greater than 15 net counts (55 - 40 = 15) during a period of 1 minute, would be regarded as greater than background.

MDC values for other counting conditions may be derived from **Equation 6-5,** depending on the detector and radionuclides of concern. For example, it may be required to determine what level of residual radioactive material, distributed over 100 square centimeters (cm^2), can be detected with a 500 cm^2 probe or what level of residual radioactive material can be detected with any probe when the area is smaller than the probe active area. **Table 6.1** lists several common field survey detectors with estimates of MDC values for uranium-238 (^{238}U) on a smooth, flat plane. As such, these represent minimum MDC values and may not be applicable at all sites. Appropriate site-specific MDC values should be determined using the DQO Process.

6.3.2 Detection Capability for Scans

Unless data logging is employed, the ability to identify a small area of elevated levels of radioactive material during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the output of an instrument. For notation purposes, the term detection capability (sometimes referred to as scanning sensitivity) is used throughout this section to describe the ability of a surveyor to detect a pre-determined level of residual radioactive material with a detector. The greater the detection capability, the lower the level of residual radioactive material that can be detected. **Table 6.1** provides examples of a set of detection capabilities.

Table 6.1: Examples of Estimated Detection Capabilities for Alpha and Beta Survey Equipment (Static 1-Minute Counts for ^{238}U Calculated Using Equations 6-3, 6-4, and 6-5)

Detector	Probe Area (cm²)	Background (cpm)	Efficiency (cpm/dpm)	Approximate Detection Capability		
				L_C (counts)	L_D (counts)	MDC (Bq/m²)[a]
Alpha proportional	50	1	0.15	2	7	150
Alpha proportional	100	1	0.15	2	7	83
Alpha proportional	600	5	0.15	5	13	25
Alpha scintillation	50	1	0.15	2	7	150
Beta proportional	100	300	0.20	40	83	700
Beta proportional	600	1,500	0.20	90	183	250
Beta GM pancake	15	40	0.20	15	32	1,800

Abbreviations: cm = centimeter; cpm = counts per minute; dpm = decays per minute; L_C = critical level; L_D = detection limit; Bq = becquerels; m = meters; GM = Geiger-Mueller.
[a] Assumes that the size of the area of radioactive material is at least as large as the probe area.

Many of the radiological instruments and monitoring techniques typically used for occupational health physics activities may not provide the detection capabilities necessary to demonstrate compliance with the DCGLs. The detection capability for a given application can be improved (i.e., lower the MDC) by (1) selecting an instrument with a higher detection efficiency or a lower background, (2) decreasing the scanning speed, or (3) increasing the size of the effective probe area without significantly increasing the background response.

Scanning is usually performed during radiological surveys to identify the presence of any areas of elevated activity. The probability of detecting residual radioactive material in the field not only depends on the detection capability of the survey instrumentation when used in the scanning mode of operation, but also is affected by the surveyor's ability (i.e., human factors). The surveyor must make a decision whether the signals represent only the background activity or residual radioactive material in excess of background. Lower levels of residual radioactive material can be detected by increasing the detection capability (i.e., detection of residual radioactive material is inversely proportional to the detection capability). Accounting for these human factors represents a significant change from the methods of estimating detection capabilities for scans used in the past.

An empirical method for evaluating the detection capability for surveys is by actual experimentation or, as it is certainly feasible, by simulating an experimental setup using computer software. The following steps provide a simple example of how one can perform this empirical evaluation:

1. A desired radionuclide activity level is selected.
2. The response of the detector to be used is determined for the selected radionuclide activity level.
3. A test source is constructed that will give a detector count rate equivalent to the detector response, determined in Step 2. The count rate is equivalent to what would be expected from the detector when placed on an actual area with residual radioactive material equal in value to that selected in Step 1.
4. The detector of choice is then moved over the source at different scan rates until an acceptable speed is determined.

The most useful aspect of this approach is that the source can then be used to show surveyors what level of residual radioactive material is expected to be targeted with the scan. They, in turn, can gain experience with what the expected response of the detector will be and how fast they can survey and still feel confident about detecting the target residual radioactive material level. The person responsible for the survey can then use this information when developing a fixed point measurement and sampling plan.

The remainder of this section provides the reader with information regarding the underlying processes involved when performing scanning surveys for alpha-, beta-, and gamma-emitting radionuclides. The purpose is to provide relevant information that can be used for estimating realistic detection capabilities for scans.

6.3.2.1 Scanning for Beta and Gamma Emitters

The scan MDC depends on several factors:

- the intrinsic characteristics of the detector (efficiency, physical probe area, etc.)

- the nature (type and energy of emissions) and relative distribution of residual radioactive material (point versus distributed source and depth of residual radioactive material)
- scan rate
- other characteristics of the surveyor

Some factors may affect the surveyor's performance (e.g., fatigue, noise, level of training, experience) and the survey's a priori expectation of the likelihood of residual radioactive material present. For example, if the surveyor believes that the potential for residual radioactive material is very low, as in a Class 3 area, a relatively large signal may be required for the surveyor to conclude that residual radioactive material is present.

<u>Signal Detection Theory</u>

Personnel conducting radiological surveys for residual radioactive material at sites must interpret the audible output of a portable survey instrument to determine when the signal ("clicks") exceeds the background level by a margin sufficient to conclude that residual radioactive material is present. It is difficult to detect low levels of residual radioactive material, because both the signal and the background vary widely. Signal detection theory provides a framework for the task of deciding whether the audible output of the survey meter during scanning is due to background or signal plus background levels. An index of sensitivity (d') that represents the distance between the means of the background and background plus signal (refer to **Figure 6.1** for determining L_D), in units of their common standard deviation can be calculated for various decision errors (correct detection and false positive rate).

As an example, for a correct detection rate of 95 percent (complement of a false negative rate of 5 percent) and a false positive rate of 5 percent, d' is 3.28 (similar to the static MDC for the same decision error rates). The index of sensitivity is independent of human factors; therefore, the ability of an ideal observer (theoretical construct) may be used to determine the minimum d' that can be achieved for particular decision errors. The ideal observer makes optimal use of the available information to maximize the percent correct responses, providing an effective upper bound against which to compare actual surveyors. **Table 6.2** lists selected values of d'.

<u>Two Stages of Scanning</u>

The framework for determining the scan MDC is based on the premise that there are two stages of scanning. That is, surveyors do not make decisions based on a single indication; rather, upon noting an increased number of counts, they pause briefly and then decide whether to move on or take further measurements. Thus, scanning consists of two components: continuous monitoring and stationary sampling. In the first component, characterized by continuous movement of the probe, the surveyor has only a brief "look" at potential sources, determined by the scan speed. The surveyor's willingness to decide that a signal is present at this stage is likely to be liberal, in that the surveyor should respond positively on scant evidence, because the only "cost" of a false positive is a little time. The second component occurs only after a positive response was made at the first stage. This response is marked by the surveyor interrupting his or her scanning and holding the probe stationary for a period of time while comparing the instrument output signal during that time to the background counting rate. Owing to the longer observation interval, detection capability is relatively high. For this decision, the criterion should be stricter, as the cost of a "yes" decision is to spend considerably more time

Table 6.2: Index of Sensitivity (d') Values for Selected True Positive and False Positive Proportions

False Positive Proportion	True Positive Proportion							
	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.05	1.90	2.02	2.16	2.32	2.48	2.68	2.92	3.28
0.10	1.54	1.66	1.80	1.96	2.12	2.32	2.56	2.92
0.15	1.30	1.42	1.56	1.72	1.88	2.08	2.32	2.68
0.20	1.10	1.22	1.36	1.52	1.68	1.88	2.12	2.48
0.25	0.93	1.06	1.20	1.35	1.52	1.72	1.96	2.32
0.30	0.78	0.91	1.05	1.20	1.36	1.56	1.80	2.16
0.35	0.64	0.77	0.91	1.06	1.22	1.42	1.66	2.02
0.40	0.51	0.64	0.78	0.93	1.10	1.30	1.54	1.90
0.45	0.38	0.52	0.66	0.80	0.97	1.17	1.41	1.77
0.50	0.26	0.38	0.52	0.68	0.84	1.04	1.28	1.64
0.55	0.12	0.26	0.40	0.54	0.71	0.91	1.15	1.51
0.60	0.00	0.13	0.27	0.42	0.58	0.82	1.02	1.38

taking a static measurement or a sample. Because scanning can be divided into two stages, it is necessary to consider the survey's scan detection capability for each stage. Typically, the minimum detectable count rate (MDCR) associated with the first scanning stage will be greater due to the brief observation intervals of continuous monitoring—provided that the length of the pause during the second stage is significantly longer. Typically, observation intervals during the first stage are on the order of 1 or 2 seconds, while the second stage pause may be several seconds longer. The greater value of MDCR from each of the scan stages is used to determine the detection capability for the surveyor.

<u>Determination of MDCR and Use of Surveyor Efficiency</u>

The minimum detectable number of net source counts in the time interval is given by s_i. Therefore, for an ideal observer, the number of source counts required for a specified level of performance can be arrived at by multiplying the square root of the number of background counts by the detectability value associated with the desired performance (as reflected in d') as shown in **Equation 6-6:**

$$\boldsymbol{s_i = d'\sqrt{b_i}} \qquad (6\text{-}6)$$

where the value of d' is selected from **Table 6.2** based on the required true positive and false positive rates and b_i is the number of background counts in the interval. The MDCR can be calculated using the **Equation 6-7:**

$$\text{MDCR} = \frac{s_i}{\Delta t_i} \qquad (6\text{-}7)$$

where Δt_i is the observation interval. **Example 2** illustrates the calculation of the MDCR for a probe with a background count rate of 1,500 counts per minute (cpm) for a 1-second interval.

Example 2: Calculation of the Minimum Detectable Count Rate for the First Stage of Scanning

Estimate the minimum detectable count rate (MDCR) by scanning in an area with a background of 1,500 counts per minute (cpm). Note that the MDCR must be considered for both scan stages, and the more conservative value is selected as the minimum count rate that is detectable. It will be assumed that a typical source remains under the probe for 1 second (s) during the first stage, therefore, the average number of background counts in the observation interval is—

$$b_i = (1500 \text{ cpm})(1 \text{ s})\left(\frac{\text{minute}}{60 \text{ s}}\right) = 25 \text{ counts}$$

where b_i is the average number of background counts in an observation interval. Furthermore, it can be assumed that at the first scanning stage, a high rate (e.g., 95 percent) of correct detections is required and that a correspondingly high rate of false positives (e.g., 60 percent) will be tolerated. From **Table 6.2,** the value of d', representing this performance goal is 1.38. The net source counts needed to support the specified level of performance (assuming an ideal observer) will be estimated by multiplying 5 (the square root of 25) by 1.38. Thus, the net source counts, s_i in interval Δt_i (in seconds), needed to yield better than 95 percent detections with about 60 percent false positives is given by **Equation 6-6:**

$$s_i = 1.38 \times \sqrt{25} = 6.9$$

The MDCR, in cpm, may be calculated using **Equation 6-7:**

$$\text{MDCR} = \frac{s_i}{\Delta t_i} = \left(\frac{6.9 \text{ counts}}{1 \text{ s}}\right)\left(\frac{60 \text{ s}}{\text{minute}}\right) = 414 \text{ cpm}$$

where s_i is the minimum detectable number of net source counts and is over a time interval specified by t_i. For this example, MDCR is equivalent to 414 cpm above a background of 1,500 cpm (1,914 cpm gross).

Example 3 illustrates the determination of the detection limit for the ideal observer (MDCR) at the first scanning stage for various background levels for a true positive proportion of 95 percent and false positive proportion of 60 percent.

Example 3: Determination of the Detection Limit for the Ideal Observer

The table below provides the minimum detection count rate and detection limit for the ideal observer at the first scanning stage for various background levels, based on an index of sensitivity (d') of 1.38 for a true positive proportion of 95 percent, a false positive proportion of 60 percent, and a 2-second observation interval.

Detection Capability of the Ideal Observer for Various Background Levels

Background (cpm)	MDCR (net cpm)	Scan Sensitivity (gross cpm)[a]
45	50	95
60	60	120
260	120	380
300	130	430
350	140	490
400	150	550
1,000	240	1,240
3,000	410	3,410
4,000	480	4,480

Abbreviations: cpm = counts per minute; MDCR = minimum detectable count rate.
[a]The detection capability of the ideal observer during the first scanning stage is based on an index of sensitivity (d') of 1.38 and a 2-second observational interval.

The minimum number of source counts required to support a given level of performance for the final detection decision (second scan stage) can be estimated using the same method. As explained earlier, the performance goal at this stage will be more demanding. **Example 4** illustrates the calculation of the MDCR for the probe from **Example 2** but with an interval of 4 seconds instead of 1 second.

Example 4: Calculation of the Minimum Detectable Count Rate for the Second Stage of Scanning

The required rate of true positives remains high (e.g., 95 percent), but fewer false positives (e.g., 20 percent) can be tolerated, such that the index of sensitivity (d') (from **Table 6.2**) is now 2.48. One will assume that the surveyor typically stops the probe over a suspect location for about 4 seconds (s) before making a decision so that the average number of background counts in an observation interval is

$$b_i = (1{,}500\text{ cpm})(4\text{ s})\left(\frac{\text{minute}}{60\text{ s}}\right) = 100\text{ counts}$$

where b_i is the average number of background counts in an observation interval. Therefore, the minimum detectable number of net source counts, s_i, needed will be estimated by multiplying 10 (the square root of b_i) by 2.48 (the d' value) using **Equation 6-6:**

$$s_i = d'\sqrt{b_i} = 2.48\times\sqrt{100} = 24.8$$

The minimum detectable count rate (MDCR) is calculated using **Equation 6-7:**

$$\text{MDCR} = \frac{s_i}{\Delta t_i} = \left(\frac{24.8\text{ counts}}{4\text{ s}}\right)\left(\frac{60\text{ s}}{\text{minute}}\right) = 372\text{ cpm}$$

where s_i is the minimum detectable number of net source counts and is over a time interval specified by t_i. The MDCR is 372 counts per minute (cpm) net, or 1,872 cpm gross. The value associated with the first scanning stage (**Example 2:** 414 cpm net or 1,914 cpm gross) will typically be greater, owing to the relatively brief intervals assumed.

Laboratory studies using simulated sources and backgrounds were performed to assess the abilities of surveyors under controlled conditions. The methodology and analysis of results for these studies are described in NUREG-1507 (NRC 1997a). The surveyor's actual performance as compared with the ideal possible performance (using the ideal observer construct) provided an indication of the efficiency of the surveyors. Based on the results of the confidence rating experiment, this surveyor efficiency (p) was estimated to be between 0.5 and 0.75.

MARSSIM recommends assuming a surveyor efficiency value at the lower end of the observed range (i.e., 0.5) when making MDC estimates. Thus, the required number of net source counts, $\text{MDCR}_{\text{surveyor}}$, is determined by dividing the MDCR by the square root of p, as in **Equation 6-8:**

$$\text{MDCR}_{\text{surveyor}} = \frac{\text{MDCR}}{\sqrt{p}} \qquad (6\text{-}8)$$

Example 5 shows the calculation of the surveyor MDCR for **Example 1:**

Example 5: Calculation of the Surveyor Minimum Detectable Count Rate for Example 1

Using the data from Example 1, the surveyor minimum detectable count rate (MDCR) is calculated using **Equation 6-8:**

$$\text{MDCR}_{\text{surveyor}} = \frac{\text{MDCR}}{\sqrt{p}} = \frac{414\text{ cpm}}{\sqrt{0.5}} = 585\text{ cpm}$$

The surveyor MDCR is 585 counts per minute (cpm) net (2,085 cpm gross).

Scan MDCs for Structure Surfaces and Land Areas

The survey design for determining the number of data points for areas of elevated activity (see **Section 5.3.5**) depends on the scan MDC for the selected instrumentation. In general, alpha or beta scans are performed on structure surfaces to satisfy the elevated activity measurements survey design, and gamma scans are performed for land areas. Because of low background levels for alpha emitters, the approach described here is not generally applied to determining scan MDCs for alpha emitters; rather, the reader is referred to **Section 6.3.2.2** for an appropriate method for determining alpha scan MDCs for building surfaces. In any case, the data requirements for assessing potential elevated areas of direct radiation depend on the scan MDC of the survey instrument (e.g., floor monitor, GM detector, sodium iodide [NaI] scintillation detector).

Scan MDCs for Building/Structure Surfaces

The scan MDC is determined from the MDCR by applying conversion factors that account for detector and surface characteristics and surveyor efficiency. As discussed above, the MDCR accounts for the background level, performance criteria (d'), and observation interval. The observation interval during scanning is the actual time that the detector can respond to the source of residual radioactive material—this interval depends on the scan speed, detector size in the direction of the scan, and area of elevated activity. Because the actual dimensions of potential areas of elevated activity in the field cannot be known a priori, MARSSIM recommends postulating a certain area (e.g., perhaps 50–200 cm^2) and then selecting a scan rate that provides a reasonable observation interval.

Finally, the scan MDC in units of decays per minute (dpm)/100 cm^2 for structure surfaces may be calculated using **Equation 6-9:**

$$\text{Scan MDC} = \frac{\text{MDCR}}{\sqrt{p}\,\varepsilon_i\,\varepsilon_s\,\frac{W}{100}} \qquad (6\text{-}9)$$

where

- MDCR is the minimum detectable count rate
- ε_i is the instrument efficiency
- ε_s is the surface efficiency
- p is the surveyor efficiency
- W is the physical probe area in square centimeters
- 100 is a units conversion from $(cm^2)^{-1}$ to $(100\ cm^2)^{-1}$

Consideration may need to be given to the size of the detector probe relative to the size of the postulated hot spot size. For example, a large area floor monitor with a probe area of approximately 600 cm^2 would fully cover the area of the postulated hot spot in the scenario presented above (i.e., 50–200 cm^2). In this situation, a probe area correction is likely not appropriate. **Example 6** illustrates the calculation of the scan MDC for the probe in **Example 3** for technetium-99 (^{99}Tc).

Example 6: Calculation of the Scan Minimum Detectable Concentration for the Probe in Example 3

As an example, the scan minimum detectable concentration (MDC) (in disintegrations per minute [dpm]/100 square centimeters [cm^2]) for technetium-99 (^{99}Tc) on a concrete surface may be determined for a background level of 300 counts per minute (cpm) and a 2-second observation interval using a hand-held gas proportional detector (126 cm^2 probe area). For a specified level of performance at the first scanning stage of 95 percent true positive rate and 60 percent false positive rate (and assuming the second stage pause is long enough to ensure that the first stage is more limiting), d' equals 1.38 (**Table 6.2**), and the minimum detectable count rate (MDCR) is 130 cpm (**Example 3**). Using a surveyor efficiency of 0.5, and assuming instrument and surface efficiencies of 0.36 and 0.54, respectively, the scan MDC is calculated using **Equation 6-9:**

$$\text{Scan MDC} = \frac{\text{MDCR}}{\sqrt{p}\ \varepsilon_i\ \varepsilon_s\ \frac{W}{100}} = \frac{130\ \text{cpm}}{\sqrt{0.5}\ (0.36 \times 0.54\ \text{cpm/dpm})\left(\frac{126\ \text{cm}^2}{100}\right)} = 750\ \text{dpm/100 cm}^2$$

The scan MDC for ^{99}Tc is 750 dpm/100 cm^2.

Additional examples for calculating the scan MDC may be found in NUREG-1507 (NRC 1997a).

Scan MDCs for Land Areas

In addition to the MDCR and detector characteristics, the scan MDC for land areas is based on the area of elevated activity, depth of contamination, and the radionuclide (i.e., energy and yield of gamma emissions).

Thallium-infused NaI (NaI(Tl)) scintillation detectors are generally used for scanning land areas. Typically, the detectors are placed just above the surveyed area. By hand, this can be done by suspending the detector from the surveyor's hand by a rope. By mechanical means, the detector can be fixed from an automated device.

An overview of the approach used to determine scan MDCs for land areas follows. The NaI(Tl) scintillation detector background level and scan rate (observation interval) are postulated, and the MDCR for the ideal observer, for a given level of performance, is obtained. After a surveyor efficiency is selected, the relationship between the surveyor MDCR ($MDCR_{surveyor}$) and the radionuclide concentration in soil, in Bq/kilogram (kg) or picocuries/gram (pCi/g) is determined.

This correlation requires two steps: First, the relationship between the detector's net count rate to net exposure rate (cpm per microroentgens/hour [μR/h]) is established, and second, the relationship between the concentration of residual radioactive material and exposure rate is determined.

For a particular gamma energy, the relationship of NaI(Tl) scintillation detector count rate and exposure rate may be determined analytically (in cpm per μR/h). The approach used to determine the gamma fluence rate necessary to yield a fixed exposure rate (1 μR/h)—as a function of gamma energy—is provided in NUREG-1507 (NRC 1997a). The NaI(Tl) scintillation detector response (in cpm) is related to the fluence rate at specific energies, considering the detector's efficiency (probability of interaction) at each energy. From this, the NaI(Tl) detector count rate versus exposure rates for varying gamma energies are determined. After the relationship between the NaI(Tl) detector response and the exposure rate is established, the $MDCR_{surveyor}$ (in cpm) of the NaI(Tl) detector can be related to the minimum detectable exposure rate (MDER) using **Equation 6-10:**

$$\text{MDER} = \frac{\text{MDCR}_{\text{surveyor}}}{\text{Ratio of Count Rate to Exposure Rate}} \qquad (6\text{-}10)$$

The MDER is used to determine the minimum detectable radionuclide concentration (i.e., the scan MDC) by modeling a specified small area of elevated activity and then dividing the MDER by the exposure rate conversion factor using **Equation 6-11:**

$$\text{Scan MDC} = \frac{\text{MDER}}{\text{Exposure Rate Conversion Factor}} \qquad (6\text{-}11)$$

Example 7 illustrates the calculation of the scan MDC for cesium-137 (^{137}Cs) using a 38 millimeter (mm; 1.5 inch [in.]) by 32 mm (1.25 in.) NaI(Tl) scintillation detector.

Example 7: Calculation of a Scan Minimum Detectable Concentration for ^{137}Cs

Modeling (using MicroShield 5.05™) of the small area of elevated activity (soil concentration) is used to determine the net exposure rate produced by a radionuclide concentration at a distance 10 centimeters (cm) above the source. This position is selected because it relates to the average height of the NaI(Tl) scintillation detector above the ground during scanning. The factors considered in the modeling include the following:

- radionuclide of interest (considering all gamma emitters for decay chains)
- expected concentration of the radionuclide of interest
- areal dimensions of the area of elevated activity
- depth of the area of elevated activity
- location of dose point (NaI(Tl) scintillation detector height above the surface)
- density and moisture content of soil

Modeling analyses are conducted by selecting a radionuclide (or radioactive material decay series) and then varying the concentration of the radionuclide. The other factors are held constant—the areal dimension of a cylindrical area of elevated activity is 0.25 square meters (m^2; radius of 28 cm), the depth of the area of elevated activity is 15 cm, the dose point is 10 cm above the surface, and the density of soil is 1.6 g/cm^3. The soil was modeled as 50 percent aluminum and 50 percent carbon by weight. The objective is to determine the radionuclide concentration that is correlated to the minimum detectable net exposure rate.

The scan MDC for cesium-137 (^{137}Cs) using a 38 millimeter (mm; 1.5 inch [in.]) by 32 mm (1.25 in.) NaI(Tl) scintillation detector is considered in detail. Assume that the background level is 4,000 counts per minute (cpm) and that the desired level of performance, 95 percent correct detections and 60 percent false positive rate, results in a d' of 1.38. The scan rate of 0.5 m/second (s) provides an observation interval of 1 second (based on a diameter of about 56 cm for the area of elevated activity). The $\text{MDCR}_{\text{surveyor}}$ may be calculated assuming a surveyor efficiency (p) of 0.5, as follows:

$$b_i = (4{,}000 \text{ cpm}) \times (1 \text{ s}) \times (1 \text{ min}/60 \text{ s}) = 66.7 \text{ counts}$$

$$\text{MDCR} = d'\sqrt{b_i} \times (60 \text{ s}/1 \text{ min}) = (1.38) \times \left(\sqrt{66.7}\right) \times (60 \text{ s}/1 \text{ min}) = 680 \text{ cpm}$$

$$\text{MDCR}_{\text{surveyor}} = \frac{\text{MDCR}}{\sqrt{p}} = \frac{680 \text{ cpm}}{\sqrt{0.5}} = 960 \text{ cpm}$$

The corresponding minimum detectable exposure rate (MDER) is determined for this detector and radionuclide. The manufacturer of this particular 38 mm (1.5 in.) by 32 mm (1.25 in.) NaI(Tl) scintillation detector quotes a count rate to exposure rate ratio for ^{137}Cs of 350 cpm per μR/hour (h), which is equivalent to the Standard International System of Units of 1.36 cpm per picocoulomb (pC) per kilogram (kg) per hour (cpm/(pC/kg)/h). MDER can be calculated by dividing the $\text{MDCR}_{\text{surveyor}}$ by the exposure rate ratio for ^{137}Cs, as shown below:

$$\text{MDER} = \frac{960 \text{ cpm}}{1.36 \text{ cpm/(pCi/kg)/h}} = 706 \text{ (pCi/kg)/h } (2.74\ \mu\text{R/h})$$

Both ^{137}Cs and its short-lived progeny, ^{137m}Ba, are chosen from the MicroShield® library. The source activity and other modeling parameters are entered into the modeling code. The source activity is selected based on an arbitrary concentration of 185 Bq/kg (5 picocuries [pCi]/g). The modeling code performed the appropriate calculations and determined an exposure rate of 337 (pCi/kg)/h (1.307 μR/h), which accounts for buildup.

Finally, the radionuclide concentrations of ^{137}Cs and ^{137m}Ba (scan MDC) necessary to yield the minimum detectable exposure rate of 706 (pCi/kg)/h (2.74 μR/h) may be calculated using the following formula:

$$\text{scan MDC} = \frac{706\ (\text{pC/kg})/\text{h}}{\left(\frac{337\ (\text{pC/kg})/\text{h}}{185\ \text{Bq/kg}}\right)} = 390\ \text{Bq/kg}$$

The scan MDC for ^{137}Cs using a 38 mm (1.5 in.) by 32 mm (1.25 in.) NaI(Tl) scintillation detector, rounded to the appropriate number of significant digits, is 390 Bq/kg (11 pCi/g).

It must be emphasized that although a single scan MDC value can be calculated for a given radionuclide, other scan MDC values may be equally justifiable, depending on the values chosen for the various factors, including the MDCR (background level, acceptable performance criteria, observation interval), surveyor efficiency, detector parameters, and the modeling conditions of the residual radioactive material. It should also be noted that determination of the scan MDC for radioactive materials—such as uranium and thorium—must consider the gamma radiation emitted from the entire decay series. NUREG-1507 (NRC 1997a) provides a detailed example of how the scan MDC can be determined for enriched uranium.

Example 7 uses ^{137}Cs as the radionuclide, which is the same radionuclide that is used to calibrate the instrument. When doing gamma surveys for other radionuclides than ^{137}Cs—the most common instrument calibration source—instruments may underestimate or overestimate the source strength because of the different energies of the gamma rays that are emitted. This uncertainty can be reduced or eliminated by cross calibrating the detector to energy compensated detectors, such as pressurized ion chambers, or the instrument can be calibrated to the specific radionuclide of concern.

Table 6.3 provides scan MDCs for common radionuclides and radioactive materials in soil. It is important to note that the variables used in the above examples to determine the scan MDCs for the 38 mm (1.5 in.) by 32 mm (1.25 in.) NaI(Tl) scintillation detector (i.e., the $MDCR_{surveyor}$ detector parameters (e.g., cpm per µR/h), and the characteristics of the area of elevated activity) have all been held constant to facilitate the calculation of scan MDCs provided in **Table 6.3.** The benefit of this approach is that generally applicable scan MDCs are provided for different radionuclides. Additionally, the relative detectability of different radionuclides is evident because the only variable in **Table 6.3** is the nature of the radionuclide.

As noted above, the scan MDCs calculated using the approach in this section are dependent on several factors. One way to validate the appropriateness of the scan MDC is by tracking the levels of residual radioactive material (both surface activity and soil concentrations) identified during investigations performed as a result of scanning surveys. The measurements performed during these investigations may provide an a posteriori estimate of the scan MDC that can be used to validate the a priori scan MDC used to design the survey.

Table 6.3: NaI(Tl) Scintillation Detector Scan MDCs for Common Radionuclides and Radioactive Materials

Radionuclide/Radioactive Material	1.25 in. by 1.5 in. NaI Detector[a]		2 in. by 2 in. NaI Detector[a]	
	Scan MDC (Bq/kg)	Weighted cpm/μR/h	Scan MDC (Bq/kg)	Weighted cpm/μR/h
^{241}Am	1,650	5,830	1,170	13,000
^{60}Co	215	160	126	430
^{137}Cs	385	350	237	900
^{230}Th	111,000	4,300	78,400	9,580
^{226}Ra (Individual radionuclide, in equilibrium with progeny)	167	300	104	760
^{232}Th decay series (Sum of all radionuclides in the thorium decay series)	1,050	340	677	830
Th-232 (Individual radionuclide, in equilibrium with progeny in decay series)	104	340	66.6	830
Depleted U[b] (0.34% U-235)	2,980	1,680	2,070	3,790
U in natural isotopic abundance[b]	4,260	1,770	2,960	3,990
3% Enriched U[b]	5,070	2,010	3,540	4,520
20% Enriched U[b]	5,620	2,210	3,960	4,940
50% Enriched U[b]	6,220	2,240	4,370	5,010
75% Enriched U[b]	6,960	2,250	4,880	5,030

Abbreviations: in. = inch; MDC = minimum detectable concentration; Bq = becquerel; kg = kilogram; cpm = counts per minute; μR/h = microroentgens/hour.

[a] Refer to text for complete explanation of factors used to calculate scan MDCs. For example, the background level for the 1.25 in. by 1.5 in. NaI detector was assumed to be 4,000 cpm, and 10,000 cpm for the 2 in. by 2 in. NaI detector. The observation interval was 1 second, and the level of performance was selected to yield a performance criteria (d′) of 1.38.

[b] Scan MDC for uranium includes the sum of ^{238}U, ^{235}U, and ^{234}U.

6.3.2.2 Scanning for Alpha Emitters

Scanning for alpha emitters differs significantly from scanning for beta and gamma emitters in that the expected background response of most alpha detectors is very close to zero. The following discussion covers scanning for alpha emitters and assumes that the surface being surveyed is similar in nature to the material on which the detector was calibrated. In this respect, the approach is purely theoretical. Surveying surfaces that are dirty, non-planar, or weathered can significantly affect the detection efficiency and therefore introduce bias to the expected MDC for the scan. The use of reasonable detection efficiency values instead of optimistic values is highly recommended. **Appendix J** contains a complete derivation of the alpha scanning equations used in this section.

Because the time an area is under the probe varies and the background count rate of some alpha instruments is less than 1 cpm, it is not practical to determine a fixed MDC for scanning. Instead, it is more useful to determine the probability of detecting an area of residual radioactive material at a predetermined DCGL for given scan rates.

For alpha survey instrumentation with backgrounds ranging from less than 1 to 3 cpm, a single count provides a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha-emitting radioactive materials on a surface can be calculated by use of Poisson summation statistics.

Given a known scan rate and a DCGL for residual radioactive material on a surface, the probability of detecting a single count while passing over the contaminated area is calculated using **Equation 6-12:**

$$P(n \geq 1) = 1 - e^{\frac{-G\varepsilon_t d}{60v}} \quad (6\text{-}12)$$

where

- $P(n \geq 1)$ is the probability of observing one or more counts
- G is the activity in disintegrations per minute (dpm)
- ε_t is the detector efficiency (4π)
- d is width of the detector in the direction of the scan in centimeters
- v is the scan speed in centimeters/second

Equation 6-12 may be solved for a minimum detectable alpha concentration by assessing the probability of detection using Poisson summation statistics. Specifically, by defining a certain probability of detection, the alpha scan minimum detectable activity (MDA) may be estimated by solving **Equation 6-12** for $G,$ as shown in **Equation 6-13,** where *i* is the observation interval (in seconds) that can be calculated as d / v from **Equation 6-12:**

$$\text{Alpha Scan MDA} = \frac{\left[-\ln\left(1 - P(n \geq 1)\right)\right] \times (60/i)}{\varepsilon_t} \quad (6\text{-}13)$$

The scan MDC calculation may be written to account for the probe area, as shown in **Equation 6-14:**

$$\text{Alpha Scan MDC} = \frac{\left[-\ln\left(1 - P(n \geq 1)\right)\right] \times (60/i)}{\varepsilon_t \times \frac{W}{100}} \tag{6-14}$$

where A is the physical probe area (cm^2) and the Alpha Scan MDC is in units of dpm/100 cm^2.

> Note: This evaluation is shown for the situation where a surveyor is expected to respond to one single count and would become more complex for 2 or more counts. It is also necessary to define an acceptable probability of detection, which should be considered during the DQO process and may require consultation with the regulator.

After a count is recorded and the guideline level of residual radioactive material is present, the surveyor should stop and wait until the probability of getting another count is at least 90 percent. This time interval can be calculated by using **Equation 6-15:**

$$t = \frac{\left[-\ln\left(1 - P(n \geq 1)\right)\right] \times 60 \times 100}{C \times W \times \varepsilon_t} = \frac{13{,}800}{C \times W \times \varepsilon_t} \tag{6-15}$$

where

- t is the time period for static count in seconds
- C is the DCGL in dpm/100 cm^2
- W is the physical probe area (in cm^2)
- ε_t is the detector efficiency (4π)

Many portable proportional counters have background count rates on the order of 5–10 cpm, and a single count should not cause a surveyor to investigate further. A counting period long enough to establish that a single count indicates that an elevated level would be prohibitively inefficient. For these types of instruments, the surveyor usually will need to get at least 2 counts while passing over the source area before stopping for further investigation.

Assuming this to be a valid assumption, the probability of getting two or more counts can be calculated using **Equation 6-16:**

$$\begin{aligned} P(n \geq 2) &= 1 - P(n = 0) - P(n = 1) \\ &= 1 - \left(1 + \frac{(G\varepsilon_t + B)t}{60}\right)\left(e^{-\frac{(G\varepsilon_t + B)t}{60}}\right) \end{aligned} \tag{6-16}$$

where $P(n \geq 2)$ is probability of getting 2 or more counts during the time interval *t*; $P(n = 0)$ is the probability of not getting any counts during the time interval *t*; $P(n = 1)$ is the probability of getting exactly 1 count during the time interval t; and B is the background count rate (cpm). All other variables are the same as in **Equation 6-10.**

Appendix J provides a complete derivation of **Equations 6-12 through 6-16** and a detailed discussion of the probability of detecting residual alpha-emitting radioactive material on surfaces for several different variables. Several probability charts are included at the end of **Appendix J** for common detector sizes. **Table 6.4** provides estimates of the probability of detecting 300 dpm/100 cm^2 for some commonly used alpha detectors.

Table 6.4: Probability of Detecting 300 dpm/100 cm^2 of Alpha Activity While Scanning with Alpha Detectors Using an Audible Output (Calculated Using Equation 6-16)

Detector Type	Detection Efficiency (cpm/dpm)	Probe Dimension in Direction of Scan (cm)	Scan Rate (cm/s)	Probability of detecting 300 dpm/100 cm^2
Proportional	0.20	5	3	80%
Proportional	0.15	15	5	90%
Scintillation	0.15	5	3	70%
Scintillation	0.15	10	3	90%

Abbreviations: cpm = counts per minute; dpm = decays per minute; cm = centimeters; s = seconds.

6.4 Measurement Uncertainty

The quality of measurement data will be directly affected by the magnitude of the measurement uncertainty associated with it. Some uncertainties, such as statistical counting uncertainties, can be easily calculated from the count results using mathematical procedures. Evaluation of other sources of uncertainty requires more effort and in some cases is not possible. For example, if an alpha activity measurement is made on a porous concrete surface, the observed instrument response when converted to units of activity will probably not exactly equal the true activity under the probe. Variations in the absorption properties of the surface for particulate radiation will vary from point to point and therefore will create some level of variation in the expected detection efficiency. This variability in the expected detector efficiency results in uncertainty in the final reported result.

The measurement uncertainty for every analytical result or series of results, such as for a measurement system, should be reported. This uncertainty, although not directly used for demonstrating compliance with the release criteria, is used for survey planning and data assessment throughout the Radiation Survey and Site Investigation (RSSI) process. In addition, the uncertainty is used for evaluating the performance of measurement systems using quality control (QC) measurement results. QC measurement results provide an estimate of random and systematic uncertainties associated with the measurement process. Uncertainty can also be used for comparing individual measurements to the DCGL. This is especially important in the early stages of remediation (i.e., scoping, characterization, remedial action support) when decisions are made based on a limited number of measurements.

Finally, where controlling uncertainty is important, a required uncertainty can be specified or a minimum quantifiable concentration (MQC) can be defined. The MQC could, for example, be that concentration of residual radioactive material that can be quantified with an uncertainty no greater than some limit (e.g., 10 percent) at some specified concentration (e.g., the DCGL).

For most sites, evaluations of uncertainty associated with field measurements are important only for data being used as part of the final status survey (FSS) documentation. The FSS data, which is used to document the final radiological status of a site, should state the uncertainties associated with the measurements. Conversely, detailing the uncertainties associated with measurements made during scoping or characterization surveys may or may not be of value, depending on what the data will be used for, as defined by the DQOs. From a practical standpoint, if the observed data are obviously greater than the DCGL and will be eventually cleaned up, then the uncertainty may be relatively unimportant. Conversely, data collected during early phases of a site investigation that may eventually be used to show that the area is below the DCGL, and therefore does not require any cleanup action, will need the same uncertainty evaluation as the FSS data. In summary, the level of effort needed to evaluate the uncertainty should match the intended use of the data.

6.4.1 Systematic and Random Uncertainties

Measurement uncertainties are often broken into two subclasses: systematic uncertainty (e.g., methodical) and random uncertainty (e.g., stochastic). Systematic uncertainties derive from a lack of knowledge about the true distribution of values associated with a numerical parameter and result in data that are consistently higher or lower than the true value. An example of a systematic uncertainty would be the use of a fixed counting efficiency value without knowledge of the frequency, even though it is known that the efficiency varies from measurement to measurement. If the fixed counting efficiency value is higher than the true but unknown efficiency—as would be the case for an unrealistically optimistic value—then every measurement result calculated using that efficiency would be biased low. Random uncertainties refer to fluctuations associated with a known distribution of values. An example of a random uncertainty would be a well-documented chemical separation efficiency that is known to fluctuate with a regular pattern about a mean. A constant recovery value is used during calculations, but the true value is known to fluctuate from sample to sample with a fixed and known degree of variation.

To minimize the need for estimating potential sources of uncertainty, the sources of uncertainty themselves should be reduced to a minimal level by using such practices as the following:

- The detector used should minimize the potential uncertainty. For example, when making field surface activity measurements for ^{238}U on concrete, a beta detector—such as a thin-window GM “pancake” probe—may provide better quality data than an alpha detector, depending on the circumstances. Less random uncertainty would be expected between measurements with a beta detector, such as a pancake probe, because beta emissions from the uranium will be affected much less by thin, absorbent layers than the alpha emissions will.

- Calibration factors should accurately reflect the efficiency of the detector used on the surface material being measured for the radionuclide or mixture of radionuclides of concern (see **Section 6.6.4**). For most field measurements, variations in the counting efficiency on different types of materials will introduce the largest amount of uncertainty in the final result.

- Uncertainties should be reduced or eliminated by using standardized measurement protocols (e.g., SOPs) when possible. Special effort should be made to reduce or eliminate systematic uncertainties, or uncertainties that are the same for every measurement simply due to an error in the process. If the systematic uncertainties are reduced to a negligible level, then the random uncertainties, or those uncertainties that occur on a somewhat statistical basis, can be dealt with more easily.
- Instrument operators should be trained and experienced with the instruments used to perform the measurements.
- Quality assurance/quality control (QA/QC) should be conducted.

Uncertainties that cannot be eliminated need to be evaluated such that the effect can be understood and properly propagated into the final data and uncertainty estimates. As previously stated, nonstatistical uncertainties should be minimized as much as possible using good work practices.

Overall random uncertainty can be evaluated using the methods described in the following sections:

- **Section 6.4.2** describes a method for calculating random counting uncertainty.
- **Section 6.4.3** discusses how to combine this counting uncertainty with other uncertainties from the measurement process using uncertainty propagation.

Systematic uncertainty is derived from calibration errors, incorrect yields and efficiencies, nonrepresentative survey designs, and “blunders.” It is difficult—and sometimes impossible—to evaluate the systematic uncertainty for a measurement process, but bounds should always be estimated and made small compared to the random uncertainty, if possible. If no other information on systematic uncertainty is available, Currie (NRC 1984) recommends using 16 percent as an estimate for systematic uncertainties (1 percent for blanks, 5 percent for baseline, and 10 percent for calibration factors).

6.4.2 Statistical Counting Uncertainty

When performing an analysis with a radiation detector, the result will have an uncertainty associated with it because of the statistical nature of radioactive decay. To calculate the total uncertainty associated with the counting process, both the background measurement uncertainty and the sample measurement uncertainty must be accounted for. The standard deviation of the net count rate, or the statistical counting uncertainty, can be calculated using **Equation 6-17:**

$$\sigma_n = \sqrt{\frac{C_{s+b}}{t_{s+b}^2} + \frac{C_b}{t_b^2}} \qquad (6\text{-}17)$$

where

- σ_n is the standard deviation of the net count rate result
- C_{s+b} is the number of gross counts (sample)
- t_{s+b} is the gross count time
- C_b is the number of background counts
- t_b is the background count time

6.4.3 Uncertainty Propagation

Most measurement data will be converted to different units or otherwise included in a calculation to determine a final result. The standard deviation associated with the final result, or the total uncertainty, can then be calculated. Assuming the individual uncertainties are relatively small, symmetric about zero, and independent of one another, then the total uncertainty for the final calculated result can be determined by solving the following partial differential equation:

$$\sigma_y = \sqrt{\left(\frac{\partial y}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \cdots + \left(\frac{\partial y}{\partial x_n}\right)^2 \sigma_{x_n}^2} \qquad \text{(6-18)}$$

where $y = f(x_1, x_2, \ldots x_n)$ is a formula that defines the calculation of a final result as a function of the collected data. All variables in this equation (i.e., $x_1, x_2, \ldots x_n$) are assumed to have a measurement uncertainty associated with them and do not include numerical constants. σ_y is the standard deviation, or uncertainty, associated with the final result, and $\sigma_{x_1}, \sigma_{x_2}, \ldots \sigma_{x_n}$ are the standard deviations, or uncertainties, associated with the parameters $x_1, x_2, \ldots x_n$, respectively. **Equation 6-18,** generally known as the error propagation formula, can be solved to determine the standard deviation of a final result from calculations involving measurement data and their associated uncertainties. The solutions for common calculations along with their uncertainty propagation formulas are included in **Table 6.5.**

> Note: In the above examples, x_1 and x_2 are measurement values with associated standard deviations, or uncertainties, equal to σ_{x_1} and σ_{x_2}, respectively. The symbol c is used to represent a numerical constant which has no associated uncertainty. The symbol σ_y is used to denote the standard deviation, or uncertainty, of the final calculated value, y.

Table 6.5: Common Uncertainty Propagation Equations

Data Calculation	Uncertainty Propagation
$y = x_1 + x_2$ or $y = x_1 - x_2$	$\sigma_y = \sqrt{\sigma_{x_1}^2 + \sigma_{x_2}^2}$
$y = x_1/x_2$ or $y = x_1 \times x_2$	$\sigma_y = y\sqrt{\left(\frac{\sigma_{x_1}}{x_1}\right)^2 + \left(\frac{\sigma_{x_2}}{x_2}\right)^2}$
$y = cx_1$ where c is a positive constant	$\sigma_y = c\sigma_{x_1}$
$y = x_1/c$ where c is a positive constant	$\sigma_y = \frac{\sigma_{x_1}}{c}$

6.4.4 Reporting Confidence Intervals

Throughout **Section 6.4,** the term “measurement uncertainty” is used interchangeably with the term “standard deviation.” In this respect, the uncertainty is qualified as numerically identical to the standard deviation associated with a normally distributed range of values. When reporting a confidence interval for a value, one provides the range of values that represent a predetermined level of confidence (i.e., 95 percent). To make this calculation, the final standard deviation—or total uncertainty σ_y, as shown in **Equation 6-18**—is multiplied by a constant factor *k*, representing the area under a normal curve as a function of the standard deviation. The values of *k* representing various intervals about a mean of normal distributions as a function of the standard deviation are given in **Table 6.6.** The following example illustrates the use of this factor in context with the propagation and reporting of uncertainty values. **Example 8** demonstrates the calculation of the activity of a sample, along with its associated activity.

Table 6.6: Areas Under Various Intervals About the Mean of a Normal Distribution

Interval ($\bar{\mu} \pm k\sigma$)	Area Under the Interval
$\bar{\mu} \pm 0.674\sigma$	0.500
$\bar{\mu} \pm 1.00\sigma$	0.683
$\bar{\mu} \pm 1.65\sigma$	0.900
$\bar{\mu} \pm 1.96\sigma$	0.950
$\bar{\mu} \pm 2.00\sigma$	0.954
$\bar{\mu} \pm 2.58\sigma$	0.990
$\bar{\mu} \pm 3.00\sigma$	0.997

Example 8: Uncertainty Propagation and Confidence Interval

A measurement process with a zero background yields a count result of 28 ± 5 counts in 5 minutes, where the ± 5 counts represents one standard deviation about a mean value of 28 counts. The detection efficiency is 0.1 ± 0.01 counts per disintegration, again representing one standard deviation about the mean.

Calculate the activity of the sample, in decays per minute (dpm), total measurement uncertainty, and the 95 percent confidence interval for the result.

The total number of disintegrations is—

$$y = \frac{x_1}{x_2} = \frac{28 \text{ counts}}{0.1 \ \text{counts/disintegration}} = 280 \text{ disintegrations}$$

Using the equation for error propagation for division, total uncertainty is—

$$\sigma_y = y\sqrt{\left(\frac{\sigma_{x_1}}{x_1}\right)^2 + \left(\frac{\sigma_{x_2}}{x_2}\right)^2} = 280\sqrt{\left(\frac{5}{28}\right)^2 + \left(\frac{0.01}{0.1}\right)^2} = 57 \text{ disintegrations}$$

The activity will then be 280/5 minutes = 56 dpm and the total uncertainty will be 57 ÷ 5 minutes = 11 dpm. (Because the count time is considered to have trivial variance, this is assumed to be a constant.)

Referring to **Table 6.6,** a *k* value of ± 1.96 represents a confidence interval equal to 95 percent about the mean of a normal distribution. Therefore, the 95 percent confidence interval would be 1.96 × 11 dpm = 22 dpm. The final result would be that a 95 percent confidence interval for mean activity is 56 ± 22 dpm at a coverage factor of *k* equal to 1.96.

6.5 Select a Service Provider to Perform Field Data Collection Activities

Often, one of the first steps in designing a survey is to select a service provider to perform field data collection activities. MARSSIM recommends that this selection take place early in the planning process so that the service provider can provide information during survey planning and participate in the design of the survey. Service providers may include in-house experts in field measurements and sample collection, health physics companies, or environmental engineering firms, among others. See **Section 6.8** and **Appendix H** for important information concerning radon service providers.

Potential service providers should be evaluated to determine their ability to perform the necessary analyses. Consideration should be given to using a field survey company that is separate from the remediation company to preclude questions of independence and conflict of interest. For large or complex sites, this evaluation may take the form of a pre-award audit. The results of this audit provide a written record of the decision to use a specific service provider. For less complex sites or facilities, a review of the potential service provider's qualifications is sufficient for the evaluation.

Six criteria should be reviewed during this evaluation:

- Does the service provider possess the validated SOPs, appropriate instrumentation, and trained personnel necessary to perform the field data collection activities, including radon/thoron measurements? Field data collection activities (e.g., scanning surveys, direct measurements, and sample collection) are defined by the data needs identified by the DQO process.
- Is the service provider experienced in performing the same or similar data collection activities?
- Does the service provider have satisfactory performance evaluation or technical review results? The service provider should be able to provide a summary of QA audits and QC measurement results to demonstrate proficiency. Equipment calibrations should be performed using National Institute of Standards and Technology (NIST) traceable reference radionuclide standards whenever possible.
- Is there adequate capacity to perform all field data collection activities within the desired timeframe? This criterion considers the number of trained personnel and quantity of calibrated equipment available to perform the specified tasks.
- Does the service provider conduct an internal QC review of all generated data that is independent of the data generators?
- Are there adequate protocols for method performance documentation, sample tracking and security (if necessary), and documentation of results?

Chapter 10 of MARLAP provides additional guidance related to field and sampling issues that affect laboratory measurements (NRC 2004). Potential service providers should have an active and fully documented quality system in place. The quality management system is typically documented in one or more documents such as a Quality Management Plan (QMP) or Quality Assurance Manual (QAM). This system should enable compliance with the objectives determined by the DQO process in **Section 2.3** (see also EPA 2006c). The elements of a quality management system are discussed in **Appendix D** and EPA QA/G-5 (EPA 2002a).

6.6 Select a Measurement Method

The combination of a measurement technique with instrumentation, or measurement method, is selected to implement a radiological survey design based on the ability to meet the MQOs (see **Section 6.1**). Note that measurement techniques are separate from survey designs. A realistic determination of the measurement method uncertainty is critical to demonstrating a method meets the MQOs. Other considerations when selecting a measurement method include—

- health and safety concerns (**Section 4.10**)
- required detection capability (**Section 6.3**)
- required measurement method uncertainty and/or required measurement quantifiability (**Section 6.4**)
- DQOs for the project

Measurement techniques are discussed in **Section 6.6.1.** Instrumentation includes a combination of a radiation detector (**Section 6.6.2**) and a display (**Section 6.6.3**). Evaluation of a measurement method and comparison to MQOs also requires an understanding of the instrument calibration (**Section 6.6.4**). Instrumentation for performing radiological measurements is varied and constantly being improved. **Section 6.6.5** provides an overview of some commonly used types of instruments and how they might be applied to FSSs. The purpose of the discussions on instrumentation is not to provide an exhaustive list of acceptable instruments, but to provide examples of how instrumentation and measurement techniques can be combined to meet the survey objectives. Additional information on instrumentation is found in **Appendix H.**

Section 6.6.6 provides information on selecting a combination of measurement technique and instrumentation to provide a measurement method. It is necessary that the selected measurement method meet the MQOs established during survey design. Selecting instrumentation can be an iterative process. Certain MQOs (e.g., MDC, required measurement method uncertainty) may not be attainable with some measurement methods. In some cases, selection of a different instrument may be all that is necessary, and in other cases a different measurement technique or an entirely different measurement method will need to be considered. Finally, in cases where the MQOs cannot be met with any available measurement methods, consult with the regulator for acceptable options.

6.6.1 Select a Measurement Technique

A measurement technique describes how a measurement is performed. The detector can be moved relative to the surface being measured (i.e., scanning), used to perform static measurements at a specified location in the survey unit (i.e., in situ or direct measurements), or some representative portion of the survey unit taken to a different location for analysis (i.e., sampling). These three measurement techniques are described in **Section 6.6.1.1, Section 6.6.1.2,** and **Section 6.6.1.3,** respectively. Smears are a type of sampling, where a portion of the removable radioactive material is collected from the surface being investigated (**Section 6.6.1.4**).

6.6.1.1 Scanning Techniques

Scanning techniques generally consist of moving portable radiation detectors at a specified distance relative to the physical surface of a survey unit at some specified speed to meet the MQOs. Scanning is used in surveys to locate radiation anomalies by searching for variations in readings, indicating gross activity levels that may require further investigation or action.

Scanning techniques can more readily provide thorough coverage of a given survey unit and are often relatively quick and inexpensive to perform.

Scanning techniques can be used alone to demonstrate that concentrations of radioactive material do not exceed release criteria. These surveys are referred to as scan-only surveys and are discussed in detail in **Section 5.3.6.1.** Important considerations include that the scan MDC and measurement method uncertainty are sufficient to meet MQOs to both quantify the average concentration of the radioactive material and to identify areas of elevated activity. Scanning equipment coupled with GPS or other locational data is strongly recommended for scan-only surveys.

Maintaining the specified distance and speed during scanning can be difficult, especially with hand-held instruments and irregularly shaped surfaces. Variations in source-to-detector distance and scan speed can result in increased total measurement method uncertainty. Determining a calibration function for situations other than surficial radionuclides uniformly distributed on a plane can be complicated and may also contribute to the total measurement method uncertainty.

6.6.1.2 Direct Measurements

Direct measurements, also referred to as in situ measurements, are taken by placing the instrument in a fixed position at a specified distance from the surface of a given survey unit and taking a discrete measurement for a pre-determined time interval. Direct measurements may be combined with scanning measurements in a FSS design. In situ measurements are used generally to provide an estimate of the average radionuclide concentration or level of activity over a certain area or volume defined by the calibration function. In situ techniques are not typically used to identify or quantify small areas or volumes of elevated radionuclide concentration or activity.

Determining a calibration function and the associated MDA/MDC can be complicated and may contribute to the total measurement method uncertainty, especially for situations other than radionuclides uniformly distributed on a plane or through a regularly shaped volume (e.g., a disk or cylinder).

However, in applicable situations and at the concurrence of the regulator, direct measurements may be substituted for laboratory analysis. For example, all or a fraction of the systematic soil samples may be measured in situ rather than traditional laboratory analysis.

6.6.1.3 Sampling

Sampling consists of removing a representative portion of the survey unit for separate laboratory analysis. This measurement method generally has greater detection capability and less measurement uncertainty than techniques that may be implemented as scanning or direct measurements. Sampling is discussed in more detail in **Chapter 7.**

6.6.1.4 Smears

Smears, sometimes referred to as smear tests, swipes, or wipes, are used to provide an estimate of removable radioactive material on the surface. Smears are a type of sample where a filter paper or other substance is used to wipe a specified area of a surface. The filter paper or other substance is then tested for the presence of removable radioactive material. The amount of removable radioactive material transferred to the smear will depend on a number of factors, including the type of swipe or smear material, the method used, the physical and chemical nature of the surface being tested, the surface roughness, and the physical and chemical nature of the radioactive material. These factors result in the need to establish a removal factor that will be subject to some uncertainty. For this reason, although smears with detectable radioactive material provide a qualitative indication of removable radioactive material, caution should be exercised when using any quantitative results from smears. EPA 600/R-11/122 (EPA 2011) provides more detailed guidance on the use of smears.

6.6.2 Select Instrumentation—Radiation Detectors

The particular capabilities of a radiation detector will establish its potential applications in conducting a specific type of survey. Radiation detectors can be divided into four general classes based on the detector material or the application: (1) gas-filled detectors, (2) scintillation detectors, (3) solid-state detectors, and (4) passive integrating detectors. See **Appendix H** for more information on the detectors discussed in this section.

6.6.2.1 Gas-Filled Detectors

Radiation interacts with the fill gas, producing ion-pairs that are collected by charged electrodes. Commonly used gas-filled detectors are categorized as ionization, proportional, or GM, referring to the region of gas amplification in which they are operated. The fill gas varies, but the most common are—

- air
- argon with a small amount of methane (usually 10 percent methane by mass, referred to as P-10 gas)
- neon or helium with a small amount of a halogen (e.g., chlorine or bromine) added as a quenching agent

6.6.2.2 Scintillation Detectors

Radiation interacts with a solid or liquid medium, causing electronic transitions to excited states in a luminescent material. The excited states decay rapidly, emitting photons that, in turn, are captured by a photomultiplier tube. The ensuing electrical signal is proportional to the scintillator light output, which, under the right conditions, is proportional to the energy loss that produced the scintillation. The most common scintillator materials are NaI(Tl), silver-activated zinc sulfide (ZnS(Ag)), cadmium telluride (CdTe), thallium-activated cesium iodide (CsI(Tl)), and plastic organic scintillators. The most traditional radiation survey instruments are the NaI(Tl) detector used for gamma surveys and the ZnS(Ag) detector for alpha surveys.

6.6.2.3 Solid-State Detectors

Radiation interacting with a semiconductor material creates electron-hole pairs that are collected by a charged electrode. The design and operating conditions of a specific solid-state detector determines the types of radiations (alpha, beta, or gamma) that can be measured, the detection limit of the measurements, and the ability of the detector to resolve the energies of the interacting radiations. The common semiconductor materials in use are germanium, silicon, and cadmium zinc telluride (CZT), which are available in both n and p types in various configurations.

Spectrometric techniques using these detectors provide a marked increase in energy resolution in many situations. When a particular radionuclide contributes only a fraction of the total particle fluence, photon fluence, or both from all sources (natural or manmade background), gross measurements are inadequate and nuclide-specific measurements are necessary. Spectrometry provides the means to discriminate among various radionuclides based on characteristic energies. Direct gamma spectrometry is particularly effective in field measurements, because the penetrating nature of the radiation allows one to “see” beyond immediate radioactive materials on the surface. The availability of large, high-efficiency germanium detectors permits measurement of low-abundance gamma emitters, such as ^{238}U.

6.6.2.4 Passive Integrating Detectors

An additional class of instruments consists of passive, integrating detectors and associated reading/analyzing instruments. The integrated ionization is read using a laboratory or hand-held reader. This class includes thermoluminescent dosimeters (TLDs), optically stimulated luminescence (OSL) dosimeters, and electret ion chambers (EICs). Because these detectors are passive and can be exposed for relatively long periods of time, they can provide better sensitivity for measuring low activity levels, such as free release limits, or for ongoing surveillance. The ability to read and present data onsite is a useful feature, and such systems are comparable to direct reading instruments.

The scintillation materials in **Section 6.6.2.2** are selected for their prompt fluorescence characteristics. In another class of inorganic crystals, called TLDs, the crystal material and impurities are chosen so that the free electrons and holes created following the absorption of energy from the radiation are trapped by impurities in the crystalline lattice, thus locking the excitation energy in the crystal. Such materials are used as passive, integrating detectors. After removal from the exposure area, the TLDs are heated in a reader, which measures the total amount of light produced when the energy is released. The total amount of light is proportional to the number of trapped, excited electrons, which, in turn, is proportional to the amount of energy absorbed from the radiation. The intensity of the light emitted from the thermoluminescent crystals is thus directly proportional to the radiation dose. TLDs come in a large number of materials, the most common of which are lithium fluoride (LiF), manganese-activated calcium fluoride (CaF_2:Mn), dysprosium-activated calcium fluoride (CaF_2:Dy), manganese-activated calcium sulfate ($CaSO_4$:Mn), dysprosium-activated calcium sulfate ($CaSO_4$:Dy), and carbon-activated aluminum oxide (Al_2O_3:C).

OSL dosimeters are similar in principle to TLDs but use light instead of heat to release the free electrons and holes trapped when radiation is absorbed. Advantages of OSL dosimeters over TLDs include lower limits of detection and the fact that OSL dosimeters can be read multiple times and can be reread later, if necessary.

The EIC consists of a very stable electret (a charged Teflon® disk) mounted inside a small chamber made of electrically charged plastic. The ions produced inside this air-filled chamber are collected onto the electret, causing a reduction of its surface charge. The reduction in charge is a function of the total ionization during a specific monitoring period and the specific chamber volume. This change in voltage is measured with a surface potential voltmeter.

6.6.3 Display and Recording Equipment

Radiation detectors are connected to electronic devices to (1) provide a source of power for detector operation and (2) enable measurement of the quantity or quality of the radiation interactions that are occurring in the detector. The quality of the radiation interaction refers to the amount of energy transferred to the detector. In many cases, radiation interacts with other material (e.g., air) before interacting with the detector or only partially interacts with the detector (e.g., Compton scattering or pair production for photons). Because the energy recorded by the detector is affected, there is an increased probability of incorrectly identifying the radionuclide.

The most common recording or display device used for portable radiation measurement systems is a ratemeter. This device provides a display on either an analog meter representing the number of events occurring over some time period (e.g., cpm), or, in the case of digital ratemeters, on a digital display. The number of events can also be accumulated over a preset time period using a digital scaling device. The resulting information from a scaling device is the total number of events that occurred over a fixed period of time, where a ratemeter display varies with time and represents a short-term average of the event rate. Determining the average level on a ratemeter will require judgment by the user, especially when a low frequency of events results in significant variations in the meter reading. The use of a ratemeter, although acceptable for certain scanning applications, is discouraged for performing fixed measurements (e.g., gross alpha/beta.)

Pulse height analyzers are specialized electronic devices designed to measure and record the number of pulses or events that occur at different pulse height levels at specific energies. These types of devices are used with detectors that produce output pulses proportional in height to the energy deposited within them by the interacting radiation. They can be used to record only those events occurring in a detector within a single band of energy or can simultaneously record the events in multiple energy ranges. In the former case, the equipment is known as a single-channel analyzer; the latter application is referred to as a multichannel analyzer. Both types of analyzers can quantify specific radionuclides.

6.6.4 Instrument Calibration

Calibration refers to the determination and adjustment of the instrument response in a particular radiation field of known intensity. Proper calibration procedures are an essential requisite toward providing confidence in measurements made to demonstrate compliance with remediation criteria. Certain factors, such as energy dependence and environmental conditions, require consideration in the calibration process, depending on the conditions of use of the instrument in the field. Considerations for the use and calibration of instruments include—

- the radiation type for which the instrument is designed
- the radiation energies within the range of energies for which the instrument is designed
- the environmental conditions for which the instrument is designed
- the influencing factors, such as magnetic and electrostatic fields, for which the instrument is designed
- the orientation of the instrument, such that geotropic (gravity) effects are not a concern
- the manner the instrument is used, such that it will not be subject to mechanical or thermal stress beyond that for which it is designed

Routine calibration commonly involves the use of one or more sources of a specific radiation type and energy and of sufficient activity to provide adequate field intensities for calibration on all ranges of concern.

Actual field conditions under which the radiation detection instrument will be used may differ significantly from those present during routine calibration. Factors that may affect calibration validity include—

- The energies of radioactive sources used for routine calibration may differ significantly from those of radionuclides in the field.
- The source-detector geometry (e.g., point source or large area distributed source) used for routine calibration may be different than that found in the field.
- The source-to-detector distance typically used for routine calibration may not always be achievable in the field.
- The condition and composition of the surface being monitored (e.g., sealed concrete, scabbled concrete, carbon steel, stainless steel, and wood) and the presence of overlaying material (e.g., water, dust, oil, paint) may result in a decreased instrument response relative to that observed during routine calibration.

If the actual field conditions differ significantly from the calibration assumptions, a special calibration for specific field conditions may be required. Such an extensive calibration need only be done once to determine the effects of the range of field conditions that may be encountered at the site. If responses under routine calibration conditions and proposed use conditions are significantly different, a correction factor or chart should be supplied with the instrument for use under the proposed conditions.

As a minimum, each measurement system (detector/readout combination) should be calibrated annually and response checked with a source following calibration (ANSI 2013). Instruments may require more frequent calibration, if recommended by the manufacturer. Re-calibration of field instruments is also required if an instrument fails a performance check or if it has undergone repair or any modification that could affect its response. The system should be calibrated to minimize potential errors during data transmission and re-transmission. The user may decide to perform calibrations following industry recognized procedures (ANSI 1997, NCRP 1978, NCRP 1985, NCRP 1991, ISO 1988, HPS 1994a, HPS 1994b), or the user can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization.

Calibration sources should be traceable to NIST. Where NIST-traceable standards are not available, standards obtained from an industry-recognized organization (e.g., the New Brunswick Laboratory for various uranium, thorium, and plutonium standards) may be used.

Calibration of instruments for measurement of residual radioactive material on surfaces should be performed such that a direct instrument response can be accurately converted to the 4π (total) emission rate from the source. An accurate determination of activity from a measurement of count rate above a surface in most cases is an extremely complex task because of the need to determine appropriate characteristics of the source, including decay scheme, geometry, energy, scatter, and self-absorption. Proper calibration ensures that systematic errors in measurements are controlled to help ensure that the MQO for measurement method uncertainty is met.

The variables that affect instrument response should be understood. Therefore, the calibration should account for the following factors (where necessary):

- Calibrations for point and large area source geometries may differ, and both may be necessary if areas of activity smaller than the probe area and regions of activity larger than the probe area are present.
- Calibration should either be performed with the radionuclide of concern or with appropriate correction factors developed for the radionuclide(s) present based on calibrations with nuclides emitting radiations similar to the radionuclide of concern.
- For portable instrumentation, calibrations should account for the substrate of concern (i.e., concrete, steel) or appropriate correction factors developed for the substrates relative to the actual calibration standard substrate. This is especially important for beta emitters because backscatter is significant and varies with the composition of the substrate. Conversion factors developed during the calibration process should be for the same counting geometry to be used during the actual use of the detector.

For building surface DCGLs, the level of residual radioactive material is typically expressed in terms of the activity per unit area, normally Bq/m^2 or dpm per 100 cm^2. In many facilities, residual radioactive material on the surface is assessed by converting the instrument response (in cpm) to surface activity using the overall total efficiency. The total efficiency may be considered to represent the product of two factors: the instrument (detector) efficiency and the source efficiency. Use of the total efficiency is not a problem, provided that the calibration source exhibits characteristics similar to the residual radioactive material on the surface (i.e., radiation energy, backscatter effects, source geometry, self-absorption). In practice, this is rarely the case; more likely, instrument efficiencies are determined with a clean, stainless steel source, and then those efficiencies are used to determine the level of residual radioactive material on a dust-covered concrete surface. By separating the efficiency into two components, the surveyor has greater ability to consider the actual characteristics of the residual radioactive material on the surface.

The instrument efficiency is defined as the ratio of the net count rate of the instrument to the surface emission rate of a source for a specified geometry. The surface emission rate is defined as the number of particles of a given type above a given energy emerging from the front face of the source per unit time. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that effect the radiation emitted from the source. Thus, the instrument efficiency is determined by the ratio of the net count rate and the surface emission rate.

The instrument efficiency is determined during calibration by obtaining a static count with the detector over a calibration source that has a traceable activity or surface emission rate. In many cases, a source emission rate is measured by the manufacturer and certified as NIST traceable. The source activity is then calculated from the surface emission rate based on assumed backscatter and self-absorption properties of the source. The maximum value of instrument efficiency is 1.

The source efficiency is defined as the ratio of the number of particles of a given type emerging from the front face of a source to the number of particles of the same type created or released within the source per unit time. The source efficiency takes into account the increased particle emission due to backscatter effects, as well as the decreased particle emission due to self-absorption losses. For an ideal source (i.e., no backscatter or self-absorption), the value of the source efficiency is 0.5. Many real sources will exhibit values less than 0.5, although values greater than 0.5 are possible, depending on the relative importance of the absorption and backscatter processes.

Source efficiencies may be determined experimentally. Alternatively, ISO-7503-1 (ISO 1988) makes recommendations for default source efficiencies. A source efficiency of 0.5 is recommended for beta emitters with maximum energies above 0.4 megaelectronvolts (MeV). Alpha emitters and beta emitters with maximum beta energies between 0.15 and 0.4 MeV have a recommended source efficiency of 0.25. Source efficiencies for some common surface materials and overlaying material are provided in NUREG-1507 (NRC 1997a).

Instrument efficiency may be affected by detector-related factors, such as detector size (probe surface area); window density thickness; geotropism; instrument response time; counting time (in static mode); scan rate (in scan mode); and ambient conditions, such as temperature, pressure, and humidity. Instrument efficiency also depends on solid angle effects, which include source-to-detector distance and source geometry.

Source efficiency may be affected by source-related factors, such as the type of radiation and its energy, source uniformity, surface roughness and coverings, and surface composition (e.g., wood, metal, concrete).

The calibration of gamma detectors for the measurement of photon radiation fields should also provide reasonable assurance of acceptable accuracy in field measurements. Use of these instruments for demonstration of compliance with DCGLs is complicated by the fact that most DCGLs produce exposure rates of at most a few μR/h. Several of the portable survey instruments currently available in the United States for exposure rate measurements of ~1 μR/h (often referred to as micro-R meters) have full scale intensities of ~3–5 μR/h on the first range. This is below the ambient background for most low radiation areas and most calibration laboratories. A typical background exposure rate of 10 mR/h gives a background dose rate of 100 millirem/year (mrem/y) Even on the second range, the ambient background in the calibration laboratory is normally a significant part of the range and must be taken into consideration during calibration. The instruments commonly are not energy-compensated and are very sensitive to the scattered radiation that may be produced by the walls and floor of the room or additional shielding required to lower the ambient background.

Low-intensity sources and large distances between the source and detector can be used for low-level calibrations if the appropriate precautions are taken. Field characterization of low-level sources with traceable transfer standards can be difficult because of the poor signal-to-noise ratio. To achieve adequate detector signal, the distance between the detector and the source generally will be as small as possible while still maintaining good geometry (5–7 detector diameters).

Corrections for scatter can be made using a shadow-shield technique in which a shield of sufficient density and thickness is placed about midway between the source and the detector to eliminate virtually all the primary radiation. The dimensions of the shield should be the minimum required to reduce the primary radiation intensity at the detector location to less than 2 percent of its unshielded value. The change in reading caused by the shield's removal is attributed to the primary field from the source at the detector position.

In some instruments that produce pulses (GM counters or scintillation counters), the detector can be separated electronically from the readout electronics, and the detector output can be simulated with a suitable pulser. Caution must be exercised to ensure that either the high voltage is properly blocked or that the pulser is designed for this application. If this can be accomplished, the instrument can first be calibrated on a higher range that is not affected by the ambient background and in a geometry where scatter is not a problem and, after disconnecting the detector, to provide the pulse-rate from the pulser, which will give the same instrument response. The pulse rate can then be related to field strength and reduced to give readings on lower ranges (with the detector disconnected) even below the ambient background. This technique does not take into account any inherent detector background independent of the external background.

Ionization chambers are commonly used to measure radiation fields at very low levels. To obtain the sensitivity necessary to measure these radiation levels, the instruments are frequently very large and often pressurized. These instruments have some of the same calibration problems as the more portable micro-R meters described above. The same precautions (shadow shield) must be taken to separate the response of the instrument to the source and to scattered radiation. Generally, it is not possible to substitute an electronic pulser for the radiation field in these instruments.

For energy-dependent gamma scintillation instruments, such as NaI(Tl) detectors, calibration for the gamma energy spectrum at a specific site may be accomplished by comparing the instrument response to that of a pressurized ionization chamber, or equivalent detector, at different locations on the site. Multiple radionuclides with various photon energies may also be used to calibrate the system for the specific energy of interest.

In the interval between calibrations, the instrument should receive a daily performance check when in use. In some cases, a performance check following use may also provide valuable information. This calibration check is merely intended to establish whether the instrument is operating within certain specified, rather large, uncertainty limits. The initial performance check should be conducted following the calibration by placing the source in a fixed, reproducible location and recording the instrument reading. The source should be identified along with the instrument, and the same check source should be used daily in the same fashion to demonstrate the instrument's operability when the instrument is in use. Location and other specific conditions should be recorded as well (e.g., indoor, outdoor, inside trailer, inside vehicle, on the roof, etc.). For analog readout (count rate) instruments, a variation of $\pm$ 20 percent is usually considered acceptable. Optionally, instruments that integrate events and display the total on a digital readout typically provide an acceptable average response range of 2 or 3 standard deviations. This is achieved by performing a series of repetitive measurements (10 or more is suggested) of background and check source response and determining the average and standard deviation of those measurements. From a practical standpoint, a maximum deviation of $\pm$ 20 percent is usually adequate when compared with other uncertainties associated with the use of the equipment. The amount of uncertainty allowed in the response checks should be consistent with the level of uncertainty allowed in the final data. Ultimately the decision maker determines what level of uncertainty is acceptable.

Instrument response, including both the background and check source response of the instrument, should be tested and recorded at a frequency that ensures the data collected with the equipment is reliable. For most portable radiation survey equipment, MARSSIM recommends that a response check be performed at least twice daily when in use—typically before beginning the day's measurements and again following the conclusion of measurements on that same day. Additional checks can be performed if warranted by the instrument and the conditions under which it is used. If the instrument response does not fall within the established range, the instrument is removed from use until the reason for the deviation can be resolved and acceptable response again demonstrated. If the instrument fails the post-survey source check, all data collected during that time period with the instrument must be carefully reviewed and possibly adjusted or discarded, depending on the cause of the failure. Ultimately, the frequency of response checks must be balanced with the stability of the equipment being used under field conditions and the quantity of data being collected. For example, if the instrument experiences a sudden failure during the day's work due to physical harm, such as a punctured probe, then the data collected up until that point is probably acceptable even though a post-use performance check cannot be performed. If no obvious failure occurred but the instrument failed the post-use response check, then the data collected with that instrument since the last response check should be viewed with great skepticism and possibly re-collected or randomly checked with a different instrument. Additional corrective action alternatives are presented in **Appendix D.** If recalibration is necessary, acceptable response ranges must be reestablished and documented.

Record requirements vary considerably and depend heavily on the needs of the user. Even though Federal and State regulatory agencies all specify requirements, the following records should be considered a minimum:

- laboratory quality control
    - records documenting the traceability of radiological standards
    - records documenting the traceability of electronic test equipment
- record-keeping of instrument calibration files
    - date the instrument was received in the calibration laboratory
    - initial condition of the instrument, including mechanical condition (e.g., loose or broken parts, dents, punctures), electrical condition (e.g., switches, meter movement, batteries), and radiological condition (i.e., presence or absence of contamination)
    - calibrator's records, including training records and signature on calibration records
    - calibration data, including model and serial number of instrument, date of calibration, recommended recalibration date, identification of source(s) used, NIST certificate or standard certificate from the industry-recognized organization (certificate must include the standard expiration date), "as found" calibration results, and final calibration results—"as returned" for use

In addition, records of instrument problems, failures, and maintenance can be included and are useful in assessing performance and identifying possible needs for altered calibration frequencies for some instruments. Calibration records should be maintained at the facility where the instruments are used as permanent records and should be available either as hard copies or in safe computer storage.

6.6.5 Select Instrumentation Type—Radiation Survey Equipment

This section briefly describes the typical types of instrumentation that may be used to conduct radiological surveys. More detailed information relevant to each type of instrument and measurement method is provided in **Appendix H.**

6.6.5.1 Hand-Held Instruments

Hand-held instruments typically are composed of a detection probe (utilizing a single detector) and an electronic instrument to provide power to the detector and to interpret data from the detector to provide a measurement display. They may be used to perform scanning surveys or direct measurements. Hand-held measurements also allow the user the flexibility to constantly vary the source-to-detector geometry for obtaining data from difficult-to-measure areas.

6.6.5.2 Large Area Detectors

Although hand-held instruments are very useful for making direct measurements and scanning small and/or difficult-to-measure areas, large area detectors provide advantages when the survey unit includes large, easily accessible areas. These detectors may consist of either a single large detector or an array of detectors. Unlike most hand-held detectors, which can only measure the concentration in a small area—typically about 100 cm^2—some detectors can measure the concentration in a much larger area. When used in combination with data logging and positioning systems, large-area detectors can be used in place of direct measurements and scanning, if the systems can meet the required MQOs.

6.6.5.3 In situ Gamma Spectroscopy

Some in situ gamma spectroscopy (ISGS) systems consist of a small hand-held unit that incorporates the detector and counting electronics into a single package. Other ISGS systems consist of a semiconductor detector, a cryostat, a multichannel analyzer electronics package that provides amplification and analysis of the energy pulse heights, and a computer system for data collection and analysis. ISGS systems typically are applied to perform direct measurements, but they may be incorporated into innovative detection equipment setups to perform scanning surveys.

6.6.5.4 Laboratory Analysis

Laboratory analysis consists of analyzing a portion or sample of the surface soil or building surface. The laboratory will generally have recommendations or requirements concerning the amount and types of samples needed for the analysis of radionuclides or radiations. Communications should be established between the field team collecting the samples and the laboratory analyzing the samples. More information on sampling is provided in **Section 7.5.** Laboratory analyses can be developed for any radionuclide with any material, given sufficient resources. Laboratory analyses typically require more time to complete than field analyses. The laboratory may be located onsite or offsite. The quality of laboratory data typically is greater than data collected in the field, because the laboratory is better able to control sources of measurement method uncertainty. The planning team should consider the resources available for laboratory analysis (e.g., time, money), the sample collection requirements or recommendations, and the requirements for data quality (e.g., MDC, required measurement method uncertainty) during discussions with the laboratory.

6.6.6 Select a Measurement Method

Table 6.7 illustrates the potential applications for combinations of the instrument and measurement techniques discussed in **Sections 6.6.1 and 6.6.5,** respectively. Sampling followed by laboratory analysis is not included in these tables but is considered "GOOD" for all applications. Please note the following qualifiers:

- GOOD: The measurement technique is well-suited for performing this application.
- FAIR: The measurement technique can adequately perform this application.
- POOR: The measurement technique is poorly suited for performing this application.
- NA: The measurement technique cannot perform this application.
- Few: A relatively small number, usually three or less.
- Many: A relatively large number, usually more than three.

Table 6.8 illustrates that most measurement techniques can be applied to almost any sample and type of radioactive material. The quantity of samples to be surveyed becomes a major factor for the selection of measurement instruments and techniques described in this chapter.

Facilities that conduct routine surveys may benefit financially from investing in measurement instruments and techniques that require less manual labor to conduct disposition surveys. Use of such automated systems will also reduce the potential for ergonomic injuries and attendant costs associated with routine, repetitive surveys performed using hand-held instruments.

Hand-held surveying remains the more economical choice for a small area, but as the area increases, the cost of an automated system becomes an increasingly worthwhile investment to reduce manual labor costs associated with surveying. Note that alpha radiation has no survey design options that are described as "GOOD" in **Table 6.7.** The planning team should revisit earlier DQO selections to see if a different approach is more acceptable.

Each type of measurement technique has associated advantages and disadvantages, some of which are summarized in **Table 6.8.** All the measurement techniques described in this table include source-to-detector geometry and sampling variability as common disadvantages.

Table 6.7: Potential Applications for Instrumentation and Measurement Technique Combinations

Radiation Type	Hand-Held Instruments	In Situ Gamma Spectroscopy
Direct Measurements		
Alpha	FAIR	NA
Beta	GOOD	NA
Photon	GOOD	GOOD
Neutron	GOOD	NA
Scanning Surveys		
Alpha	POOR	NA
Beta	GOOD	NA
Photon	GOOD	GOOD
Neutron	FAIR	NA

6.7 Data Conversion

This section describes methods for converting survey data to appropriate units for comparison to radiological criteria. As stated in **Chapter 4,** conditions applicable to satisfying decommissioning requirements include determining that any residual radioactive material will not result in individuals' being exposed to unacceptable levels of radiation or radioactive materials.

Radiation survey data are usually obtained in units that have no intrinsic meaning relative to DCGLs, such as the number of counts per unit time. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. Alternatively, the DCGL can be converted into the same units used to record survey results.

6.7.1 Surface Activity

When measuring surface activity, it is important to account for the physical surface area assessed by the detector to make probe area corrections and report data in the proper units (i.e., Bq/m2, dpm/100 cm2). This is termed the physical probe area. A common misuse is to make probe area corrections using the effective probe area, which accounts for the amount of the physical probe area covered by a protective screen. **Figure 6.2** illustrates the difference between the physical and effective probe areas. The physical probe area is used because the reduced detector response due to the screen is accounted for during instrument calibration as long as the screen is in place during calibration.

Table 6.8: Advantages and Disadvantages of Instrumentation and Measurement Technique Combinations

Instrument	Measurement Technique	Advantages	Disadvantages
Hand-Held Instruments	Direct	• Generally allows flexibility in media to be measured. • Detection equipment is usually portable. • Detectors are available to efficiently measure alpha, beta, gamma, x-ray, and neutron radiation. • Measurement equipment is relatively low cost. • May provide a good option for small areas.	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large areas labor-intensive. • Detector windows may be fragile. • Most do not provide nuclide identification.
Hand-Held Instruments	Scanning	• Generally allows flexibility in media to be measured. • Detection equipment is usually portable. • Detectors are available to efficiently measure beta, gamma, x-ray, and neutron radiation. • Measurement equipment is relatively low cost. • May provide a good option for small areas.	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large areas labor-intensive. • Detector windows may be fragile. • Most do not provide nuclide identification. • Incorporates more potential sources of uncertainty than most instrument and measurement technique combinations. • Potential ergonomic injuries and attendant costs associated with repetitive surveys.

Instrument	Measurement Technique	Advantages	Disadvantages
Hand-Held Instruments	Smear	• Only measurement technique for assessing removable radioactive material. • Removable radioactive material can be transferred and assessed in a low background counting area.	• Instrument background may not be sufficiently low. • Detectors with a counting sensitive region larger than the smear surface area may require counting adjustments to account for inherent backgrounds associated with other media located under the detector sensitive region. • The results are not always reproducible and may not be considered quantitative.
ISGS	Direct	• Provides quantitative measurements with flexible calibration. • Generally requires a moderate amount of labor. • May be cost-effective for measuring large areas. • Good peak resolution with high purity germanium detectors.	• Instrumentation may be expensive and difficult to set up and maintain. • May require liquid nitrogen supply (with ISGS semiconductor systems). • Size of detection equipment may discourage portability. • Poor peak resolution with NaI(Tl) detectors.
ISGS	Scanning	• Provides quantitative measurements with flexible calibration. • Generally requires a moderate amount of labor. • May be cost-effective for measuring large areas.	• Instrumentation may be expensive and difficult to set up and maintain. • May require liquid nitrogen supply (with ISGS semiconductor systems). • Size of detection equipment may discourage portability.

Instrument	Measurement Technique	Advantages	Disadvantages
Laboratory Analysis	Sampling	• Generally provides the lowest MDCs and measurement method uncertainties, even for difficult-to-measure radionuclides. • Allows positive identification of radionuclides without gammas.	• Most costly and time-consuming measurement technique. • May incur increased overhead costs while personnel are waiting for analytical results. • Great care must be taken to ensure samples are representative. • Detector windows may be fragile.
Laboratory Analysis	Smear	• Only measurement technique for assessing removable radioactive material. • Removable radioactive material can be transferred and assessed in a low background counting area.	• Instrument background may not be sufficiently low. • Detectors with a counting sensitive region larger than the smear surface area may require counting adjustments to account for inherent backgrounds associated with other media located under the detector's sensitive region. • The results are not always reproducible and may not be considered quantitative.

Abbreviation: ISGS = in situ gamma spectrometer; MDC = minimum detectable concentration.

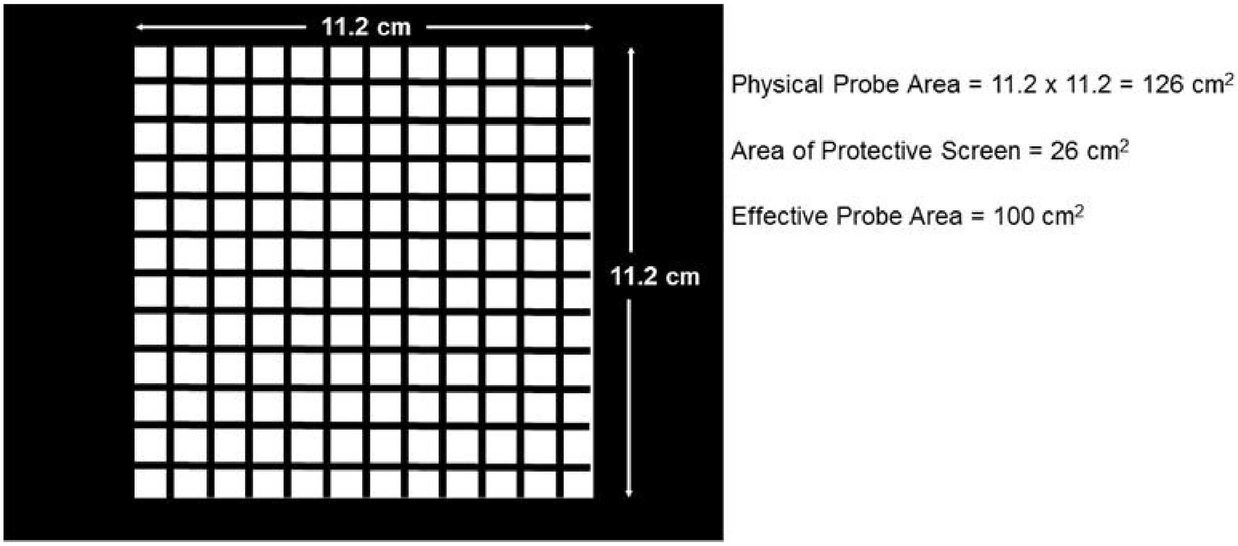


Figure 6.2: The Physical Probe Area of a Detector: Gas Flow Proportional Detector with Physical Probe Area of 126 cm^2

The conversion of instrument display in counts to surface activity units of Bq/m^2 is obtained using **Equation 6-19:**

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times W} \tag{6-19}$$

where C_s is the integrated counts recorded by the instrument, t_s is the time period over which the counts were recorded in seconds, ε_t is the total efficiency of the instrument in counts per disintegration, effectively the product of the instrument efficiency (ε_i) and the source efficiency (ε_s), and W is the physical probe area in square meters (m^2).To convert instrument counts to conventional surface activity units of decays per minute per 100 cm^2, **Equation 6-19** can be modified as shown in **Equation 6-20:**

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times (W/100)} \tag{6-20}$$

where t_s is recorded in minutes instead of seconds, and W is recorded in square centimeters instead of square meters.

Most instruments have background counts associated with the operation of the instrument. A correction for instrument background can be included in the data conversion calculation, as shown in **Equation 6-21:**

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t \times W} \tag{6-21}$$

where C_b is the background counts recorded by the instrument, and t_b is the time period over which the background counts were recorded in seconds. Note that the instrument background is not the same as the measurements in the background reference area used to perform the statistical tests described in **Chapter 8. Equation 6-17** can be modified to provide conventional surface activity units of decays per minute per 100 cm^2, as shown in **Equation 6-22:**

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t \times (W/100)} \qquad (6\text{-}22)$$

where t_s and t_b are recorded in minutes instead of seconds, and W is recorded in square centimeters instead of square meters.

The presence of multiple radionuclides at a site requires additional considerations for demonstrating compliance with a dose- or risk-based requirement. As demonstrated in **Section 4.5.3,** a gross activity DCGL should be determined. **Example 9** illustrates the calculation of a weighted efficiency for a gross activity DCGL.

Example 9: Calculation of a Weighted Efficiency for a Gross Activity Derived Concentration Guideline Level

Consider a site contaminated with cesium-137 (^{137}Cs) and strontium/yttrium-90 (^{90}Sr/Y), with ^{137}Cs representing 60 percent of the total activity. The relative fractions are 0.6 for ^{137}Cs and 0.4 for ^{90}Sr/Y. If the derived concentration guideline level (DCGL) for ^{137}Cs is 8,300 becquerels per square meter (Bq/m^2; 5,000 decays per minute [dpm]/100 square centimeters [cm^2]) and the DCGL for ^{90}Sr/Y is 12,000 Bq/m^2 (7,200 dpm/100 cm^2), the gross activity DCGL is calculated using **Equation 4-10,** as shown below:

$$\text{DCGL}_{\text{Gross Activity}} = \frac{1}{\frac{f_{\text{Cs}}}{\text{DCGL}_{\text{Cs}}} + \frac{f_{\text{Sr/Y}}}{\text{DCGL}_{\text{Sr/Y}}}} = \frac{1}{\frac{0.6}{8{,}300 \text{ Bq/m}^2} + \frac{0.4}{12{,}000 \text{ Bq/m}^2}}$$
$$= 9{,}500 \text{ Bq/m}^2 \ (5{,}700 \text{ dpm/100 cm}^2)$$

Note that because the half-lives of ^{137}Cs and ^{90}Sr are approximately the same, the relative fractions of the two radionuclides will not change because both decay at the same rate. For other radionuclides, the relative fractions will change over time from the decay of one radionuclide relative to the other.

It is important to use an appropriately weighted total efficiency to convert from instrument counts to surface activity units using **Equations 6-19 through 6-22.** In this example, the individual efficiencies for ^{137}Cs and ^{90}Sr/Y should first be independently evaluated. The maximum energies for beta particles for ^{137}Cs and ^{90}Sr/Y are 0.51 MeV and 2.28 MeV, respectively. The corresponding instrument efficiencies for ^{137}Cs and ^{90}Sr/Y are determined to be 0.38 and 0.45, respectively. The surface efficiency of both nuclides is estimated to be 0.5.

The total efficiencies are calculated by multiplying the surface efficiency by the instrument efficiency, as shown below (see **Section 4.12.5.1** for further explanation):

$$\varepsilon_{t,\mathrm{Cs}} = \varepsilon_{s,\mathrm{Cs}} \times \varepsilon_{i,\mathrm{Cs}} = (0.5)(0.38) = 0.19$$

$$\varepsilon_{t,\mathrm{Sr/Y}} = \varepsilon_{s,\mathrm{Sr/Y}} \times \varepsilon_{i,\mathrm{Sr/Y}} = (0.5)(0.45) = 0.22$$

The overall efficiency is then determined by weighting each individual radionuclide efficiency by the relative fraction of each radionuclide (**Equation 4-21**):

$$\varepsilon_t = f_{\mathrm{Cs}}\varepsilon_{t,\mathrm{Cs}} + f_{\mathrm{Sr/Y}}\varepsilon_{t,\mathrm{Sr/Y}} = (0.6)(0.19){+}(0.4)(0.22) = 0.20$$

The overall efficiency is 0.20 (20 percent).

6.7.2 Soil Radionuclide Concentration and Exposure Rates

Analytical procedures, such as alpha and gamma spectrometry, are typically used to determine the radionuclide concentration in soil in units of Bq/kg. Net counts are converted to soil DCGL units by dividing by the time, detector or counter efficiency, mass or volume of the sample, and by the fractional recovery or yield of the chemistry procedure (if applicable). Refer to **Chapter 7** for examples of analytical procedures.

Instruments, such as a pressurized ionization chamber (PIC) or micro-R meter are used to measure exposure rate. Typically, exposure rates are read directly in millisieverts per hour (mSv/h) (Standard International System of Units) or microroentgens (μR) per hour. A gamma scintillation detector (e.g., NaI(Tl)) provides data in cpm, and conversion to mSv/h is accomplished by using site-specific calibration factors developed for the specific instrument (**Section 6.6.4**).

In situ gamma spectrometry data may require special analysis routines before the spectral data can be converted to soil concentration units or exposure rates. Commercially available measurement systems may use proprietary methods to convert instrument counts to the reported units. Although it is not always necessary to understand the conversion calculations, any deviations from assumptions included in the conversion must be accounted for in the estimate of total measurement uncertainty (**Section 6.4**). Consult the manufacturer to ensure the total measurement uncertainty is determined correctly.

6.8 Radon Measurements

There are three radon isotopes in nature: ^{222}Rn (radon) in the ^{238}U decay chain, ^{220}Rn (thoron) in the ^{232}Th decay chain, and ^{219}Rn (actinon) in the ^{235}U decay chain. ^{219}Rn is the least abundant of these three isotopes, and because of its short half-life of 4 seconds, it has the least probability of emanating into the atmosphere before decaying. ^{220}Rn, with a 55-second half-life, is somewhat more mobile. ^{222}Rn, with a 3.8-day half-life, is capable of migrating through soil or building material and reaching the atmosphere. Therefore, in most situations, ^{222}Rn should be the predominant airborne radon isotope. In other instances, thorium-containing building material or interior building structures where processed thorium ore is present can result in thoron's becoming the predominant airborne radon isotope.

In some cases, radon may be detected within structures that do not contain residual radioactive material, and conversely, some structures that contain residual radioactive material may not yield detectable radon or thoron. Consult with your regulator for the applicability of radon or thoron measurements as part of a site survey.

Because of the widespread nature of indoor air radon, many states have developed requirements for certification/qualification of people who perform radon services. Therefore, as part of the qualifications for the service provider, determine whether the measurement provider or the laboratory analyzing the measurements is required to be certified by the state or locality where the work is being performed. State radon contacts can be found at https://www.epa.gov/radon/find-information-about-local-radon-zones-and-state-contact-information.

Many techniques have been developed over the years for measuring radon (Jenkins 1986) and radon progeny in air. In addition, considerable attention is given by the U.S. Environmental Protection Agency to the measurement of radon and radon progeny in homes (EPA 1992e). Radon and radon progeny emit alpha and beta particles and gamma rays. Therefore, numerous techniques can and have been developed for measuring these radionuclides based on detecting alpha particles, beta particles, or gamma rays, independently or in some combination. This section contains an overview of information dealing with the measurement of radon and radon progeny. The information is focused on the measurement of ^{222}Rn; however, the information may be adapted for the measurement of ^{219}Rn and ^{220}Rn. There are commercial options for measurements of ^{220}Rn, but options for ^{219}Rn are limited. More consideration should be given to the two latter radon isotopes because of their short half-lives, which may prevent the shipment of the sample for off-site laboratory analyses, depending on the sampling and measurement methods.

Radon concentrations within a fixed structure can vary significantly from one section of the building to another and can fluctuate over time. If a home has a basement, for instance, it is usually expected that a higher radon concentration will be found there. Radon primarily enters buildings that are at negative pressure with respect to the soil. A small increase in the relative pressure between the soil and the inside of a structure can cause a significant increase in the amount of radon entering the building from the soil. Many factors play a role in these variations, but from a practical standpoint it is only necessary to recognize that fluctuations are expected and that they should be accounted for. Long-term measurement periods (91 days or greater) are required to determine a mean concentration inside a structure; however, a mean may not be necessary to determine if a risk-reduction strategy is required. It may also not be necessary if radon is being used as an indicator of nearby residual radioactive material.

Two analytical end points are of interest when performing radon measurements. The first and most commonly used is radon concentration, which is stated in terms of activity per unit volume, in Bq/m^3 or picocuries per liter (pCi/L). Although this terminology is consistent with most Federal requirements, it only implies the potential dose equivalent associated with radon. The second analytical end point is the potential alpha energy concentration (PAEC) (or equilibrium equivalent concentration) of the radon progeny. Radon progeny usually attach very quickly to charged aerosols in the air following creation. The fraction that remains unattached is usually quite small (i.e., 5–10 percent). Because most aerosol particles carry an electrical charge and are relatively massive (≥ 0.1 μm), they are capable of attaching to the surfaces of the lung. Essentially all dose or risk from radon is associated with alpha decays from radon progeny deposited in the respiratory system. If an investigator is interested in accurately determining the potential dose or risk associated with radon in the air of a room, the radon progeny concentration must be known. It should be noted, however, that various processes remove radon progeny from a room. If the radon is removed or prevented from entering, there will be no risk from decay products.

Radon progeny concentrations are usually reported in units of working levels, where one working level is equal to the potential alpha energy associated with the radon progeny in secular equilibrium with 100 pCi/L of radon. One working level is equivalent to 1.3×10^5 MeV/L of potential alpha energy. Given a known breathing rate and lung attachment probability, the expected mean lung dose from exposure to a known working level of radon progeny can be calculated.

Radon progeny are not usually found in secular equilibrium with radon indoors because of the plating out of the charged aerosols onto walls, furniture, etc. The ratio of ^{222}Rn progeny activity to ^{222}Rn activity usually ranges from 0.2 to as high as 0.8 indoors (NCRP 1988). If only the ^{222}Rn concentration is measured and it is not practical to measure the progeny concentrations, then general practice is to assume a progeny to ^{222}Rn equilibrium ratio for indoor areas. The appropriate regulatory agency should be consulted to determine the appropriate equilibrium factor. This allows one to estimate the expected dose or risk associated with a given radon concentration.

In general, the following generic guidelines should be followed when performing radon measurements during site investigations:

- The radon measurement method used should be well understood, documented, and carried out in compliance with certification requirements as applicable. Measurements in buildings should conform to current radon standards of practice as required by the regulator.[3]
- Long-term measurements should be considered where short-term (screening) tests are close to guidance levels.
- In nonresidential buildings, such as schools and commercial buildings, the impact of the heating, ventilation, and air conditioning system on radon entry should be considered, because radon levels may change significantly between occupied and non-occupied periods.
- The impact of variable environmental conditions (e.g., humidity, temperature, dust loading, and atmospheric pressure) on the measurement process should be accounted for when

[3] Contact the American Association of Radon Scientists and Technologists for the current radon standards of practice.

necessary. Consideration should be given to effects on both the air collection process and the counting system.

- The background response of the detection system should be accounted for.
- If measuring the potential alpha energy concentration directly is impractical to measure the potential alpha energy concentration directly, then the progeny activities can be estimated by assuming a specific equilibrium with radon. The concentrations of the radon progeny are then estimated by applying an equilibrium factor to the measured radon concentration. The appropriate regulatory agency should be consulted to determine the appropriate equilibrium factor.

For a general overview, a list of common radiation detectors with their usual applications during radon surveys is provided in **Table 6.9.** Descriptions and costs for specific equipment used for the measurement of radon are contained in **Appendix H.**

The following provides a general overview of radon sampling and measurement concepts. The intent of this section is to provide an overview of common methods and terminology.

6.8.1 Direct Radon Measurements

Direct radon measurements are performed by gathering radon into a chamber and measuring the ionizations produced. A variety of methods have been developed, each making use of the same fundamental mechanics but employing different measurement processes. The first step is to get the radon into a chamber without collecting any radon progeny from the ambient air. A filter is normally used to capture charged aerosols while allowing the radon gas to pass through. Most passive monitors rely on diffusion of the ambient radon in the air into the chamber to establish an equilibrium between the concentrations of radon in the air and in the chamber. Active monitors use some type of air pump system for the air exchange method.

Once inside the chamber, the radon decays by alpha emission to form ^{218}Po, which usually takes on a positive charge within thousandths of a second following formation. Some monitor types collect these ionic molecules and subsequently measure the alpha particles emitted by the radon progeny. Other monitor types, such as the electret ion chamber, measure the ionization produced by the decay of radon and progeny in the air within the chamber by directly collecting the ions produced inside the chamber. The electrets are influenced by the ambient gamma radiation level; therefore, correction factors based on the gamma radiation level must be established to adjust the radon results. Simple systems measure the cumulative radon during the exposure period based on the total alpha decays that occur. More complicated systems measure the individual pulse height distributions of the alpha and/or beta radiation emissions and derive the radon plus progeny isotopic concentration in the air volume.

Care must be taken to accurately calibrate a system and to understand the effects of humidity, temperature, dust loading, air currents, and atmospheric pressure on the system. These conditions create a small adverse effect on some systems and a large influence on others.

Table 6.9: Radiation Detectors with Applications to Radon Surveys

Category	Measures	System	Description	Application	Time	Remarks
Integrating/ Averaging Methods	^{222}Rn	Activated charcoal adsorption	Activated charcoal is opened to the ambient air, then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measure radon concentration in indoor air.	2–7 days	LLD is 0.007–0.04 Bq/L (0.2–1.0 pCi/L). Must wait 3 hours after deployment ends to begin analysis. Not a true integrating device. Must be returned to the laboratory promptly.
	^{222}Rn ^{220}Rn Radon Flux	Electret ion chamber	This is a charged plastic vessel that can be opened for air to pass through. Voltage drop is then measured.	Measure radon concentration in air.	2–7 days for short term 91–365 days for long term	Must correct reading for gamma background concentration. Electret is sensitive to extremes of temperature and humidity. Reader is sensitive to temperature changes. LLD is 0.007–0.02 Bq/L (0.2-0.5 pCi/L).
		Alpha track detection	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure radon concentration in air.	91–365 days	LLD is 0.04 Bq/L-d (1 pCi/L-d). Typical deployment is a minimum of 90 days.

Category	Measures	System	Description	Application	Time	Remarks
	^{222}Rn Progeny ^{220}Rn Progeny	Filter/ detector unit	Air pump and filtration unit with TLD chips or nuclear track detectors.	Measure progeny concentration in air.	1 day – a few weeks	LLD is 0.0002 Working Level for a week-long measurement.
Continuous Monitors	^{222}Rn ^{220}Rn	Ionization chambers, scintillation detectors, solid state detectors	Measure radon concentrations and log results on real-time basis. May provide spectral data, depending on device.	Measure radon concentration in air; “sniffer” to locate radon entry points in building.	Minutes to a few days	LLD is 150 Bq/m^3 (4 pCi/L) in 10 minutes.
Radon Progeny Measurements	^{222}Rn Decay Products ^{220}Rn Decay Products	Continuous radon progeny monitors	Air pump and solid-state detector.	Measurement of PAEC. Can calculate equilibrium.	1 day– 1 week “grab samples” for some models	LLD is 20 nJ/m^3 (0.001 Working Level).
Short-Term Radon Flux Measurements	^{222}Rn	Large-area activated charcoal collector	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short-term radon flux measurements.	24 hours	The LLD is 0.007 Bq/m^2/s (0.2 pCi/m^2 s).
		Electret Ion Chamber	Ion Chamber has filtered outlets to prevent saturation.	Short term radon flux measurements.	8 – 24 hours	Gamma correction for background required. LLD is 0.08 pCi/m^2 s

Abbreviations: Bq = becquerels; L = liters; pCi = picocuries; d = day; LLD = lower limit of detection; TLD = thermoluminescent dosimeter; m = meter; PAEC = potential alpha energy concentration; nJ = nanoJoules; s = second.

6.8.1.1 Integrating/Averaging Methods

With integrating methods, measurements are made over a period of days, weeks, or months, and the device is subsequently read by an appropriate device for the detector media used. The most common detectors used are activated charcoal adsorbers (good for up to 1 week), EICs (good for days to weeks), and alpha track plastics (good for weeks to months). Short-term fluctuations are averaged out, thus making the measurement representative of average concentration. Results in the form of an average value provide no way to determine the fluctuations of the radon concentration over the measurement interval. Successive short-term measurements can be used in place of single long-term measurements to gain better insight into the seasonal dependence of the radon concentration. Continuous measurements can be used to get better insight into the time dependence of the radon concentration, which can be of particular importance in large buildings. Because charcoal allows continual adsorption and desorption of radon, the method does not give a true integrated measurement over the exposure time. Use of a diffusion barrier over the charcoal reduces the effects of drafts and high humidity.

6.8.1.2 Continuous Monitors

Devices that measure direct radon concentrations over successive time increments are generally called continuous radon monitors. These systems are more complex than integrating devices, in that they measure the radon concentration and log the results to a data recording device on a real-time basis. The monitor must take a reading at least once per hour to be considered a continuous monitor. Continuous radon measurement devices normally allow the noble gas radon to pass through a filter into a detection chamber where the radon decays and the radon or the resulting progeny are measured. Common detectors used for real time measurements are ion chambers, solid state surface barrier detectors, and ZnS(Ag) scintillation detectors.

A principle of operation for monitors equipped with solid state detectors is an electrostatic collection of alpha emitters with spectral analysis. The electric field within the sample cell drives the positively charged ion to the detector where it attaches. The detector converts alpha radiation directly to an electrical signal proportional in strength to the energy of alpha particle. This makes it possible to tell which radionuclide produced the radiation; therefore, one can distinguish ^{222}Rn from ^{220}Rn. If operated in air with a relatively high radon concentration, these monitors need to be purged with filtered, fresh dry air with a normal radon concentration before taking the next series of measurements. Continuous methods offer the advantage of providing successive, short-term results over long periods of time. This allows the investigator not only to determine the average radon concentration, but also to analyze the fluctuations in the values over time. More complicated systems are available that measure the relative humidity and temperature at the measurement location and log the values along with the radon concentrations to the data logging device. This allows the investigator to make adjustments, if necessary, to the resulting data before reporting the results.[4]

6.8.2 Radon Progeny Measurements

Radon progeny measurements are usually performed by collecting aerosols onto filter paper and subsequently counting the filter for attached progeny. Some systems pump air through a filter and then automatically count the filter for alpha or beta emissions. An equivalent but more labor-intensive method is to collect a sample using an air sampling pump and then count the filter in standalone alpha or beta counting systems. The measurement system may make use of any number of different techniques, ranging from full alpha and beta spectrometric analysis of the filters to simply counting the filter for total alpha and or beta emissions.

When performing total (gross) counting analyses, the assumption is usually made that the only radioisotopes in the air are due to ^{222}Rn and its progeny. This uncertainty, which is usually very small, can be essentially eliminated when performing manual sampling and analysis by performing a followup measurement of the filter after the radon progeny have decayed to a negligible level. This value can then be used as a background value for the air. Of course, such a simple approach is applicable only when ^{222}Rn is the isotope of concern. For ^{219}Rn or ^{220}Rn, other methods would have to be used.

Time is a significant element in radon progeny measurements. Given any initial equilibrium condition for the progeny isotopes, an investigator must be able to correlate the sampling and measurement technique back to the true concentration values. When collecting radon progeny, the buildup of total activity on the filter increases asymptotically until the activity on the filter becomes constant (after approximately 3 hours of sampling). At this point, the decay rate of the progeny atoms on the filter is equal to the collection rate of progeny atoms. This is an important parameter to consider when designing a radon and progeny sampling procedure. Depending on sensitivity requirements, collection times can be as short as 5 minutes (Maiello 2010). Although it is possible to sample for other time periods, the equations developed for the three major ^{222}Rn progeny concentrations are valid for sampling times of 5 minutes only. Samples should be shipped and analyzed as expeditiously as possible after sampling is concluded.

Note that the number of charged aerosol particles in the air can affect the results for radon progeny measurements. If the number of particles is few, as is possible when humidity is low and a room is very clean, then most of the progeny will not be attached and can plate out on room surfaces before reaching the sample filter.

[4] Depending on the device, these measurements would indicate unexpected disruptions when the device is used for radon testing. The theory is that opening windows or moving the device would cause a noticeable disruption in the measurement.

6.8.3 Radon Flux Measurements

Sometimes it is desirable to characterize the source of radon in terms of the rate at which radon is emanating from a surface—that is, soil, uranium mill tailings, or concrete. One method used for measuring radon flux is briefly described here.

The measurement of radon flux can be achieved by adsorption onto charcoal using a variety of methods, such as a charcoal canister or a large-area collector (e.g., 25 cm polyvinyl chloride [PVC] end cap). The collector is deployed by sealing the collection device onto the surface of the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. Because the area of the surface is well defined and the deployment period is known, the radon flux (in units of Bq/m^2-s or pCi/m^2-s) can be calculated.

This method is reliable for measuring radon flux in normal environmental situations. However, care should be taken if an extremely large source of radon is measured with this method. The collection time should be chosen carefully to avoid saturating the canister with radon. If saturation is approached, the charcoal loses its ability to absorb radon, and the collection rate decreases. Even transporting and handling of a canister that is saturated with radon can be a problem because of the dose rate from the gamma rays being emitted. One would rarely encounter a source of radon that is so large that this would become a problem; however, the potential for it should be recognized. Charcoal also can become saturated with water, which will affect the absorption of radon. This can occur in areas with high humidity.

An alternative method for making passive radon flux measurements has been developed recently using EICs. EIC technology has been widely used for indoor radon measurements. The passive EIC procedure is similar to the procedures used with large-area activated charcoal canisters. To provide the data for the background corrections, an additional EIC monitor is located side-by-side on a radon-impermeable membrane. These data are used to calculate the net radon flux. The Florida State Bureau of Radiation Protection has compared the results from measurements of several phosphogypsum flux beds using the charcoal canisters and EICs and has shown that the two methods give comparable results. The passive method seems to have overcome some of the limitations encountered in the use of charcoal. The measurement periods can be extended from hours to several days to obtain a better average, if needed. EIC flux measurements are not affected by such environmental conditions as temperature, humidity, and air flow. The measured detection capabilities are comparable to the charcoal method, but—unlike charcoal—EICs do not become saturated by humidity. Intermediate readings can be made if needed. In view of the low cost of the EIC reading and analysis equipment, the cost per measurement can be as much as 50 percent lower than the charcoal method, with additional savings in time. There are handling and storage requirements associated with these methods and detectors. For more information, refer to the manufacturer and **Appendix H.**

6.9 Special Equipment

Various specialized systems have been developed that can be used during the performance of RSSIs. These range from specially designed quick radiation scanning systems to commercial global positioning systems (GPSs). The equipment may be designed to detect radiation directly, detect and locate materials associated with the residual radioactive material (e.g., metal containers), or locate the position where a particular measurement is performed. Because these specialized systems are continuously being modified and developed for site-specific applications, it is not possible to provide detailed descriptions of every system. The following sections provide examples of specialized equipment that have been applied to radiation surveys and site investigations.

6.9.1 Local Microwave and Sonar Positioning Systems

Local microwave or sonar beacons and receivers may provide useful location data in small areas and tree-covered locales. With a number of fixed beacons in place, a roving unit can be oriented and provide location data with similar accuracy and precision as the differential GPS (DGPS). If the beacons are located at known points, the resulting positions can be determined using simple calculations based on the known reference locations of the beacons.

The logistics of deploying the necessary number of beacons properly and the short range of the signals are the major limitations of the system. In addition, multipathing of signals within wooded areas or interior areas can cause jumps in the positioning data. These systems have applicability both indoors and outdoors but require setting up a site-specific system that may require adjustment for different locations (e.g., each room in a building).

6.9.2 Laser Positioning Systems

Laser positioning systems are becoming more popular for monitoring positions in three dimensions. The newest systems use reflectorless electronic distance measurement to measure the distance to an object without actually accessing the object. Laser systems use the principles of phase shift and pulse (or time of flight) or a hybrid combination to measure distance. This allows mapping of distant or inaccessible objects in hazardous areas. Using a reflector, or retroprism, to identify the location of a surveyor or detector allows the system to track the location of individual measurements. Laser systems are accurate to within a few millimeters at distances up to 1,000 m. Laser systems require a clear line of sight between the object and the laser. Systems with multiple lasers at different locations can be used to minimize issues with line-of-sight interference.

6.9.3 Mobile Systems with Integrated Positioning Systems

In recent years, the advent of new technologies has introduced mobile sensor systems for acquiring data that include fully integrated positioning systems. Portable and vehicle-based versions of these systems record survey data while moving over surfaces to be surveyed and simultaneously recording the location data from a roving DGPS receiver, local microwave/sonar receiver, or special retroprism for a laser system. All measurement data are automatically stored and processed with the measurement location for later posting (see **Section 8.2.2.2** for a discussion of posting plots) or for mapping the results using a geographic information system. These systems are designed with a variety of detectors for different applications. For example, alpha or beta detectors have been mounted on a robot at a fixed distance over a smooth surface. The robot moves at a predetermined speed over the surface to provide scanning results and records individual direct measurements at predetermined intervals. This type of system not only provides the necessary measurement data, but also reduces the uncertainty associated with human factors. Other systems are equipped with several types of radiation detectors, magnetometers, electromagnetic sensors, or various combinations of multiple sensors. The limitations of each system should be evaluated on a site-specific basis to determine if the positioning system, the detector, the transport system, or some combination based on site-specific characteristics will represent the limits of the system.

6.9.4 Radar, Magnetometer, and Electromagnetic Sensors

The number of sensors and sensor systems applicable to the detection and location of buried waste have increased in use and reliability in recent years. These systems are typically applicable to scoping and characterization surveys where the identification of residual radioactive materials in the subsurface is a primary concern. However, the results of these surveys may be used during FSS planning to demonstrate that subsurface materials are not a concern for a particular site or survey unit. Some of the major technologies are briefly described in the following sections.

6.9.4.1 Ground Penetrating Radar

For most sites, ground-penetrating radar (GPR) is the only instrument capable of collecting images of buried objects *in situ*, as compared to magnetometers (**Section 6.9.3.2**) and electromagnetic sensors (**Section 6.9.3.3**), which detect the strength of signals as measured at the ground surface. Additionally, GPR is unique in its ability to detect both metallic and nonmetallic (e.g., plastic, glass) containers. GPR techniques are being studied to monitor the performance and stability of soil covers at uranium mill tailings sites and other land disposal sites with earthen covers (Necsoiu and Walter 2015).

Subsurface radar detection systems have been the focus of study for locating and identifying buried or submerged objects that otherwise could not be detected. There are two major categories of radar signals: (1) time domain and (2) frequency domain. Time-domain radar uses short impulses of radar-frequency energy directed into the ground being investigated. Reflections of this energy, based on changes in dielectric properties, are then received by the radar. Frequency-domain radar, on the other hand, uses a continuous transmission, where the frequency of the transmission can be varied either stepwise or continuously. The changes in the frequency characteristics due to effects from the ground are recorded. Signal processing, in both cases, converts this signal to represent the location of radar reflectors against the travel time of the return signal. Greater travel time corresponds to a greater distance beneath the surface.

Examples of existing GPR technologies currently being applied to subsurface investigations include the following:

- narrow-band radar
- ultra-wideband radar
- synthetic aperture radar

- frequency modulated continuous radar
- polarized radar waves

The major limitation to GPR is the difficulty in interpreting the data, which is often provided in the form of hazy, “waterfall-patterned” data images requiring an experienced professional to interpret. Also, GPR can vary depending on the soil type—highly conductive clay soils often absorb a large amount of the radar energy and may even reflect the energy. GPR can be deployed using ground-based or airborne systems.

6.9.4.2 Magnetometers

Although soil affected by residual radioactive material and most radioactive waste possess no ferromagnetic properties, the containers commonly used to hold radioactive waste (e.g., 55-gallon drums) are made from steel. These containers possess significant magnetic susceptibility, making the containers detectable using magnetometry.

Magnetometers sense the pervasive magnetic field of the Earth. This field, when encountering an object with magnetic susceptibility, induces a secondary magnetic field in that object. This secondary field creates an increase or decrease in Earth’s ambient magnetic field. Magnetometers measure these changes in the expected strength of the ambient magnetic field. Some magnetometers, called “vector magnetometers,” can sense both the direction and the magnitude of these changes. However, for subsurface investigations only the magnitude of the changes is used.

The ambient magnetic field on Earth averages 55,000 gamma in strength. The variations caused by the secondary magnetic fields typically range from 10–1,000 gamma and average around 100 gamma. Most magnetometers currently in use have a detection capability in the 0.1–0.01 gamma range and can detect these secondary fields.

An alternate magnetometer survey can be performed using two magnetometers in a gradiometric configuration. This means that the first magnetometer is placed at the ground surface, and the second is mounted approximately 0.5 m above the first. Data are recorded from both sensors and compared. When the readings from both detectors are nearly the same, it implies that there is no significant disturbance in the Earth’s ambient magnetic field or that such disturbances are broad and far away from the gradiometer. When a secondary magnetic field is induced in an object, it affects one sensor more strongly than the other, producing a difference in the readings from the two magnetometers. This approach is similar to the use of a guard detector in anti-coincidence mode in a low-background gas-flow proportional counter in a laboratory (see **Appendix H** for a description of gas-flow proportional counters). The gradiometric configuration filters out the Earth’s ambient magnetic field, large-scale variations, and objects located far from the sensor to measure the effects of nearby objects, all without additional data processing. Fifty-five-gallon drums buried 5–7 meters below the surface may be detectable using a magnetometer. At many sites, multiple drums have been buried in trenches or pits, and detection is straightforward. A single operator carrying a magnetometer with the necessary electronics in a backpack can cover large areas in a relatively small amount of time.

The limitations on the system are related to the size of the objects and their depth below the surface. Objects that are too small or buried too deep will not provide a secondary magnetic field that can be detected at the ground surface.

6.9.4.3 Electromagnetic Sensors

Electromagnetic sensors emit an electromagnetic wave, in either a pulsed or continuous wave mode, and then receive the result of that transmission. The result of the transmission is two signals: quadrature and in-phase. As the wave passes through some material other than air, it is slowed down by a resistive medium or sped up by a conductor through dielectric effects. This produces the quadrature signal. If the electromagnetic wave encounters a highly conductive object, it induces a magnetic field in the object. This induced electromagnetic field returns to the sensor as a reflection of the original electromagnetic wave and forms the in-phase signal.

The in-phase signal is indicative of the presence, size, and conductivity of nearby objects (e.g., 55-gallon drums), and the quadrature signal is a measure of the dielectric properties of the nearby objects, such as soil. This means that electromagnetic sensors can detect all metallic objects (including steel, brass, and aluminum), such as the metal in waste containers, and sample the soil for changes in properties, such as those caused by leaks of contents.

Depths of interest are largely determined by the spacing between the coil used to transmit the primary electromagnetic wave and the receiver used to receive that transmission. The rule of thumb is that the depth of interest is on the order of the distance between the transmitter and the receiver. A system designed with the transmitter and receiver placed tens of meters apart can detect signals from tens of meters below the surface. A system with the transmitter and receiver collocated can detect signals only from depths on the order of the size of the coil, which is typically about 1 m. The limitations of electromagnetic sensors include a lack of clearly defined signals and decreasing resolution of the signal as the distance below the surface increases.

6.9.5 Aerial Radiological Surveys

Low-altitude aerial radiological surveys are designed to encompass large areas and may be useful in—

- providing data to assist in the identification of residual radioactive materials and their corresponding concentrations and spatial distributions
- characterizing the nature, extent and impact of the residual radioactive materials

The detection capability and data processing procedures provide total area coverage and a detailed definition of the extent of gamma-producing isotopes for a specific area. The gamma radiation spectral data are processed to provide a qualitative and quantitative analysis of the radionuclides in the survey area. Flyover surveys establish a grid pattern (e.g., east–west) of parallel lines approximately 60–150 m (200–500 feet) above the ground surface.

The survey consists of airborne measurements of natural and manmade gamma radiation from the terrain surface. These measurements allow the determination of terrestrial spatial distribution of isotopic concentrations and equivalent gamma exposure rates (e.g., ^{60}Co, ^{234m}Pa, and ^{137}Cs). The results are reported as isopleths or data points for the isotopes and are usually superimposed on scale maps of the area.

7 SAMPLING AND PREPARATION FOR LABORATORY MEASUREMENTS

7.1 Introduction

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides three methods for collecting radiation data while performing a survey: direct measurement, scanning, and sampling.[1] A direct measurement is a radioactivity measurement obtained by placing the detector near the surface or media being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly. Scanning is an evaluation technique performed by moving a portable radiation detection instrument at a constant speed and distance relative to the surface to detect radiation. These measurement techniques are discussed in **Chapter 6.** The third method of obtaining radiation data involves collecting a portion of a larger quantity of media for sample analysis using instrumentation in the field or in a laboratory (NRC 2004).

Chapter 7 discusses issues involved in collecting and preparing samples for analysis. This information will assist in communications with the laboratory during survey planning.

Samples should be collected and analyzed by qualified individuals using the appropriate equipment and procedures. This manual assumes that the samples taken during the survey will be submitted to a qualified laboratory for analysis. The laboratory should have written procedures that document its analytical capabilities for the radionuclides of interest and a quality assurance/quality control (QA/QC) program that documents the compliance of the analytical process with established criteria. The method used to assay the radionuclides of concern should be recognized as a factor affecting analysis time.

Commonly used radiation detection and measuring equipment for radiological survey field applications is described in **Chapter 6** and **Appendix H.** Many of these equipment types may also be used for laboratory analyses, usually under more controlled conditions that provide for lower detection limits and measurement method uncertainties and greater abilities to identify and quantify between radionuclides. Laboratory methods often involve combinations of both chemical and physical preparation and instrument techniques to quantify the low levels expected in the samples. This chapter provides guidance to assist the MARSSIM user in selecting appropriate procedures for collecting and handling samples for laboratory analysis. More detailed information is available in documents listed in the reference section of this manual.

The development of data quality objectives (DQOs) and measurement quality objectives (MQOs) to define the data needs for a survey is described in **Section 7.2.** This includes making decisions regarding the need to collect samples, the appropriate sampling methods, and QC measurements implemented as part of the survey process. **Section 7.3** describes

[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

communication with laboratory personnel during survey planning, before and during sample collection, and during and after sample analysis. Collaborative communication with the laboratory is an important aspect of the sampling and analysis process that helps ensure that survey DQOs are met.

The selection of radiochemical laboratories based on their capability to meet technical, reporting, and other contractual requirements is described in **Section 7.4. Section 7.5** covers sample collection considerations to enhance the representativeness of the sample, and the establishment of field sample preparation and preservation criteria is included in **Section 7.6.**

Section 7.7 describes the selection of appropriate analytical methods to ensure that the residual radionuclides—either as individual radionuclides or as a total amount of radioactivity as identified in the DQOs and MQOs—can be detected at appropriate levels of sensitivity and that requirements for measurement uncertainties are met. Sample tracking from field activities through laboratory analysis and reporting is covered in **Section 7.8. Section 7.9** covers the packaging and shipping of samples containing radioactive material to minimize radiation exposure to the general public and meet applicable Federal and international requirements.

7.2 Data Quality Objectives and Measurement Quality Objectives

The survey design is developed and documented using the DQO process (see **Appendix D**). The third step of the DQO process involves identifying the data needs for a survey. One decision that can be made at this step is the selection of either a scan-only survey, direct measurements in conjunction with scanning for performing a survey, or sampling and laboratory analysis in conjunction with scanning as the appropriate data collection strategy for the survey. This chapter addresses the sampling and laboratory analysis of samples.

Because DQOs apply to both sampling and analytical activities, what are needed from an analytical perspective are performance objectives specifically for the analytical process of a project. Chapter 3 of the Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP; NRC 2004) refers to these performance objectives as MQOs. An MQO is a quantitative or qualitative statement of a performance objective or requirement for a performance characteristic of a particular method. The MQOs can be viewed as the analytical portion of the overall project DQOs. In a performance-based approach, the MQOs are used initially for the selection and evaluation of analytical methods and protocols and are subsequently used for the ongoing and final evaluation of the analytical data.

7.2.1 Identifying Data Needs

The decision maker and the survey planning team need to identify the data needs for the survey being performed, including the following:

- type of samples to be collected or measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.3**)
- number of samples to be collected (**Sections 5.3.3–5.3.5**)
- type and frequency of field QC samples to be collected (**Section 4.9**)

- amount of material to be collected for each sample (**Section 4.7.3** and **Section 7.5**)
- sampling locations and frequencies (**Section 5.3.7**)
- standard operating procedures (SOPs) to be followed or developed
- measurement method uncertainty (**Section 6.4**)
- target detection capabilities for each radionuclide of interest (**Section 6.3**)
- cost of the methods being evaluated (cost per analysis as well as total cost) (**Appendix H**)
- necessary turnaround time
- sample preservation and shipping requirements (**Section 7.6**)
- specific background for each radionuclide of interest (**Section 4.5**)
- derived concentration guideline level (DCGL) for each radionuclide of interest (**Section 4.3**)
- measurement documentation requirements (**Section 5.3.11**)
- sample tracking requirements (**Section 7.8**)

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process may be needed to identify all of the data needs. Consulting with a radiochemist or health physicist may be necessary to properly evaluate the information before deciding what combination of scan-only, direct measurements and scanning, or sampling methods and scanning will be required to meet the DQOs. Surveys might require data from all three collection methods (i.e., sample analysis, direct measurements, and scans) to demonstrate compliance with the applicable regulations and DQOs for the project.

7.2.2 Data Quality Indicators

Precision, bias, representativeness, comparability, and completeness are some of the historical data quality indicators (DQIs) recommended for quantifying the amount of error in survey data (EPA 2002a). The first two of these DQIs represent different aspects of the measurement method uncertainty (**Section 6.4**), with *precision* representing that portion of the measurement method uncertainty due to random uncertainty and *bias* representing that portion of the measurement method uncertainty due to systematic uncertainty. Together, these DQIs should be considered when selecting a measurement technique (i.e., scanning, direct measurement, or sampling) or an analytical technique (e.g., radionuclide-specific analytical procedure). In some instances, the DQI requirements will help in the selection of an analytical technique. In other cases, the analytical requirements will assist in the selection of appropriate levels for the DQIs.

7.2.2.1 Precision

Precision is a measure of agreement among replicate measurements of the same property under prescribed similar conditions (ASQC 1995). Precision is determined quantitatively based on the results of replicate measurements (equations are provided in EPA 1990). The number of replicate analyses needed to determine a specified level of precision for a project is discussed in **Section 4.9.** Several types of replicate analyses are available to determine the level of precision, and these replicates are typically distinguished by the point in the sample collection and analysis process where the sample is divided. Determining precision by replicating measurements with results at or near the detection limit of the measurement system is not recommended, because the measurement uncertainty is usually greater than the desired level of precision.

- *Field replicates*[2] are two or more separate samples collected at the same point in time and space (EPA 2002b). These samples, also known as collocated samples, are collected adjacent to the routine field sample to determine local variability of the radionuclide concentration. Typically, including for MARSSIM collection, field replicates are collected about 0.5–3 feet away from the selected sample location. Analytical results from field replicates can be used to assess site variation, but only in the immediate sampling area. Field replicates should not be used to assess variability across a site and are not recommended for assessing error (EPA 1995). Field replicates can be non-blind, single-blind, or double-blind.

- *Field splits* are two or more representative portions taken from a single, usually homogenized, sample collected in the field (EPA 2002b). These portions are divided into separate containers and treated as separate samples throughout the remaining sample handling and analytical processes and are used to assess error associated with sample heterogeneity, sample methodology, and analytical procedures. Field splits are used when determining total error for critical samples with residual radioactive material concentrations near the action level. A minimum of eight field split samples is recommended for valid statistical analysis (EPA 1995). Counting multiple split samples of a homogenized field sample will decrease the uncertainty of the sample, because the sample count times can be combined to derive the overall count time for the sample. In some cases, homogenization may not be possible (e.g., discrete [small] radioactive particles). Field split samples can be non-blind, single-blind, or double-blind and are recommended for determining the level of precision for a radiation survey or site investigation.

- An *analytical laboratory replicate* is two or more representative aliquots (portions of a homogeneous sample, removed for the purpose of analysis or other chemical treatment) whose independent measurements are used to determine the precision of laboratory preparation and analytical procedures (NRC 2004). It is used to determine method precision, but because it is a non-blind sample (i.e., known to the analyst), it can be used by the analyst only as an internal control tool and not as an unbiased estimate of analytical precision (EPA 1990).

- A *laboratory instrument replicate* is the repeated measurement of a sample that has been prepared for counting (i.e., laboratory sample preparation and radiochemical procedures have been completed). It is used to determine precision for the instrument (repeated measurements of the same sample using same instrument) and the instrument calibration

[2] The term “field replicates” is used in some documents to refer to what this guidance calls field splits.

(repeated measurements of the same sample using different instruments, such as two different germanium detectors with multichannel analyzers). A laboratory instrument replicate is generally performed as part of the laboratory QC program and is a non-blind sample. It is typically used as an internal control tool and not as an unbiased estimate of analytical precision.

7.2.2.2 Bias

Bias is the systematic or persistent distortion of a measurement process that causes error in one direction (ASQC 1995). Bias is determined quantitatively based on the analysis of samples with a known concentration. There are several types of samples with known concentrations. QC samples used to determine bias should be included as early in the analytical process as possible.

- *Reference materials* are one or more materials or substances with property values that are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials (ISO 2008). A certified reference material is one for which each certified property value is accompanied by an uncertainty at a stated level of confidence. Radioactive reference materials may be available for certain radionuclides (e.g., uranium) in soil, but reference building materials may not be available. Because reference materials are prepared and homogenized as part of the certification process, they are rarely available as double-blind samples. When appropriate reference materials are available (i.e., proper matrix, proper radionuclide, and proper concentration range), they are recommended for use in determining the overall bias for a measurement system.

- *Performance evaluation (PE) samples* are used to evaluate the overall bias of the analytical laboratory and detect any error in the analytical method used. These samples are usually prepared by a third party, using a quantity of analyte(s) known to the preparer but unknown to the laboratory, and always undergo certification analysis. The analyte(s) used to prepare the PE sample is the same as the analyte(s) of interest. Laboratory procedural error is evaluated by the percentage of analyte identified in the PE sample (EPA 1995). PE samples are recommended for use in determining overall bias for a measurement system when appropriate reference materials are not available. PE samples are equivalent to matrix spikes prepared by a third party that undergo certification analysis and can be non-blind, single-blind, or double-blind.

- *Matrix spike samples* are environmental samples that are spiked in the laboratory with a known concentration of a target analyte(s) to verify percent recoveries. They are used primarily to check sample matrix interferences but can also be used to monitor laboratory performance. However, a data set of at least three or more results is necessary to distinguish between laboratory performance and matrix interference (EPA 1995). Matrix spike samples are often replicated to monitor method performance and evaluate error due to laboratory bias and precision (when four or more pairs are analyzed). These replicates are often collectively referred to as a matrix spike/matrix spike duplicate (MS/MSD).

Several additional terms are applied to samples prepared by adding a known amount of the radionuclide of interest to the sample. The majority of these samples are designed to isolate individual sources of bias within a measurement system by preparing pre- and post-operation spikes. For example, the bias from the digestion phase of the measurement system can be determined by comparing the result from a pre-digest spike to the result from a post-digest spike.

Several types of samples are used to estimate bias caused by contamination during the sample collection or analytical process:

- *Background samples* are collected from a non-impacted area with similar characteristics (either onsite or offsite) where there is little or no chance of migration of the radionuclides of concern (EPA 1995). Background samples are collected from the background reference area (**Section 4.5**), to determine the natural composition and variability of the soil (especially important in areas with high concentrations of naturally occurring radionuclides). They provide a basis for comparison of radionuclide concentration levels with samples collected from the survey unit when the statistical tests described in **Chapter 8** are performed.

- *Field blanks* are samples prepared in the field using certified clean sand, soil, or water and then submitted to the laboratory for analysis (EPA 1995). A field blank is used to evaluate contamination error associated with sampling methodology and laboratory procedures. It also provides information about contaminants that may be introduced during sample collection, storage, and transport. Field blanks are recommended for determining bias resulting from contamination for a radiation survey or site investigation.

- *Method blanks* are analytical control samples used to demonstrate that reported analytical results are not the result of laboratory contamination (ATSDR 2005). A method blank contains distilled or deionized water and reagents and is carried through the entire analytical procedure (laboratory sample preparation, digestion, and analysis).[3]

7.2.2.3 Representativeness

Representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point (ASQC 1995). Representativeness is a qualitative term that is reflected in the survey design through the selection of a measurement technique (e.g., direct measurement or sampling) and the size of a sample collected for analysis.

Sample collection and analysis is typically less representative of true radionuclide concentrations at a specific measurement location than performing a direct measurement. This is caused by the additional steps required in collecting and analyzing samples, such as sample collection, field sample preparation, laboratory sample preparation, and radiochemical analysis. However, direct measurement techniques with acceptable detection limits are not always available. When sampling is required as part of a survey design, it is critical that the sample collection procedures consider representativeness. The location of the sample is determined as described in **Section 5.3.7,** but the size and content of the sample are usually determined as

[3] The method blank is also referred to as a reagent blank. The method blank is generally used as an internal control tool by the laboratory because it is a non-blind sample.

the sample is collected. Sample size and content are discussed in **Section 4.7.3** and **Section 7.5.** Sample collection procedures also need to consider the development of the DCGLs when determining the representativeness of the samples.

7.2.2.4 Comparability

Comparability is a qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Generally, comparability is provided by using the same measurement system for all analyses of a specific radionuclide. In many cases, equivalent procedures used within a measurement system are acceptable. For example, using a liquid-liquid extraction purification step to determine the concentration of plutonium-238 (^{238}Pu) using alpha spectrometry may be equivalent to using an ion-exchange column purification step. However, using a gross alpha measurement made with a gas proportional counting system would not be considered equivalent. Comparability is usually not an issue except in cases where historical data have been collected and are being compared to current analytical results or when multiple laboratories are used to provide results as part of a single survey design and the analytical methods have not been clearly communicated to the laboratories.

7.2.2.5 Completeness

Completeness is a measure of the amount of valid data obtained from the measurement system, expressed as a percentage of the number of valid measurements that should have been collected. Valid data is all data that are usable for an intended purpose, including data with no validation qualifiers and data found to be estimated that are justifiable for use. For example, data below the DCGL determined using the Wilcoxon Rank Sum test ($DCGL_W$) that are estimated with high bias would be considered usable data. Completeness is of greater concern for laboratory analyses than for direct measurements, because the consequence of having incomplete data often requires the collection of additional samples. Direct measurements can usually be repeated easily. The collection of additional samples generally requires a remobilization of sample collection personnel, which can be expensive. Conditions at the site may have changed, making it difficult or impossible to collect representative and comparable samples without repeating the entire survey. On the other hand, if it is simply an analytical problem and sufficient samples were originally collected, the analysis can be repeated using archived sample material. Samples collected on a grid to locate areas of elevated activity are also a concern for completeness. If one sample analysis result is not valid, the survey design may not be able to detect areas of elevated activity near or at the missing sample location.

7.2.2.6 Other Data Quality Indicators

Several additional data quality indicators that influence the final status survey (FSS) design are identified as DQOs and MQOs in **Section 2.3.1.** Many of these (e.g., selection and classification of survey units, decision error rates, variability in the contaminant concentration, lower bound of the gray region) are used to determine the number of measurements and are discussed in detail in **Section 5.3.** The required detection capability (**Section 6.3**) and measurement method uncertainties (**Section 6.4**) are directly related to the selection of a measurement method and a radionuclide-specific analytical technique.

Cost, time, best available technology, or other constraints may create situations where the required detection capabilities or measurement method uncertainties are deemed impracticable.

Under these circumstances, different values may be acceptable. Although laboratories will state detection limits, these are usually based on ideal or optimistic situations and may not be achievable under actual measurement conditions. Detection limits and measurement method uncertainties are subject to variation from sample to sample, instrument to instrument, and procedure to procedure, depending on sample size, geometry, background, instrument efficiency, chemical recovery, abundance of the radiations being measured, counting time, self-absorption in the prepared sample, and interferences from radionuclides or other materials present in the sample.

7.3 Communications with the Laboratory

Laboratory analyses of samples are generally performed by personnel not directly involved in the collection of the samples being analyzed. Samples are typically collected by one group working in the field and analyzed by a second group located in a laboratory. This separation of tasks can potentially lead to problems based on the lack of communication between the two groups. For this reason, communications between the project manager, field personnel, and laboratory personnel are vital to ensuring the success of a project. The MARLAP manual (NRC 2004), Section 11.2.1 provides more information on communications with a laboratory.

7.3.1 Communications During Survey Planning

The radioanalytical laboratory is a valuable resource during survey planning. Information on available analytical techniques, measurement method uncertainty, method detection capability, required measurement uncertainties, analytical costs, and turnaround times can easily be provided by the laboratory. All this information is used to make the decision to perform direct measurements or collect samples for laboratory measurements. Additional information, such as required sample size/volume, type of sample container, preservative requirements, and shipping requirements—including the laboratory's availability for receipt of samples on weekends or holidays—can be obtained and factored into the survey plan.

Involving the radioanalytical laboratory during survey planning also provides the laboratory with site-specific information about the project. Information on the radionuclides of interest, possible chemical and physical form of the residual radioactive material, and mechanism for release of the residual radioactive material to the environment is used to modify or develop the analytical method for site-specific conditions, if required. The laboratory should also be provided with the site-specific action levels (i.e., DCGLs, investigation levels) early in the survey planning process.

In some cases, it is not practical to select a radioanalytical laboratory early in the survey process to participate in the survey planning activities. For example, Federal procurement procedures require that a statement of work (SOW) identifying the tasks to be performed by the laboratory be developed before selecting a laboratory. Unfortunately, the details of the tasks for the laboratory to perform are developed during survey planning. This means that the information provided by the laboratory and used during survey planning will be obtained from another source, usually a radiochemist or health physicist trained in radiochemistry. The uncertainty associated with this information and subsequent decisions made based on this information increases. This may lead to increased costs caused by specifying an unnecessarily expensive analytical method in the SOW, repeated sampling and analysis of samples that did not meet the required detection capabilities, or measurement method uncertainties because the specified analytical method was not sufficient. In addition, unnecessary or inappropriate analytical methods may be selected by the laboratory because site-specific information concerning the samples was not provided.

The laboratory should be consulted when planning the schedule for the survey to ensure that the expected turnaround times can be met based on the projected laboratory workload.

7.3.2 Communications Before and During Sample Collection

In most situations, the sample collection and shipping containers are supplied by the laboratory; therefore, the laboratory should be notified well in advance of the sampling trip so that these items will be available to the sampling team during the survey.

The main purpose of communications with the laboratory during sample collection is to inform the laboratory of modifications to the survey design specified in the planning documents (e.g., Quality Assurance Project Plan [QAPP] and SOPs). The laboratory should have a copy of the survey design in its possession before samples' being collected.

Modifications to the survey design are often minor deviations from the SOPs caused by site-specific conditions and usually affect a small number of samples. For example, a rock outcropping covered by a thin layer of soil may restrict the depth of the surface soil sample to 5 centimeters (cm; 2 inches [in.]) instead of the 10 cm (4 in.) specified in the SOP. If the mass of the samples collected from this area of the site is one-half the expected sample mass, the laboratory needs to be informed of this deviation from the SOP. Also, the laboratory should be notified of the proper sample handling requirements (i.e., inform the laboratory of the proper handling of gravel in the samples, as some residual radioactive material could be present in the form of small gravel). Finally, the laboratory should be notified of the approximate activity concentrations to be expected in samples to ensure that the laboratory is licensed and equipped to handle samples with elevated activity concentrations.

In other situations, there may be an extensive modification to the number or types of samples collected at the site that will affect the analytical methods, detection capabilities, required measurement uncertainties, analytical costs, or even the assumptions used to develop the DCGL. For example, a large portion of the site may have been converted to a parking lot. A large pile of material that may represent the former surface soil will be sampled, as well as soil collected from beneath the parking lot surface. The number of samples to be analyzed has doubled compared to the original SOW.

If the expected timing of receipt of samples at the laboratory changes because of sample collection schedule deviations, the laboratory should be notified. Most laboratories require prior notification for samples to be received on weekends.

7.3.3 Communications During Sample Analysis

The laboratory should communicate with the project manager and field personnel during sample analysis. The laboratory should provide a list of missing or damaged samples as soon as practical after the samples are received. This allows the project manager to determine if resampling is required to replace the missing or damaged samples. The project manager may also request notification from the laboratory when samples are damaged or lost, or if any security seals are missing or broken. Preliminary reports of analytical results may be useful to help direct sampling activities and provide early indications of whether the survey objectives defined by the DQOs and MQOs are being met. However, if preliminary results have not been verified or validated, their usefulness is limited.

7.3.4 Communications Following Sample Analysis

Following sample analysis, the laboratory will provide documentation of the analytical results as specified in the survey design, which should include the measurement result, measurement uncertainty, minimum detectable activity, and quality control and chain-of-custody (COC) documentation. Laboratory personnel should be available to assist with interpretation, data verification, and data validation.

7.4 Selecting a Radioanalytical Laboratory

After the decision to perform sampling activities is made, the next step is to select the analytical methods and determine the data needs for these methods. It is advisable to select a radiochemical laboratory as early as possible in the survey planning process so it may be consulted on the analytical methodology and the sampling activities. The laboratory provides information on personnel, capabilities, and current workload that are necessary inputs to the decision-making process. In addition, mobile laboratories can provide on-site analytical capability. Obtaining laboratory or other services may involve a specific procurement process. Federal procurement procedures may require additional considerations beyond the method described here.

The procurement of laboratory services usually starts with the development of a request for proposal (RFP) that includes an SOW describing the analytical services to be procured. Careful preparation of the SOW is essential to the selection of a laboratory capable of performing the required services in a technically competent and timely manner.

The technical proposals received in response to the procurement RFP must be reviewed by personnel familiar with radioanalytical laboratory operations to select the most qualified offeror. For complicated sites with a large number of laboratory analyses, it is recommended that a portion of this evaluation take the form of a pre-award audit. The provision for this audit must be in the RFP. The results of this audit provide a written record of the decision to use a specific laboratory. Smaller sites or facilities may decide that a review of the laboratory's qualifications is sufficient for the evaluation.

Six criteria should be reviewed during this evaluation:

- Does the laboratory possess the appropriate well-documented procedures, instrumentation, and trained personnel to perform the necessary analyses? Necessary analyses are defined by the data needs (radionuclide(s) of interest, required measurement uncertainties, and target detection limits) identified by the DQO process.
- Is the laboratory experienced in performing similar analyses?

- Does the laboratory have satisfactory performance evaluation results from formal monitoring or accreditation programs? The laboratory should be able to provide a summary of QA audits and proof of participation in interlaboratory cross-check programs. Equipment calibrations should be performed using National Institute of Standards and Technology (NIST)-traceable reference radionuclide standards whenever possible.
- Is there an adequate capacity to perform all analyses within the desired timeframe? This criterion considers whether the laboratory possesses a radioactive materials–handling license or permit for the samples to be analyzed. Very large survey designs may indicate that more than one analytical laboratory is necessary to meet the survey objectives. If several laboratories are performing analyses as part of the survey, the analytical methods used to perform the analyses should be similar to ensure comparability of results (see **Appendix D**).
- Does the laboratory provide an internal QC review of all generated data that is independent of the data generators?
- Are there adequate protocols for method performance documentation and sample security?

Providers of radioanalytical services should have an active and fully documented QA program in place, typically via one or more documents, such as a Quality Management Plan, Quality Assurance Manual, or QAPP. This program should comply with the objectives determined by the DQO process in **Section 2.3.**

Requirements for the QA program (e.g. QAPP), COC requirements, and the numbers of samples to be analyzed should be specified, communicated to the laboratory in writing, and agreed upon. The Sampling and Analysis Plan (SAP), analytical procedures, and the documentation and reporting requirements should also be specified, communicated to the laboratory in writing, and agreed upon. The laboratory's accreditation, if required, should be confirmed by contacting the organization that provided the certification. These topics are discussed in detail in the following sections of this chapter. Additional guidance on obtaining laboratory services can be found in Chapter 5 of the MARLAP manual (NRC 2004).

7.5 Sampling

This section provides guidance on developing appropriate sample collection procedures for surveys designed to demonstrate compliance with a dose- or risk-based regulation. Sample collection procedures are concerned mainly with ensuring that collected samples are representative of the sample media, are large enough to provide sufficient material to achieve the desired detection limit and required measurement uncertainties, and are consistent with assumptions used to develop the conceptual site model and the DCGLs. Additional considerations for sample collection activities are discussed in **Section 4.7.3.**

Commingled chemical and radioactive waste at a site can influence sample handling and laboratory requirements. Also, the external exposure rates or radioactivity concentration of a specific sample may limit the time that workers will be permitted to remain in intimate contact with the samples or may dictate that smaller samples be taken and special holding areas be provided for collected samples before shipment. These special handling considerations may conflict with the size specifications for the analytical method, normal sampling procedures, or equipment. There is a potential for biasing sampling programs by selecting samples that can be safely handled or legally shipped to support laboratories, which could be a concern for scoping, characterization, and Radiation Survey and Site Investigation (RSSI) samples.

7.5.1 Surface Soil

The purpose of surface soil sampling is to collect samples that accurately and precisely represent the radionuclides and their concentrations at the location being sampled. To do this and plan for sampling, a decision must be made as to the survey design. The selection of a survey design is based on the Historical Site Assessment, results from preliminary surveys (i.e., scoping characterization, remedial action support), and the objectives of the survey developed using the DQO process. The selection between judgment, random, and systematic survey designs is discussed in **Section 5.3.**

7.5.1.1 Sample Volume

The volume of soil collected should be specified in the sample collection procedure. In general, large volumes of soil are more representative than small volumes of soil. In addition, large samples provide sufficient material to ensure that required detection limits can be achieved and that sample reanalysis can be done if there is a problem. However, large samples may cause problems with shipping, storage, and disposal. All of these issues should be discussed with the sample collection team and the analytical laboratory during development of sample collection procedures. In general, surface soil samples range in size from 100 grams up to several kilograms.

The sample collection procedure should also make clear if it is more important to meet the volume requirement of the survey design or the surface area the sample represents. Constant volume is related to comparability of the results, while surface area is more closely related to the representativeness of the results. Maintaining a constant surface area and depth for samples collected for a particular survey can eliminate problems associated with different depth profiles. The actual surface area included as part of the sample may be important for estimating the probability of locating areas of elevated concentration.

7.5.1.2 Sample Content

The material present in the field at the sample location may or may not provide a representative sample. Vegetative cover, soil particle size distribution, inaccessibility, and lack of sample material are examples of problems that may be identified during sample collection. All deviations from the survey design as documented in the SOPs should be recorded as part of the field sample documentation.

Sample content is generally defined by the assumptions used to develop the conceptual site model and the DCGLs. A typical agricultural scenario assumes that the top few centimeters of soil are available for resuspension in air; that the top 15 cm (6 in.) are homogenized by agricultural activities (e.g., plowing); that roots can extend down several meters to obtain water and nutrients, depending on the plant; and that external exposure is based on an assumed thickness of contaminated soil (usually at the surface). Depending on the dominant exposure pathways for each radionuclide, this can result in a complicated set of instructions for collecting representative samples. This situation can be further complicated by the fact that the site is not currently being used for agricultural purposes. For this situation, it is necessary to look at the analytical results from the preliminary surveys (i.e., scoping, characterization, remedial action support) to determine the expected depth of residual radioactive material.

In most situations the vegetative cover is not considered part of the surface soil sample and is removed in the field. It is important that the sample collection procedure clearly indicate what is and what is not considered part of the sample.

7.5.1.3 Sampling Equipment

The selection of proper sampling equipment is important to ensure that samples are collected in a reproducible manner and to minimize the potential for cross-contamination. Sampling equipment generally consists of a tool to collect the sample and a container to place the collected sample in. Sample tracking begins as soon as the sample is collected, so it may be necessary to consider security of collected samples required by the objectives of the survey.

Sampling tools are selected based on the type of soil, sample depth, number of samples required, and training of available personnel. The selection of a sampling tool may also be based on the expected use of the results. For example, if a soil sample is collected to verify the depth profile used to develop the calibration for in situ gamma spectrometry, it is important to preserve the soil core. **Table 7.1** lists several examples of tools used for collecting soil samples, situations where they are applicable, and some advantages and disadvantages involved in their use.

Samples collected below the surface are useful in establishing the extent of residual radioactive material in the vertical profile. Understanding the extent of residual radioactive material below the surface can be helpful in determining remediation alternatives and release criteria. Sample containers are generally not a major concern for collecting surface soil samples. Polyethylene bottles with screw caps and wide mouths are recommended and should be new or clean, dry, and checked for residual radioactive material before reuse. Polyethylene bags are acceptable, especially with heavy gauge plastic to avoid sample spillage from tears in the bags. These containers are fairly economical, provide easy access for adding and removing samples, and resist chemicals, breaking, and temperature extremes. Glass containers are also acceptable, but they are fragile and tend to break during shipment. Metal containers are sometimes used, but sealing the container can present a problem, and corrosion can be an issue if the samples are stored for a significant length of time.

Table 7.1: Soil Sampling Equipment[4]

Equipment	Application	Advantages	Disadvantages/ Considerations
Scoop, Trowel, or Post-Hole Digger	Soft surface soil	• Inexpensive	• Trowels with painted surfaces should be avoided.

[4] Reproduced and adapted from EPA 1995.

Equipment	Application	Advantages	Disadvantages/ Considerations
		• Easy to use and decontaminate	
Bulb Planter	Soft Soil, 0–15 cm (0–6 in.)	• Easy to use • Uniform diameter and sample volume • Preserves soil core	• Limited depth capability • Can be difficult to decontaminate
Soil Coring Device	Soft soil, 0–60 cm (0–24 in.)	• Relatively easy to use • Preserves soil core	• Limited depth capability • Can be difficult to decontaminate
Thin-Wall Tube Sampler	Soft soil, 0–3 m (0–10 ft)	• Easy to use • Preserves soil core • Easy to decontaminate	• Can be difficult to remove cores
Split Spoon Sampler	Soil, to bedrock	• Excellent depth range • Preserves soil core • Useful for hard soils	• Often used in conjunction with drill rig for obtaining deep cores
Shelby Tube Sampler	Soft soil, to bedrock	• Excellent depth range • Preserves soil core • Tube may be used for shipping core to lab	• May be used in conjunction with drill rig for obtaining deep cores
Bucket Auger	Soft soil, 7.5 cm–3 m (3 in.–10 ft)	• Easy to use • Good depth range • Uniform diameter and sample volume	• May disrupt and mix soil horizons greater than 15 cm
Hand-Operated Power Auger	Soil, 15 cm–4.5 m (6 in.–5 ft)	• Good depth range • Generally used in conjunction with bucket auger	• Destroys soil core • Requires two or more operators • Can be difficult to decontaminate

Abbreviations: cm = centimeters; in. = inches; m = meters; ft = feet.

7.5.2 Building Surfaces

Because building surfaces tend to be relatively smooth, and the radioactive material is assumed to be on or near the surface, direct measurements are typically used to provide information on residual radioactive material concentrations. Sometimes, however, it is necessary to collect actual samples of the building material surface for analysis in a laboratory.

7.5.2.1 Sample Volume

The sample volume collected from building surfaces is usually a less significant DQO concern than the area from which the sample was collected. This is because building surface DCGLs are usually expressed in terms of activity per unit area. It is still necessary to consider the sample volume to account for sample matrix effects that may reduce the chemical recovery, which in turn affects the detection limit.

7.5.2.2 Sample Content

If residual radioactive material is covered by paint or some other treatment, the underlying surface and the coating itself may contain residual radioactive material. If the residual radioactive material is a pure alpha or low-energy beta emitter, measurements at the surface will probably not be representative of the actual residual activity level. In this case, the surface layer is removed from the known area, such as by using a commercial stripping agent or by physically abrading the surface. The removed coating material is analyzed for activity content and the level converted to appropriate units (i.e., becquerels/square meter [Bq/m^2], decays per minute [dpm]/100 cm^2) for comparison with surface activity DCGLs. Direct measurements can be performed on the underlying surface after removal of the coating.

Residual radioactive material may be incorporated into building materials, such as pieces of concrete or other unusual matrices. Developing SOPs for collecting these types of samples may involve consultation with the analytical laboratory to help ensure that the objectives of the survey are achieved.

The thickness of the layer of building surface to be removed as a sample should be consistent with the development of the conceptual site model and the DCGLs. For most sites, the surface layer will only be the first few millimeters of the material being sampled.

7.5.2.3 Sampling Equipment

Tools used to provide samples of building surfaces depend on the material to be sampled. Concrete may require chisels, hammers, drills, or other tools specifically designed to remove a thin layer of the surface. Wood surfaces may require using a sander or a saw to collect a sample. Paint may be chemically or physically stripped from the surface.

Sample containers for these samples are generally the same as those recommended for soil samples. If chemicals are used to strip paint or other surface materials, the chemical resistance of the container should be considered.

7.5.3 Other Media

Surface soil and building surfaces are the media addressed in MARSSIM during the FSS design. Other media may be involved and may have been remediated. Data collection activities during preliminary surveys (i.e., scoping, characterization, remedial action support) may involve collecting samples of other media to support the FSS design. Examples of other media that may be sampled include—

- subsurface soil
- ground water
- surface water
- sediments
- sewers and septic systems
- flora and fauna (plants and animals)
- airborne particulates
- air (gas)

7.6 Field Sample Preparation and Preservation

Proper sample preparation and preservation are essential parts of any radioactive material sampling program. The sampling objectives should be specified before sampling activities begin. Precise records of sample collection and handling are necessary to ensure that data obtained from different locations or time frames are correctly compared.

The appropriateness of sample preparation techniques is a function of the analysis to be performed (EPA 1992a, 1992b). Field sample preparation procedures are a function of the specified analysis and the objectives of the survey. It is essential that these objectives be clearly established and agreed on in the early stages of survey planning (see **Section 2.3**).

7.6.1 Surface Soil

Soil and sediment samples, in most protocols, require no field preparation and are not preserved. In some protocols (e.g., if the sample will be analyzed for both volatile organics and radionuclides), cooling of soil samples to 4 degrees Celsius is required during shipping and storage of soil samples.

When replicate samples are prepared in the field, it is necessary to homogenize the sample before separation into replicates. There are standard procedures for homogenizing soil in the laboratory (ASTM 2010), but the equipment required for these procedures may not be available in the field. Simple field techniques, such as cone and quarter, or using a riffle splitter to divide the sample may be appropriate if the sample can be dried (ASTM 2003, EPA 1995). If the sample contains significant amounts of residual water (e.g., forms clumps of soil) and there are no facilities for drying the sample, it is recommended that the homogenization and separation into replicates be performed in a laboratory. It is preferable to use non-blind replicates where the same laboratory prepares and analyzes the replicates rather than use poorly homogenized or heterogeneous samples to prepare replicate samples.

7.6.2 Building Surfaces

Field preparation and preservation of building and associated materials, including smear samples, is not generally required. Homogenization of samples to prepare replicates is the same for building surface material and soil.

7.6.3 Other Media

Other media may have significant requirements related to field sample preparation and preservation. For example, water samples may need filtering and acidification. Storage at reduced temperatures (i.e., cooling or freezing) to reduce biological activity may be necessary for some samples. Adding chemical preservatives for specific radionuclides or media may also be required. Guidance on sample preparation and preservation in matrices not discussed above can be found in Chapter 10 of MARLAP.

7.7 Analytical Procedures

The selection of the appropriate radioanalytical methods is normally made before the procurement of analytical services and is included in the SOW of the request for proposal. The SOW may dictate the use of specific methods or be performance based. Unless there is a regulatory requirement, such as conformance to the EPA drinking water methods (EPA 1980b), the specification of performance-based methodology is encouraged. One reason for this is that a laboratory will usually perform better using the methods it routinely employs, rather than other methods with which it has less experience. The laboratory is also likely to have historical data on performance for methods routinely used by that laboratory. However, the methods employed in a laboratory should be derived from a reliable source.

This section briefly describes specific equipment and procedures to be used once the sample is prepared for analysis. The results of these analyses (i.e., the concentrations of radioactive material found in these samples) are the values used to determine the level of residual radioactive material at a site. In a decommissioning effort, the DCGLs are expressed in terms of the concentrations of certain radionuclides. It is of vital importance, therefore, that the analyses be accurate, of adequate sensitivity, and have adequate minimum measurement uncertainties for the radionuclides of concern. The selection of analytical procedures should be coordinated with the laboratory and specified in the survey plan.

Analytical methods should be adequate to meet the data needs identified in the DQO process. Consultation with the laboratory performing the analysis is recommended before selecting a course of action. MARSSIM is not intended to limit the selection of analytical procedures; rather, all applicable methods should be reviewed to provide results that meet the objectives of the survey. The decision maker and survey planning team should decide whether routine methods will be used at the site or if non-routine methods may be acceptable.

- Routine analytical methods are documented with information on minimum performance characteristics, such as detection limit, minimum measurement uncertainty, precision and accuracy, and useful range of radionuclide concentrations and sample sizes. Routine methods may be issued by a recognized organization (e.g., Federal or State agency, professional organization), published in a refereed journal, or developed by an individual laboratory. The following are examples of sources for routine methods:

  - Methods of Air Sampling and Analysis (Lodge 1988)
  - Annual Book of ASTM Standards, Water and Environmental technology. Volume 11.05, Environmental Assessment, Risk Management and Corrective Action (ASTM 2012)
  - Standard Methods for the Examination of Water and Wastewater (APHA 2012)
  - Environmental Measurements Laboratory Procedures Manual (DOE 1997)
  - Inventory of Radiological Methodologies for Sites Contaminated With Radioactive Materials (EPA 2006d)
  - Radiochemistry Procedures Manual (EPA 1984)
  - ANSI-AARST Radon Protocols/Standards
    - MAH-2014, Protocol for Conducting Measurements of Radon and Radon Decay Products in Homes (AARST 2014a)
    - MAMF-2017, Protocol for Conducting Measurements of Radon and Radon Decay Products in Multifamily Buildings (AARST 2017)
    - MALB-2014, Protocol for Conducting Measurements of Radon and Radon Decay Products in Schools and Large Buildings (AARST 2014b)
    - MS-PC-2015, Performance Specifications for Instrumentation Systems Designed to Measure Radon Gas in Air (AARST 2015)
    - MS-QA-2019, Radon Measurement Systems Quality Assurance (AARST 2019)

- Non-routine methods address situations with unusual or problematic matrices; low detection limits; or new parameters, procedures or techniques. Non-routine methods include adjustments to routine methods, new techniques published in refereed literature, and development of new methods.

References that provide information on radiochemical methodology and should be considered in the methods review and selection process are available from such organizations as—

- National Council on Radiation Protection and Measurements
- American Society of Testing and Materials
- American National Standards Institute
- Radiological and Environmental Sciences Laboratory, Idaho Falls, Idaho (operated by the U.S. Department of Energy)

- National Urban Security Technology Laboratory, New York City, NY (operated by the U.S. Department of Homeland Security)

Equipment vendor literature, catalogs, and instrument manuals are often a source of useful information on the characteristics of radiation detection equipment. **Table 7.2** provides a summary of common laboratory methods with estimated detection limits.

Analytical procedures in the laboratory consist of several parts that are assembled to produce an SOP for a specific project or sample type. These procedures may include all or only some of the following elements:

- laboratory sample preparation
- sample dissolution
- sample purification
- preparation for counting
- counting
- data reduction

7.7.1 Photon-Emitting Radionuclides

There is minimal special sample preparation required for counting samples using a germanium detector or a sodium iodide (NaI) detector beyond placing the sample in a known geometry for which the detector has been calibrated. The procedures to be followed to process a raw soil sample to obtain a representative subsample for analysis depend, to some extent, upon the size of the sample, the amount of processing already undertaken in the field, and—most important—the radionuclide of interest (NRC 2004). The samples can be measured as they arrive at the laboratory, or the sample can be dried, ground to a uniform particle size, and mixed to provide a more homogeneous sample if required by the SOPs. Guidance on the preparation of samples, including soil samples, can be found in Chapter 12 of MARLAP (NRC 2004).

The samples are typically counted using a germanium detector with a multichannel analyzer or a NaI detector with a multichannel analyzer. Germanium detectors have better resolution and can identify peaks (and the associated radionuclides) at lower concentrations. NaI detectors often have a higher efficiency and are significantly less expensive than germanium detectors. Low-energy photons (i.e., x-rays and gamma rays below 50 kilo-electron volts) can be measured using specially designed detectors with an entrance window made from a very light metal, typically beryllium. Descriptions of germanium and NaI detectors are provided in **Appendix H.**

Data reduction is usually the critical step in measuring photon-emitting radionuclides. Often several hundred individual gamma ray energies are detected within a single sample. Computer software is usually used to identify energy peaks and associate these peaks with their respective radionuclides. The software is also used to correct for the efficiency of the detector and the geometry of the sample and to provide results in terms of concentrations with the

Table 7.2: Typical Measurement Sensitivities for Laboratory Radiometric Procedures

Sample Type	Radionuclides or Radiation Measured	Procedure	Approximate Detection Capability
Smears (Filter Paper)	Gross alpha	Gas-flow proportional counter; 5 min count Alpha scintillation detector with scaler; 5 min count	0.08 Bq (5 dpm) 0.33 Bq (20 dpm)
	Gross beta	Gas-flow proportional counter; 5 min count End window GM with scaler; 5 min count (unshielded detector)	0.17 Bq (10 dpm) 1.33 Bq (80 dpm)
	Low energy beta (^{3}H, ^{14}C, ^{63}Ni)	Liquid scintillation spectrometer; 5 min count	0.50 Bq (30 dpm)
Soil Sediment	^{137}Cs, ^{60}Co, ^{226}Ra (^{214}Bi)[a], ^{232}Th (^{228}Ac), ^{235}U	Germanium detector (25% relative efficiency) with multichannel analyzer; pulse height analyzer; 500 g sample; 15 min analysis	0.04–0.1 Bq/g (1–3 pCi/g)
	$^{234, 235, 238}$U; $^{238, 239, 240}$Pu; $^{227, 228, 230, 232}$Th; other alpha emitters	Alpha spectroscopy with multichannel analyzer—pyrosulfate fusion and solvent extraction; surface barrier detector; pulse height analyzer; 1 g sample; 16 h count	0.004–0.02 Bq/g (0.10.5 pCi/g)
Water	Gross alpha	Gas-flow proportional counter; 100 ml sample, 200 min count	0.04 Bq/L (1 pCi/L)
	Gross beta	Gas-flow proportional counter; 100 ml sample, 200 min count	0.04 Bq/L (1 pCi/L)
	^{137}Cs, ^{60}Co, ^{226}Ra (^{214}Bi), ^{232}Th (^{228}Ac), ^{235}U	Germanium detector (25% relative efficiency) with multichannel analyzer; pulse height analyzer; 3.5 L sample, 16 h count	0.4 Bq/L (10 pCi/L)
	$^{234, 235, 238}$U; $^{238, 239, 240}$Pu; $^{227, 228, 230, 232}$Th; other alpha emitters	Alpha spectroscopy with multichannel analyzer—solvent extraction; surface barrier detector; pulse height analyzer; 100 ml sample, 30 min count	0.004–0.02 Bq/L (0.1–0.5 pCi/L)
	^{3}H	Liquid scintillation spectrometry; 5 ml sample, 30 min count	10 Bq/L (300 pCi/L)

Abbreviations: min = minute; Bq = becquerel; dpm = disintegrations per minute; GM = Geiger-Mueller; g = grams; h = hour; pCi = picocuries; ml = milliliters; L = liters

[a] Indicates that a member of the decay series is measured to determine activity level of the parent radionuclide of primary interest.

associated uncertainty. It is important that the software be either a well-documented commercial package or thoroughly evaluated and documented before use.

7.7.2 Beta-Emitting Radionuclides

Laboratory sample preparation is an important step in the analysis of surface soil and other solid samples for beta-emitting radionuclides. The laboratory will typically have a sample preparation procedure that involves drying the sample and grinding the soil so that all particles are smaller than a specified size to provide a homogeneous sample. A small portion of the homogenized sample is usually all that is required for the individual analysis.

Once the sample has been prepared, a small portion is dissolved, fused, or leached to provide a clear solution containing the radionuclide of interest. The only way to ensure that the sample is solubilized is to completely dissolve the sample. However, this can be an expensive and time-consuming step in the analysis. In some cases, leaching with strong acids can consistently provide greater than 80 percent recovery of the radionuclide of interest (NCRP 1976) and may be acceptable for certain applications. After dissolution, the sample is purified using a variety of chemical reactions to remove bulk chemical and radionuclide impurities. The objective is to provide a chemically and radiologically pure sample for measurement. Examples of purification techniques include precipitation, liquid-liquid extraction, ion-exchange chromatography, distillation, and electrodeposition. Gross beta measurements may also be performed on material that has not been purified.

After the sample is purified, it is prepared for counting. Beta-emitting radionuclides are usually prepared for a specific type of counter in a specified geometry. Some samples can be precipitated and collected on a filter in a circular geometry to provide a homogeneous sample. Other samples can be converted to the appropriate chemical form and diluted to a specified volume in preparation for counting.

Measurements of some samples may be performed using a gas-flow proportional counter. Because total beta activity is measured, it is important that the purification step be performed to remove any interfering radionuclides. Other samples can be added to a liquid scintillation cocktail and counted using a liquid scintillation spectrometer. Liquid scintillation spectrometers can be used for low-energy beta-emitting radionuclides, such as ^{3}H and ^{63}Ni. Proper applications can decrease lower limits of detection for all nuclides; however, typical applications in many labs limit the minimum detectable activity to those that are higher than standard gas proportional counting. Gas-flow proportional counters have a very low background. **Appendix H** provides a description of both the gas-flow proportional counter and the liquid scintillation spectrometer.

7.7.3 Alpha-Emitting Radionuclides

Laboratory sample preparation for alpha-emitting radionuclides is similar to that for beta-emitting radionuclides. Sample dissolution and purification tasks are also similar to those performed for beta-emitting radionuclides.

Because of the limited penetrating power of alpha particles, the preparation for counting is often a critical step. Gross alpha measurements can be made using small sample sizes with a gas-flow proportional counter, but self-absorption of the alpha particles results in a relatively high detection limit for this technique. Liquid scintillation spectrometers can also be used to measure alpha-emitting radionuclides, but the resolution limits the usefulness of this technique. Most alpha-emitting radionuclides are measured in a vacuum (to limit absorption by air) using alpha spectroscopy. This method requires that the sample be prepared as a virtually weightless mount in a specific geometry. Electrodeposition is the traditional method for preparing samples for counting. This technique provides the highest resolution, but it requires a significant amount of training and expertise on the part of the analyst to produce a high-quality sample. Precipitation of the radionuclide of interest on the surface of a substrate is often used to prepare samples for alpha spectroscopy. While this technique generally produces a spectrum with lower resolution, the preparation time is relatively short compared to electrodeposition, and personnel can be trained to prepare acceptable samples relatively quickly.

Alpha-emitting radionuclides are typically measured using alpha spectroscopy. The data reduction requirements for alpha spectroscopy are greater than those for beta-emitting radionuclides and similar to those for photon-emitting radionuclides. Alpha spectroscopy produces a spectrum of alpha particles detected at different energies, but because the sample is purified before counting, all of the alpha particles come from radionuclides of a single element. This simplifies the process of associating each peak with a specific radionuclide, but the lower resolution associated with alpha spectroscopy increases the difficulty of identifying the peaks. Although commercial software packages are available for interpreting alpha spectroscopy results, an experienced operator is required to ensure that the software is working properly.

7.8 Sample Tracking

Sample tracking refers to the identification of samples, their location, and the individuals responsible for their custody and transfer of the custody. This process covers the entire process from collection of the samples and remains intact through the analysis and final holding or disposal. It begins with the taking of a sample where its identification and designation of the sample are critical to being able to relate the analytical result to a site location.

Tracking samples from collection to receipt at the analytical laboratory is normally done through a COC process and documented on a COC or tracking record. The purpose of the COC record is to ensure the security and legal defensibility of the sample throughout the process. When samples are received by the laboratory, internal tracking and COC procedures should be in place. These procedures should be documented through SOPs that ensure integrity of the samples. Documentation of changes in the custody of a sample is important. This is especially true for samples that may be used as evidence to establish compliance with release criteria. In such cases, there should be sufficient evidence to demonstrate that the integrity of the sample is not compromised from the time it is collected to the time it is analyzed. During this time, the sample should either be under the positive control of a responsible individual or secured and protected from any activity that could change the true value of the results or the nature of the sample. When this degree of sample handling or custody is necessary, written procedures should be developed for field operations and for interfacing between the field operations and the analytical laboratory. This ensures that a clear transfer of the custodial responsibility is well-documented and that no questions exist as to who is responsible for the sample at any time.

7.8.1 Field Tracking Considerations

Suggestions for field sample tracking are given below:

- Field personnel are responsible for maintaining field logbooks with adequate information to relate the sample identifier (sample number) to its location and for recording other information necessary to adequately interpret results of sample analytical data. Logbooks may use electronic records, provided information is stored in manner that is tamper-proof and retrievable if electronic media fail.

- The sample collector is responsible for the care and custody of the samples until they are properly transferred or dispatched. This means that samples are in their possession, under constant observation, or secured. Samples may be secured in a sealed container, locked vehicle, locked room, etc.
- Sample labels should be completed for each sample using waterproof ink or in a tamper-proof and recoverable electronic medium.
- The survey manager or designee determines whether or not proper custody procedures were followed during the field work and decides if additional sampling is indicated.
- If photographs are included as part of the sampling documentation, the name of the photographer, date, time, site location, and site description should be entered sequentially in a logbook as the photos are taken. After the photographs are printed, the prints should be serially numbered. Alternatively, the information can be filed in a tamper-proof electronic form or database.

7.8.2 Transfer of Custody

Suggestions for transferring sample custody are given below:

- All samples leaving the site should be accompanied by a COC record. This record should be standardized and document sample custody transfer from the sampler, often through another person, to the laboratory. The sample collector is responsible for initiating the tracking record. The record should include a list, containing sample designation (number), of the samples in the shipping container and the analysis requested for each sample.
- Shipping containers should be sealed and include a tamper-indicating seal that will indicate if the container seal has been disturbed. The method of shipment, courier name, or other pertinent information should be listed in the COC record.
- The original COC record should accompany the samples. A copy of the record should be retained by the individual or organization relinquishing the samples. If a sample is to be split and distributed to more than one analytical laboratory, multiple forms will be needed to accompany sample sets.
- Discuss the custody objectives with the shipper to ensure that the objectives are met. For example, if the samples are sent by mail and the originator of the sample requires a record that the shipment was delivered, the package should be registered with return receipt requested. If, on the other hand, the objective is to simply provide a written record of the shipment, a certificate of mailing may be a less expensive and appropriate alternative.
- The individual receiving the samples should sign, date, and note the time of receipt on the record. The condition of the container and the tamper-indicating seal should be documented on the COC. Any problems with the individual samples, such as a broken container, should be noted on the record.
- COC procedures may utilize tamper-proof electronic media, as appropriate.

7.8.3 Radiochemical Holding Times

In some circumstances, sample holding times are particularly important. For example, liquid samples are usually analyzed as quickly as possible. This would also be true for short half-lived radionuclides. Minimizing the holding times in these situations can reduce the measurement uncertainties and lower the minimum detectable concentrations.

For this reason, the SOW should contain the requirements for radiological holding and sample turnaround times. It is important that the laboratory review the specifications for radionuclides that have short half-lives (less than 30 days), because the method proposed by the laboratory may depend on the required radiological holding time. For very short-lived radionuclides, it is crucial to analyze the samples within the first two half-lives to meet the MQOs conveniently. Additionally, samples requiring parent decay or progeny ingrowth should be held for sufficient time before counting. Limits for minimum ingrowth and maximum or minimum decay times should be established for all analytical methods where they are pertinent. For ingrowth, the limits should reflect the minimum time required to ensure that the radionuclides of interest have accumulated sufficiently to not adversely affect the detection limit or uncertainty (e.g., holding samples for ^{226}Ra analysis to permit ingrowth of ^{222}Rn). Alternatively, requirements for holding times may be set to ensure that interfering radionuclides have a chance to decay sufficiently Conversely, the time for radioactive decay of the radionuclides of interest should be limited such that the decay factor does not elevate the minimum detectible concentration or adversely affect the measurement uncertainty (NRC 2004).

7.8.4 Laboratory Tracking

When the samples are received by the laboratory, they are prepared for radiochemical analyses, which includes dividing the sample into aliquots. The tracking and COC documentation within the laboratory become somewhat complicated because several portions of the original sample may exist in the laboratory at a given time. The term “tracking” refers to an accountability process that meets generally acceptable laboratory practices as described by accrediting bodies but is less stringent than a formal COC process. Similar to the COC process, tracking also develops a record of all individuals responsible for the custody and transfer of samples. The use of a computer-based laboratory information management system can greatly assist in tracking samples and fractions through the analytical system.

The minimal laboratory tracking process consists of the following:

- transfer of custody on receipt of the samples (original COC form is retained by the laboratory and submitted with the data package for the samples)
- documentation of sample storage (location and amount)
- documentation of removal and return of sample aliquots (amount, date and time, person removing or returning, and reason for removal)
- transfer of the samples and residues to the receiving authority (usually the site from which they were taken)
- tamper-proof electronic systems acceptable for laboratory tracking

The procedure for accomplishing the above varies from laboratory to laboratory, but the exact details of performing the operations of sample tracking should be contained in an SOP.

7.9 Packaging and Transporting Samples

All samples being shipped for radiochemical analysis should be properly packaged and labeled before transport offsite or within the site. The primary concern is the possibility of spills, leaks, or breakage of the sample containers. In addition to resulting in the loss of samples and cross-contamination, the possible release of hazardous material poses a threat to the safety of persons handling and transporting the package.

Suggestions for packaging and shipping radioactive environmental samples are listed below:

- Review NRC requirements (10 CFR Part 71) and U.S. Department of Transportation (DOT) requirements (49 CFR Parts 171–177) for packaging and shipping radioactive environmental samples.
- Visually inspect each sample container for indication of leaks or defects in the sample container.
    - Liquid samples should be shipped in plastic containers, if possible, and the caps on the containers should be secured with tape. One exception to the use of plastic bottles is samples collected for ^{3}H analyses, which may require glass containers.
    - Heavy plastic bags with sealable tops can be used to contain solid samples (e.g., soil, sediment, air filters). The zipper lock should be secured with tape. Heavy plastic lawn bags can be used to contain vegetation samples. The tops should be closed with a “tie” that is covered by tape to prevent it from loosening and slipping off.
- Wipe individual sample containers with a damp cloth or paper towel to remove any exterior contamination. The outer surfaces of containers holding samples collected in an area containing residual radioactive material should be surveyed with one or more hand-held instruments appropriate for the suspected type of radioactive material.
- If glass sample containers are used, place sample containers inside individual plastic bags and seal to contain the sample in case of breakage.
- Use packing material (e.g., paper, Styrofoam™, bubble wrap) to immobilize and isolate each sample container and buffer hard knocks on the outer container during shipping. This is especially important in cold weather, when plastic containers may become brittle and water samples may freeze.
- When liquid samples are shipped, include a sufficient quantity of an absorbent material (e.g., vermiculite) to absorb all liquid packed in the shipping container in case of breakage. This absorbent material also may suffice as the packing material.
- Include the original signed and dated COC form, identifying each sample in the package. It is good practice to place the COC form in a plastic bag to prevent it from becoming wet or contaminated in case of a spill during shipment. If possible, avoid having multiple packages of samples covered by a single COC form.
- Seal closed the package and apply COC tape in such a manner that it must be torn (broken) to open the package. The tape should carry the signature of the sender, and the date and time, so that it cannot be removed and replaced undetected.

- Ice chests constructed of metal or hard plastic make excellent shipping containers for radioactive environmental samples.
- Regulations may require specific labeling and markings on the external surface of each shipping container and may also require handling instructions and precautions be attached to the shipping container. Some information should be included on the package even if not required by the regulations, such as the sender's and receiver's (consignee and consignor) names, addresses, and telephone numbers. When required by shipping regulation, proper handling instructions and precautions should be clearly marked on shipping containers.
- Shipments with dry ice or other hazardous packaging material are subject to requirements pertaining to the packaging, apart from the radioactive or hazardous contents.

If samples are sent offsite for analysis, the shipper is responsible for complying with all applicable Federal, State, and local regulations. Applicable Federal regulations are briefly addressed below. Any State or local regulation will very likely reflect a Federal regulation.

7.9.1 U.S. Nuclear Regulatory Commission Regulations

NRC regulations for packaging, preparation, and shipment of licensed material are contained in 10 CFR Part 71: "Packaging and Transportation of Radioactive Materials."

- Samples containing low levels of radioactive material are exempted as set forth in §§ 71.10.
- Low Specific Activity material (LSA) is defined in §§ 71.4: "Definitions." Samples classified as LSA need only meet the requirements of the DOT, discussed below, and the requirements of §§ 71.88: "Air transport of plutonium." Most environmental samples either will fall into this category or will be exempt of any DOT regulations.

7.9.2 U.S. Department of Transportation Regulations

The DOT provides regulations governing the transport of hazardous materials under the Hazardous Materials Transportation Act of 1975 (88 Stat. 2156, Public Law 93-633). Applicable requirements of the regulations are found in 49 CFR Parts 171–177. Shippers of samples containing radioactive material should be aware of the current rules in the following areas:

- Accident reporting: 49 CFR 171
- Marking and labeling packages for shipment: 49 CFR 172
- Packaging: 49 CFR 173
- Placarding a package: 49 CFR 172
- Registration of shipper/carrier: 49 CFR 107
- Shipper required training: 49 CFR 172
- Shipping papers and emergency information: 49 CFR 172
- Transport by air: 49 CFR 175
- Transport by rail: 49 CFR 174

- Transport by vessel: 49 CFR 176
- Transport on public highway: 49 CFR 177

7.9.3 U.S. Postal Service Regulations

Any package containing radioactive materials may not be mailed if it is required to bear the DOT's Radioactive White-1 (49 CFR 172.436), Radioactive Yellow-II (49 CFR 172.438), or Radioactive Yellow-III (49 CFR 172.440) label, or if it contains quantities of radioactive material in excess of those authorized in Publication 6, Radioactive Material, of the U.S. Postal Service.

7.9.4 International Atomic Energy Agency Regulations

In the event that samples or other radioactive materials, such as calibration sources, are shipped outside the boundaries of the United States, the shipment of those materials must comply with the International Atomic Energy Agency *Regulations for the Safe Transport of Radioactive Material* (IAEA 2005). The areas addressed in the Regulations include—

- activity limits and material restrictions
- requirements and controls for transport
- radioactive material package and packaging requirements
- test procedures
- administrative controls and requirements

8 INTERPRETATION OF SURVEY RESULTS

8.1 Introduction

This chapter discusses the interpretation of survey results, primarily those of the final status survey (FSS). Interpreting a survey's results is most straightforward when measurement data are entirely higher or lower than the wide-area derived concentration guideline level ($DCGL_W$). In such cases, the decision that a survey unit meets or exceeds the release criteria requires little in terms of data analysis. However, formal statistical tests provide a valuable tool when a survey unit's measurements are neither clearly above nor exclusively below the $DCGL_W$. Nevertheless, the survey design always makes use of the statistical tests to help ensure that the number of sampling points and the measurement detectability and uncertainty are adequate, but not excessive, for the decision to be made. Although most statistical analysis is completed using statistical software packages, this chapter provides an explanation to facilitate the reader's understanding of the mechanics behind the calculations of these statistical tests.

Section 8.2 discusses the assessment of data quality. The remainder of **Chapter 8** deals with application of the statistical tests used in the decision-making process and the evaluation of the test results. In addition, an example checklist is provided to assist the user in obtaining the necessary information for interpreting the results of an FSS. **Section 8.3** discusses the application of the Sign test to survey data involving radionuclides that are not in the background. **Section 8.4** discusses the application of the Wilcoxon Rank Sum (WRS) test to survey data involving radionuclides that are in the background and, for Scenario B, the application of the quantile test when the null hypothesis is not rejected. Comparisons of scan-only results to an upper confidence limit are discussed in **Section 8.5. Section 8.6** discusses the results, including the elevated measurement comparison (EMC), and interpretation of the statistical tests. **Section 8.7** discusses the documentation requirements.

8.2 Data Quality Assessment

Data Quality Assessment (DQA) is a scientific and statistical evaluation that determines whether the data are of the right type, quality, and quantity to support their intended use. An overview of the DQA process is presented in **Section 2.3** and **Appendix D.** The DQA process has five steps:

- Review the Data Quality Objectives (DQOs), Measurement Quality Objectives (MQOs) and Survey Design (**Section 8.2.1**)
- Conduct a Preliminary Data Review (**Section 8.2.2**)
- Select the Statistical Test (**Section 8.2.3**)
- Verify the Assumptions of the Statistical Test (**Section 8.2.4**)
- Draw Conclusions from the Data (**Section 8.2.5**)

The effort applied to DQA should be consistent with the graded approach used to develop the survey design. More information on DQA can be found in *Data Quality Assessment: A User's Guide* (EPA QA/G-9R, EPA 2006a) and *Data Quality Assessment: Statistical Tools for Practitioners* (EPA QA/G-9S, EPA 2006b).

Data should be verified and validated as described in the Quality Assurance Project Plan (QAPP). Guidance on data verification and validation can be found in **Appendix D** and Multi-Agency Radiation Laboratory Analytical Protocols (MARLAP) (NRC 2004) Chapter 8. Guidance on developing a QAPP is available in EPA QA/G-5 (EPA 2002a) and MARLAP Chapter 4.

8.2.1 Review the Data Quality Objectives, Measurement Quality Objectives, and Survey Design

The first step in the DQA evaluation is a review of the DQO outputs to ensure that they are still applicable. The review of the DQOs and survey design should also include the MQOs (e.g., measurement uncertainty, detectability). For example, if the data suggest the survey unit was misclassified as Class 3 instead of Class 1 (i.e., because measurement results above the $DCGL_W$ were obtained), then the original DQOs should be redeveloped for the correct classification; or, for example, if the data show the measurement uncertainty exceeds the estimate used to design the survey, the DQOs and MQOs should be revisited.

The survey design and data collection documentation should be reviewed for consistency with the DQOs. For example, the review should check that the calculated N number of samples was taken in the correct locations and that the samples were analyzed using measurement systems with required detection capability and uncertainty. Example checklists for different types of surveys are given in **Chapter 5.**

Determining that the survey design provides adequate power is important to decision making, particularly in cases where the average levels of residual radioactive material are near the $DCGL_W$. This can be done both prospectively during survey design to test the efficacy of a proposed design and retrospectively during interpretation of survey results to determine that the objectives of the design are met. The procedure for generating power curves for specific tests is discussed in **Appendix M.** Note that the accuracy of a prospective power curve depends on having good estimates of the data variability, σ, and the number of measurements. After the data are analyzed, a sample estimate of the data variability, namely the sample standard deviation (s) and the actual number of valid measurements will be known. While the Type I (α) decision error rate will always be achieved, the consequence of inadequate power is an increased Type II (β or false negative) decision error rate.

- For Scenario A, this means that a survey unit that actually meets the release criteria has a higher probability of being incorrectly deemed *not to meet* the release criteria**.**
- For Scenario B, this means that a survey unit that does not meet the release criteria has a higher probability of being incorrectly deemed to *meet* the release criteria.

Regulators are primarily concerned with errors that result from determining that a survey unit meets the release criteria when it does not. This incorrect decision is a Type I error under Scenario A and a Type II error under Scenario B. Site owners are also concerned with errors that result from determining that a survey unit does not meet the release criteria when it does. This incorrect decision is a Type II error under Scenario A and a Type I error under Scenario B.

8.2.2 Conduct a Preliminary Data Review

To learn about the structure and quality of the data—identifying patterns, relationships, or potential anomalies—it is recommended that the quality assurance (QA) and quality control (QC) reports be reviewed and that basic statistical quantities be calculated and graphs of the data, or populations estimators, be prepared so that objective evidence is provided to support conclusions about the data set.

8.2.2.1 Data Evaluation and Conversion

Radiological survey data are usually obtained in units that have no intrinsic meaning relative to DCGLs, such as the number of counts per unit time. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements are converted to DCGL units. Further information on instrument calibration and data conversion is given in **Section 6.7.**

Basic statistical quantities that should be calculated for the sample data set are the—

- sample mean
- sample standard deviation
- sample median[1]

Other statistical quantities that may be calculated are—

- the standard error for the mean
- the highest measurement
- the lowest measurement

The sample mean, $\bar{x}$, can be calculated using **Equation 8-1:**

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (8\text{-}1)$$

[1] The term "sample" here is a statistical term and should not be confused with laboratory samples. For the calculation of basic statistical quantities above, data may consist of scan data, direct measurement data, or laboratory sample data. See also the glossary definition of sample.

where N is the number of samples, and x_i are the results of the individual samples. The sample standard deviation, s, can be calculated using **Equation 8-2:**

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{8-2}$$

The median is the middle value of the data set when the number of data points is odd and is the average of the two middle values when the number of data points is even. Thus, 50 percent of the data points are above the median, and 50 percent are below the median. **Example 1** illustrates how to calculate the sample standard deviation.

Example 1: Calculate the Sample Standard Deviation

Suppose the following 20 concentration values are from a survey unit:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

First, the sample mean of the data should be calculated:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$
$$= \frac{1}{N}(90.7 + 83.5 + 86.4 + \cdots + 92.4 + 75.5 + 80.5)$$
$$= 83.5$$

The sample mean is 83.5. The sample standard deviation should also be calculated:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$
$$= \sqrt{\frac{1}{20\text{-}1}[(90.7 - 83.5)^2 + (83.5 - 83.5)^2 + \cdots + (75.5 - 83.5)^2 + (80.5 - 83.5)^2]}$$
$$= 5.7$$

The sample standard deviation is 5.7.

For Scenario A, the mean concentration of the survey unit should always be compared to the $DCGL_W$. A mean survey unit concentration less than the $DCGL_W$ is a necessary, but not sufficient, requirement for the release of the survey unit if the radionuclide is not present in the background. Where remediation is inadequate, this comparison may readily reveal that a survey unit contains excess residual radioactive material—even before applying statistical tests. For example, if the sample mean of the data exceeds the $DCGL_W$ and the radionuclide of interest does not appear in background, then the survey unit clearly does not meet the release criteria. On the other hand, if every measurement in the survey unit is below the $DCGL_W$, the survey unit clearly meets the release criteria.[2]

The value of the sample standard deviation is especially important. If the standard deviation is too large compared to that assumed during the survey design, this may indicate that an insufficient number of samples were collected to achieve the desired power of the statistical test. Again, inadequate power can lead to unnecessary remediation for Scenario A (of particular interest to the regulated) or inadequate remediation for Scenario B (of particular interest to the regulator).

Large differences between the mean and the median would be an indication of skewness in the data. This would also be evident in a histogram of the data. **Example 2** illustrates a comparison of the sample mean and median.

Example 2: Comparison of the Sample Mean and the Median

Using the data from the earlier example, take the 20 concentration values from the survey unit:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

Sort and rank the data from lowest to highest:

1	2	3	4	5	6	7	8	9	10
74.2	75.5	76.3	77.4	77.6	78.2	79.1	80.5	83.5	84.1

11	12	13	14	15	16	17	18	19	20
84.4	86.4	86.4	86.5	87.6	88.5	90.1	90.3	90.7	92.4

For the example data above, the median is 84.25 (i.e., (84.1 + 84.4)/2). The difference between the median and the mean (i.e., 84.25 - 83.5 = 0.75) is a small fraction of the sample standard deviation (i.e., 5.7). Thus, in this instance, the mean and median would not be considered significantly different.

Examining the minimum, maximum, and range of the data may provide additional useful information. The maximum is the value of the largest observed sample, the minimum is the

[2] It can be verified that if every measurement is below the $DCGL_W$, the conclusion from the statistical tests will always be that the survey unit does not exceed the release criteria.

value of the smallest observed sample, and the range is the difference between the maximum and minimum. When there are 30 or fewer data points, values of the range much larger than about 4 to 5 standard deviations would be unusual. For larger data sets, the range might be wider. **Example 3** illustrates how to determine the sample range.

Example 3: Determination of the Sample Range

The minimum in the previous example is 74.2 and the maximum is 92.4, so the range is 18.2 (92.4 - 74.2 = 18.2). Dividing the range by the standard deviation indicates how many standard deviations wide the sample data represent:

$$\frac{18.2}{5.7} = 3.2$$

This is only 3.2 standard deviations. Thus, the range is not unusually large.

8.2.2.2 Graphical Data Review

At a minimum, a graphical data review should consist of a posting plot and a histogram. Quantile plots are also useful diagnostic tools, particularly in the two-sample case, to compare the survey unit and reference area in cases where the radionuclide is present in the background or measurements are not radionuclide specific. Quantile plots are discussed in **Appendix L, Section L.2.**

A posting plot is simply a map of the survey unit with the data values entered at the measurement locations. This potentially reveals heterogeneities in the data, especially possible areas of elevated residual radioactive material. Even in a reference area, a posting plot can reveal spatial trends in background data that might affect the results of the statistical tests used when the radionuclide is present in the background or measurements are not radionuclide specific.

If the data given in the examples above were obtained using a triangular grid in a rectangular survey unit, the posting plot might resemble the display in **Figure 8.1. Figures 8.1a and 8.1c** show no unusual patterns in the data, whereas **Figures 8.1b and 8.1d** show the exact same values (and therefore the same mean) but with a different distribution of residual radioactive material. **Figures 8.1b and 8.1d** also reveal an obvious trend toward smaller values as one moves from left to right across the survey unit, which can be discerned only if spatial information is available and analyzed. The graphical display of data in a posting plot is beneficial to better understanding the distribution of residual radioactive material at a site.

If the posting plot reveals systematic spatial trends in the survey unit, the cause of the trends would need to be investigated. In some cases, such trends could be due to residual radioactive material, but they may also be due to inhomogeneities in the survey unit background. Other diagnostic tools for examining spatial data trends may be found in EPA Guidance Document QA/G-9S (EPA 2006b). The use of geostatistical tools to evaluate spatial data trends may also be useful in some cases (EPA 1989b).

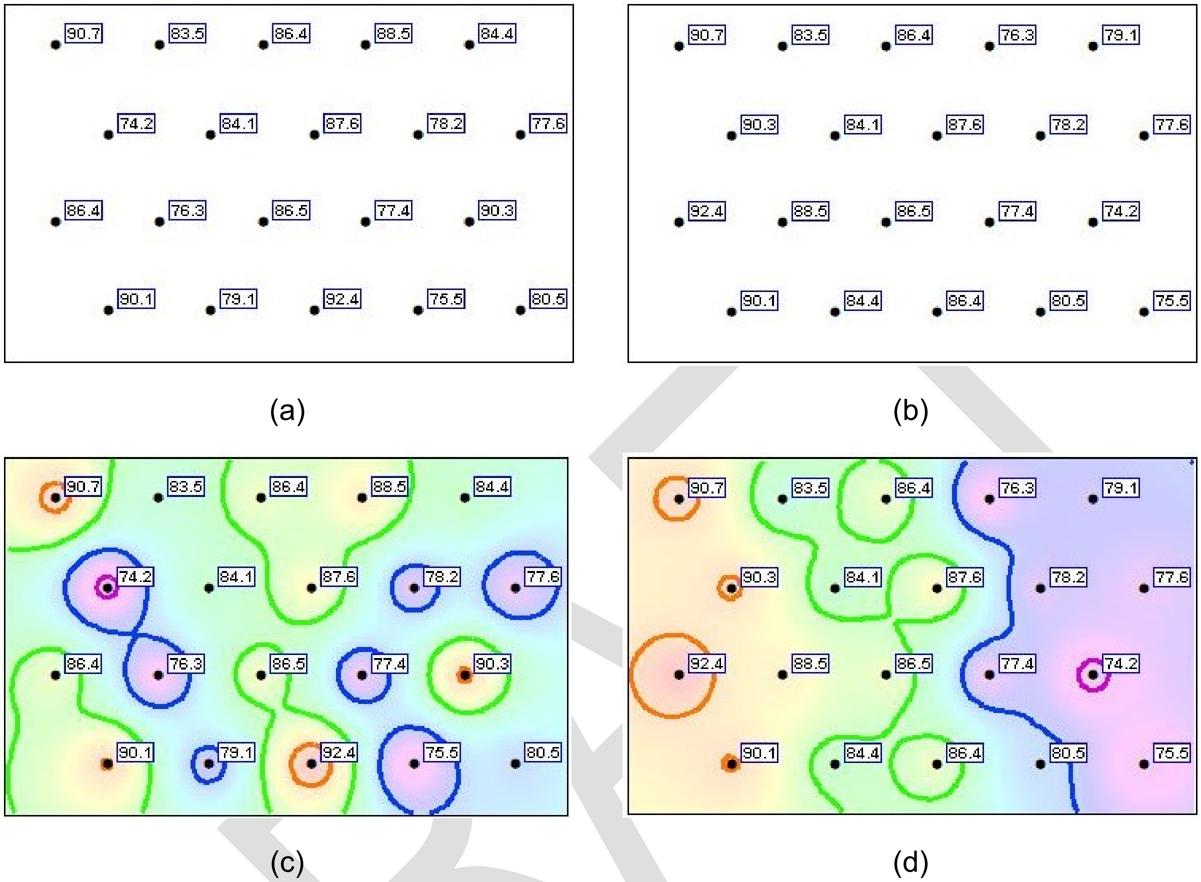


Figure 8.1: Examples of Posting Plots

Geographic information system (GIS) tools can also be used to help with creation of conceptual models (e.g., provide spatial context and a better understanding of site features that may control or enhance radionuclide transport in the environment). Figures created with GIS tools can also assist with identifying relatively homogeneous areas of residual radioactivity for delineation of survey units. Examples of features that can be captured on a figure using GIS tools include the following:

- study area and property boundary
- buildings where residual radioactivity may be present
- roads
- surface water features (streams, ponds, runoff basins, ditches, culverts)

- underground features (underground storage tanks, piping)
- topography, surface geology, and outcrop locations
- hydrostratigraphic surfaces and isopach maps
- water table and potentiometric surfaces
- sampling locations
- monitoring well locations
- contaminant distributions

For example, **Figure 8.2a** shows a map that includes the location of two hypothetical tanks. Leaks are known to have occurred near the tanks. GIS information on the location of important features and topography of surficial (or subsurface) structures can be used to identify areas where residual radioactivity may be present and more likely to have been transported (e.g., surface water runoff direction). GIS information and geostatistical tools can be helpful in designing survey plans and identifying areas most likely to be above risk-based thresholds. For example, the geostatistical tools available in such codes as Visual Sample Plan and Spatial Analysis and Decision Assistance (SADA) can be used to analyze data and extrapolate data in areas where no data are available. **Figure 8.2** illustrates the use of SADA (Version 5) in creating a three-dimensional visualization of the volume of soil most likely to be affected based on sampling results and use of geostatistical tools available in the code. **Figure 8.2b** illustrates how geostatistical tools can help interpolate and extrapolate data to determine the probability of exceeding a threshold following characterization.

A frequency plot (or a histogram) is a useful tool for examining the general shape of a data distribution. This plot is a bar chart of the number of data points within a certain range of values. A frequency plot of the example data from **Figure 8.1** is shown in **Figure 8.3.** A simple method for generating a rough frequency plot is the stem-and-leaf display discussed in **Appendix L, Section L.1.** The frequency plot may reveal any obvious departures from symmetry, such as skewness or bimodality (two peaks), in the data distributions for the survey unit or reference area. The presence of two peaks in the survey unit frequency plot may indicate the existence of isolated areas of residual radioactive material, which may need to be further investigated as part of the EMC tests.

The presence of two peaks in the background reference area or survey unit frequency plot may also indicate a mixture of background concentration distributions due to different soil types, construction materials, etc., or it could indicate the presence of residual radioactivity in the background reference area.[3] The greater variability in the data due to the presence of such a mixture will reduce the power of the statistical tests to detect an adequately remediated survey unit that meets the release criteria for Scenario A or to detect a survey unit that does not meet

[3] In some cases, it may be necessary to perform additional investigation to determine if background reference areas were properly classified as non-impacted.

the release criteria for Scenario B. These situations should be avoided whenever possible by carefully matching the background reference areas to the survey units and choosing more homogeneous survey units, as discussed in more detail in **Appendix D.** If relatively homogenous survey units cannot be identified, consistent with the underlying assumptions in the $DCGL_W$ derivation, then other approaches may need to be taken to evaluate the acceptability of the survey units for release (e.g., increased focus on evaluation of the risk of elevated areas). Consult with your regulator for highly heterogeneous survey units.

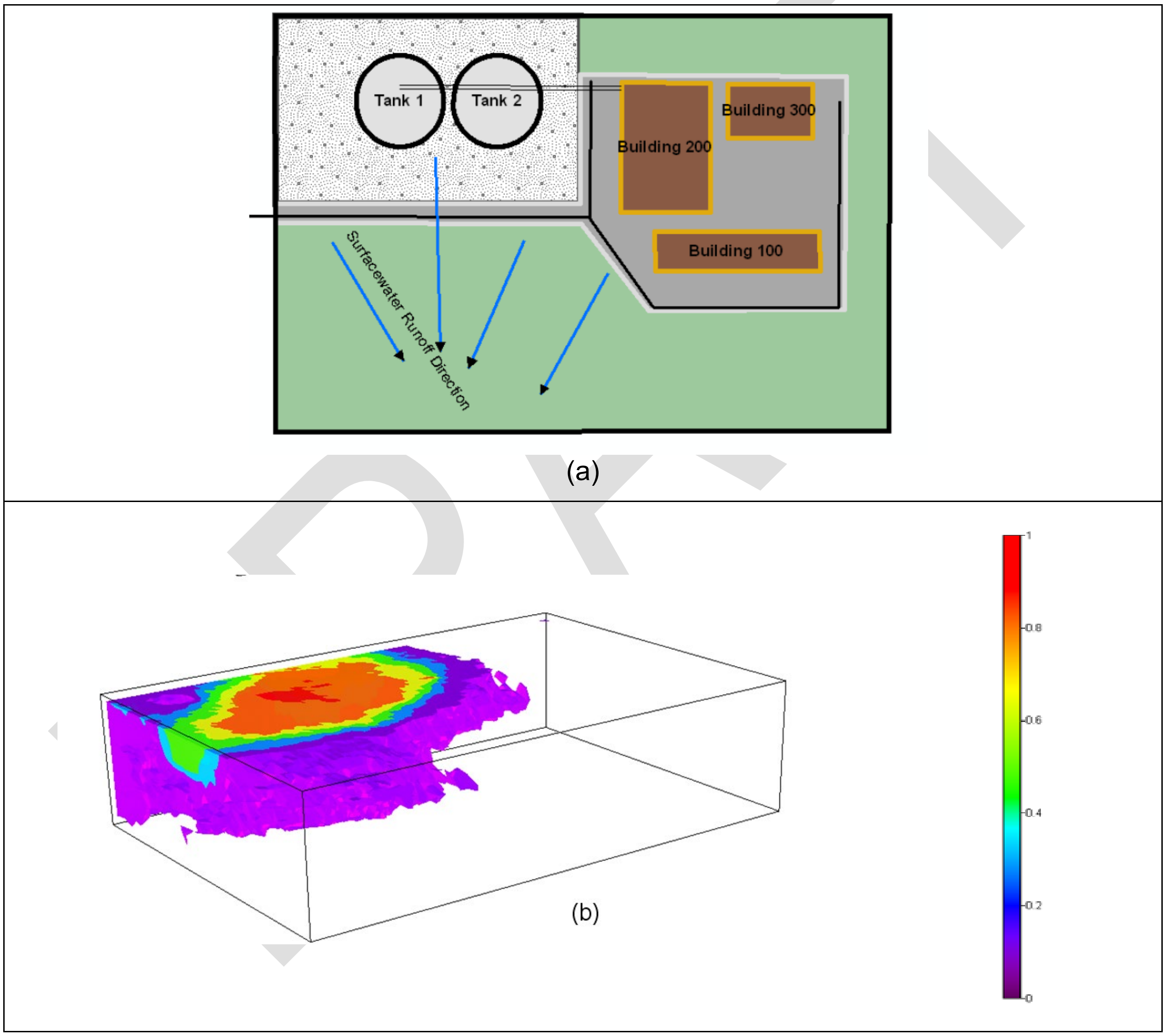
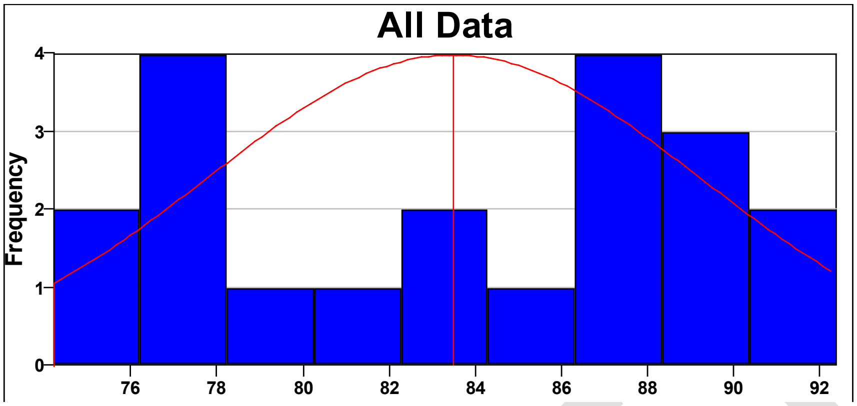
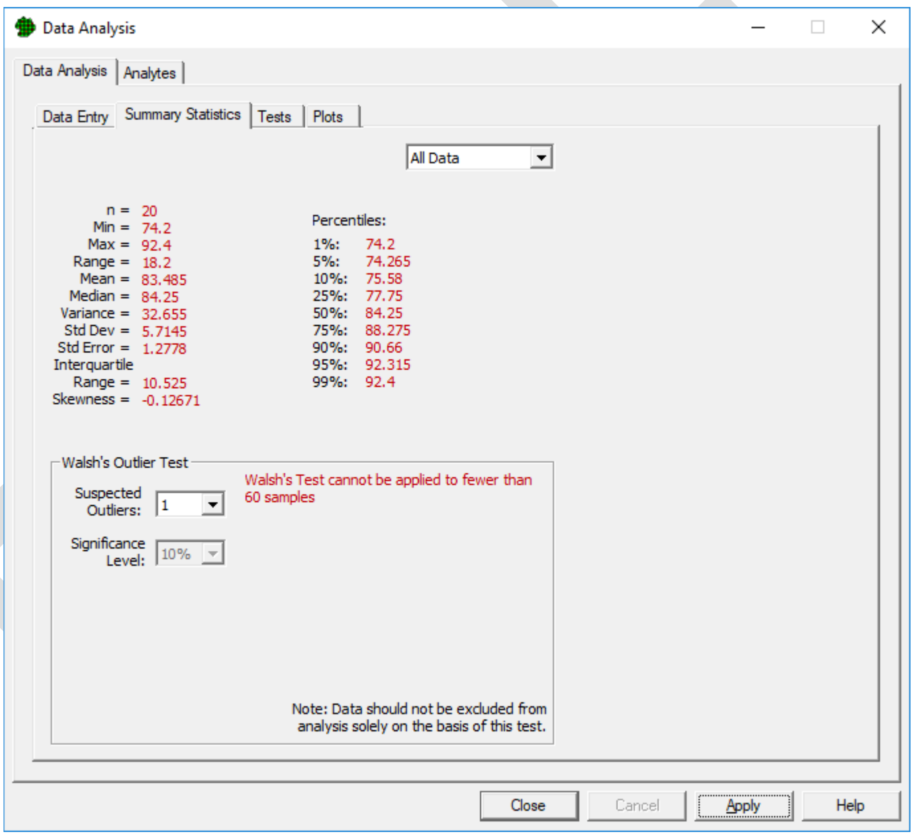


Figure 8.2: Sample GIS Visualization, Modified from Figures 3.4 and 7.8 in NUREG/CR-7021 (NRC 2012**).**



(a)



(b)

Figure 8.3: Example of a Frequency Plot (a) and Other Statistical Information Output from Visual Sample Plan v. 7 (b)

Caution should be exercised when developing frequency plots (commonly referred to as histograms). The shape of a histogram can depend on the choice of the bin widths and ranges. If bins are too wide, features of the underlying distribution within the bin width may be missed. If bins are too narrow, the bin-to-bin variability can be mistaken as a feature of the underlying distribution. Additional caution should be exercised when interpreting histograms for small data sets where smaller features, such as a second smaller peak, may not be observed.

Skewness or other asymmetry can impact the accuracy of the statistical tests. When the underlying data distribution is highly skewed, it is often because there are a few elevated areas. Because the Elevated Measurement Comparison derived concentration guideline level ($DCGL_{EMC}$) is specifically used to evaluate the acceptability of elevated areas (i.e., the ability of a site with elevated areas of residual radioactivity material above the $DCGL_W$ to meet release criteria), the limitations associated with use of statistical tests based on the median or mean for nonhomogeneous residual radioactivity are mitigated. In cases where highly heterogeneous residual radioactive material is present, care should be taken to ensure that the lateral extent of the elevated area is delineated and a $DCGL_{EMC}$ is calculated consistent with the actual size of the elevated area. When a number of elevated areas are present, techniques can be used to evaluate the cumulative risk of the elevated areas dependent on the distribution of the elevated areas in the survey unit.

8.2.2.3 Draw Conclusions from the Preliminary Data Review

In some instances, a preliminary review of the data may be sufficient to draw conclusions without performing the statistical tests described in **Section 8.2.3.** For example, under Scenario A, the sample mean of the survey unit data can be compared to the reference area sample mean and the $DCGL_W$ to get a preliminary indication of the survey unit status. If the difference of the survey unit sample mean and the reference area sample mean is greater than $DCGL_W$, then the survey unit cannot be released. Alternatively, significantly higher concentrations in the reference area compared to the survey unit may be an indicator that the reference area is not appropriate for the survey unit and warrants further investigation

Tables 8.3–8.5 describe examples of other circumstances leading to specific conclusions based on a simple examination of the data without the need to perform certain statistical tests.

8.2.3 Select the Statistical Test

An overview of the statistical considerations important for FSSs appears in **Section 2.5** and **Appendix D.** The parameter of interest is the mean concentration in the survey unit. The nonparametric tests recommended in this manual, in their most general form, are tests of the median. For data that are from a skewed distribution, the mean could be significantly larger than the median. Therefore, the mean should be compared to the $DCGL_W$ to ensure that the mean is less than the $DCGL_W$, as indicated in **Section 8.2.2.3.** If the data are highly skewed because of the presence of elevated areas, the EMC test helps ensure that the site is acceptable for release.

If one assumes that the data are from a symmetric distribution where the median and the mean are effectively equal, these statistical evaluations are also tests of the mean. If the assumption of symmetry is violated, then nonparametric tests of the median approximately test the mean. Computer simulations (Hardin and Gilbert, 1993) have shown that the approximation is a good one—that is, the correct decision will be made about whether the mean concentration exceeds the $DCGL_W$, even when the data come from a skewed distribution. In this regard, Hardin and Gilbert found the nonparametric tests to be correct more often than the commonly used Student's *t* test. The robust performance of the Sign and WRS tests over a wide range of conditions is the reason that they are recommended in this manual.

When a given set of assumptions is true, a parametric test designed for exactly that set of conditions will have the highest power. For example, if the data are from a normal distribution, the Student's *t* test will have higher power than the nonparametric tests. It should be noted that for large enough sample sizes (e.g., large number of measurements), the Student's *t* test is not a great deal more powerful than the nonparametric tests. On the other hand, when the assumption of normality is violated, the nonparametric tests can be much more powerful than the *t* test. Therefore, any statistical test may be used, provided that the data are consistent with the assumptions underlying their use. When these assumptions are violated, the prudent approach is to use the nonparametric tests, which generally involve fewer assumptions than their parametric equivalents.

The Sign test, described in **Section 5.3.4,** is typically used when the radionuclide is not present in background and radionuclide-specific measurements are made. The Sign test may also be used if the radionuclide is present in the background at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In this case, background concentrations of the radionuclide are included with the residual radioactive material (i.e., the entire amount is attributed to facility operations). Thus, the total concentration of the radionuclide is compared to the release criteria. This option should be used only if one expects that ignoring the background concentration will not affect the outcome of the statistical tests. The advantage of ignoring a small background contribution is that no reference area is needed. This can simplify the FSS considerably. Some alternative statistical tests to the Sign test are described in Chapter 14 of NUREG-1505, *A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys* (NRC 1998a) and in **Chapter 2**.

The Sign test (**Section 8.3.1**) evaluates whether the median of the data is above or below the $DCGL_W$. If the data distribution is symmetric, the median is equal to the mean. In cases where the data are severely skewed, the mean may be above the $DCGL_W$, while the median is below the $DCGL_W$. In such cases, the survey unit does not meet the release criteria regardless of the result of the statistical tests. On the other hand, if the largest measurement is below the $DCGL_W$, the Sign test will always show that the survey unit meets the release criteria.

For FSSs, the WRS test discussed in **Section 5.3.3** can be used when the radionuclide of concern appears in background or if measurements used are not radionuclide-specific. The WRS test (**Section 8.4.1**) assumes the reference area and survey unit data distributions are similar except for a possible shift in the medians. When the data are severely skewed, the value for the mean difference may be above the $DCGL_W$, while the median difference is below the $DCGL_W$. In such cases, the survey unit does not meet the release criteria regardless of the result of the statistical test. On the other hand, if the difference between the largest survey unit measurement and the smallest reference area measurement is less than the $DCGL_W$, the WRS test will always show that the survey unit meets the release criteria.

The use of paired observations for survey units with different backgrounds and some alternative statistical tests to the WRS test are described in Chapters 12 and 14, respectively, of NUREG-1505, *A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys* (NRC 1998a). If Scenario B was selected during the DQO process, the quantile test is performed to test for skewness when the WRS test does not reject the null hypothesis.

If individual scan-only survey results are recorded, a nonparametric confidence interval can be used to evaluate the results of the FSS. Similarly, a confidence interval can be used to evaluate a series of in situ measurements with overlapping fields of view. A one-tailed version of Chebyshev's inequality or software (e.g., EPA's ProUCL software) can be used to evaluate the probability of exceeding the upper bound of the grey region (UBGR) using an upper confidence limit (UCL). The use of a UCL applies to both Scenario A (where the UBGR equals the $DCGL_W$) and Scenario B (where the UBGR equals the discrimination limit [DL]). **Table 8.1** provides a summary of the statistical tests and evaluation methods discussed in this chapter.

Table 8.1: Summary of Statistical Tests and Evaluation Methods

Statistical Test or Evaluation Method	Applicability
Sign Test (see **Section 8.3** and **Table 8.3**)	• Radionuclide not in background *and* nuclide-specific measurements • Scenario A or B
WRS Test (see **Section 8.4** and **Table 8.4**)	• Radionuclide in background *or* non-nuclide specific measurements • Scenario A or B
Quantile Test (see **Section 8.4**)	• Test for non-uniform distribution of radioactive material • Combined with WRS Test • Scenario B only
Comparison to UCL (see **Section 8.5** and **Table 8.5**)	• Scan-only surveys or in situ surveys • Scenario A or B

Abbreviations: WRS test = Wilcoxon Rank Sum test; UCL = upper confidence limit.

8.2.4 Verify the Assumptions of the Statistical Tests

An evaluation to determine that the data are consistent with the underlying assumptions made for the statistical procedures helps to validate the use of a test. One may also determine that certain departures from these assumptions are acceptable when given the actual data and other information about the study.

For surveys consisting of a combination of scanning with samples or direct measurements, the nonparametric tests described in this chapter assume that the data from the reference area or survey unit consist of independent samples from each distribution. Spatial dependencies that potentially affect the assumptions can be assessed using posting plots (**Section 8.2.2.2**). More sophisticated tools for determining the extent of spatial dependencies are also available (e.g., EPA QA/G-9S, EPA 2006b). These methods tend to be complex and are best used with guidance from a professional statistician.

Asymmetry in the data can be diagnosed with a stem-and-leaf display, a histogram, or a quantile plot.

One of the primary advantages of the nonparametric tests is that they involve fewer assumptions about the data than their parametric counterparts. If parametric tests are used, (e.g., Student's *t* test), then any additional assumptions made in using them should be verified (e.g., testing for normality). These issues are discussed in detail in EPA QA/G-9S (EPA 2006b).

One of the more important assumptions made in the survey designs described in **Sections 5.3.3 and 5.3.4** is that the sample sizes determined for the tests are sufficient to achieve the DQOs set for the Type I and Type II error rates. Verification of the power of the tests $(1-\beta)$ correctly determines a site that does not meet the release criterion is not released under Scenario B, regardless of what the test determined, which may be of particular interest to the regulator and is, therefore, required for surveys conducted under Scenario B. For Scenario A, verification of the power of the tests to correctly release a site that meets the release criteria, regardless of what the test determined, may be of particular interest to the site owner/operator. Methods for assessing the power are discussed in **Appendix M.**

For these reasons, it is better to plan the surveys cautiously, including—

- overestimating the potential data variability
- taking more than the minimum number of measurements
- overestimating minimum detectable concentrations (MDCs) and measurement method uncertainties

If one is unable to show that the DQOs and MQOs were met with reasonable assurance, a resurvey may be needed. Examples of assumptions and possible methods for their assessment are summarized in **Table 8.2.**

For scan-only surveys where data are compared to a UCL, Chebyshev's inequality should be used with caution when there are very few points in the data set. **Section 6.7** provides information on converting the instrument reading to the appropriate units for reporting the UCL. This is because the population mean and standard deviation in the Chebyshev formula are being estimated by the sample mean and sample standard deviation. In a small data set from a highly skewed distribution, the sample mean and sample standard deviation may be underestimated if the high concentration but low probability portion of the distribution is not captured in the sample data set.

Table 8.2: Methods for Checking the Assumptions of Statistical Tests

Assumption	Diagnostic
Spatial Independence	Posting Plot
Symmetry	Histogram, Quantile Plot
Data Variance	Sample Standard Deviation
Adequate Power	Retrospective Power Chart

8.2.5 Draw Conclusions from the Data

The types of measurements that can be made in a survey unit are direct measurements, laboratory samples, and scans.

Specific details for conducting the statistical tests are given in **Section 8.3** (Sign test), **Section 8.4** (WRS test and quantile test), and **Section 8.5** (upper confidence limit test). When the data clearly show that a survey unit meets or exceeds the release criteria, the result is often obvious without performing the formal statistical analysis. The data still need to meet the assumptions for the statistical tests, (e.g., ensuring adequate power in Scenario B.) **Tables 8.3–8.5** display various survey results and their conclusions.

Table 8.3: Summary of Statistical Tests for Radionuclide Not in Background and Radionuclide-Specific Measurement

Survey Result	Conclusion
Scenario A	
All measurements are less than $DCGL_W$.	Survey unit meets release criteria.
Sample mean is greater than $DCGL_W$.	Survey unit does not meet release criteria.
Any measurement is greater than $DCGL_W$, and the sample mean is less than $DCGL_W$.	Conduct Sign test and EMC.
Scenario B	
Sample mean is less than the AL.	Survey unit meets release criteria.
All measurements are greater than AL.	Survey unit does not meet release criteria.
Any measurement is greater than the AL, and the sample mean is greater than AL.	Conduct Sign test and EMC.

Abbreviations: $DCGL_W$ = wide-area derived concentration guideline level; EMC = elevated measurement comparison; AL = action level.

Table 8.4: Summary of Statistical Tests for Radionuclide in Background or Radionuclide Non-Specific (Gross) Measurements

Survey Result	Conclusion
Scenario A	
Difference between largest survey unit measurement and smallest reference area measurement is less than the $DCGL_W$.	Survey unit meets release criteria.
Difference between survey unit sample mean and reference area sample mean is greater than the $DCGL_W$.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is greater than $DCGL_W$, and the difference between survey unit sample mean and reference area sample mean is less than the $DCGL_W$.	Conduct WRS test and EMC.
Scenario B	
Difference between survey unit sample mean and reference area sample mean is less than the AL.	Conduct quantile test.
Difference between smallest survey unit measurement and largest reference area measurement is greater than the AL.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is less than the AL, and the difference between survey unit sample mean and reference area sample mean is greater than AL.	Conduct WRS test, quantile test, and EMC.

Abbreviations: $DCGL_W$ = wide-area derived concentration guideline level; WRS test = Wilcoxon Rank Sum test; EMC = elevated measurement comparison; AL = action level.

If applicable release criteria for elevated measurements exist, then both the measurements at discrete locations and the scans are also subject to the EMC. The result of comparing individual measurements to $DCGL_{EMC}$ is not conclusive as to whether the survey unit meets or exceeds the release criteria, but it is a flag or trigger for further investigation. The investigation may involve taking further measurements to determine that the area and level of the elevated residual radioactive material are such that the resulting dose or risk meets the release criteria.[4] The investigation should also provide adequate assurance, using the DQO process, that there

[4] Rather than, or in addition to, taking further measurements, the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs and the consistency of the results obtained with the Historical Site Assessment and the scoping, characterization, and remedial action support surveys.

Table 8.5: Summary of Results for Scan-Only Surveys

Survey Result[a]	Conclusion
Scenario A	
UCL is less than $DCGL_W$.	Survey unit meets average release criteria; conduct the EMC.
UCL is greater than $DCGL_W$.	Survey unit does not meet release criteria.
Scenario B	
UCL is less than DL.	Survey unit meets average release criteria; conduct the EMC.
UCL is greater than DL.	Survey unit does not meet release criteria.

Abbreviations: UCL = upper confidence limit; $DCGL_W$ = wide-area derived concentration guideline level; EMC = elevated measurement comparison; DL = discrimination limit.
[a] See **Section 8.5** for additional details on calculating the UCL.

are no undiscovered areas of elevated residual radioactive material in the survey unit that might otherwise result in a dose or risk exceeding the release criteria when considered in conjunction with the dose or risk posed by the remainder of the survey unit. In some cases, this may lead to reclassifying all or part of a survey unit unless the results of the investigation indicate that reclassification is not necessary. The investigation level appropriate for each class of survey unit and type of measurement is shown in **Table 5.4** and is described in **Section 5.3.8. Example 4** provides background information that will be used in **Examples 5–8.**

Example 4: Illustrative Examples Background Information

This example provides the background for **Examples 5–8.**

To illustrate the data interpretation process, consider an example facility with 14 survey units consisting of interior concrete surfaces, one interior survey unit with drywall surfaces, and two outdoor surface soil survey units. The radionuclide of concern is cobalt-60 (^{60}Co). The interior surfaces were measured with a gas-flow proportional counter (see **Appendix H**) with an active surface area of 100 square centimeters (cm^2) to determine gross beta activity. Because these measurements are not radionuclide-specific, appropriate reference areas were chosen for comparison. The exterior surface soil was measured with a germanium spectrometer to provide radionuclide-specific results. A reference area is not needed because ^{60}Co does not have a significant background in soil.

The exterior surface soil Class 3 survey unit incorporates areas that are not expected to contain residual radioactive material. The exterior surface soil Class 2 survey unit is similar to the Class 3 survey unit but is expected to contain concentrations of residual radioactive material below the wide-area derived concentration guideline level ($DCGL_W$). The Class 1 interior concrete survey units are expected to contain small areas of elevated activity that may or may not exceed the $DCGL_W$. The Class 2 interior drywall survey unit is similar to the Class 1 interior concrete survey unit, but the drywall is expected to have a lower background, less measurement variability, and a more uniform distribution of radioactive material. The Class 2 survey unit is not expected to contain areas of residual radioactive material above the $DCGL_W$. The survey design parameters and DQOs developed for these survey units under Scenario A are summarized in **Table 8.6.**

Table 8.7 provides survey design parameters and DQOs developed for two survey units under Scenario B where the lower bound of the gray region is zero or indistinguishable from background for a radionuclide that is in the natural background.

Table 8.6: Final Status Survey Parameters for Example Survey Units for Scenario A

Survey Unit	Type	DQO		LBGR	$DCGL_W$[a]	Estimated Standard Deviation, σ[b]		Test/Section
		α	β			Survey	Reference	
Exterior Surface Soil	Class 2	0.025	0.025	128 Bq/kg	140 Bq/kg	4.0 Bq/kg	N/A	Sign/ **Example 5**
Exterior Surface Soil	Class 3	0.025	0.01	128 Bq/kg	140 Bq/kg	4.0 Bq/kg	N/A	Sign/ **Example 6**
Interior Concrete	Class 1	0.05	0.05	3,000 dpm/ 100 cm^2	5,000 dpm/ 100 cm^2	625 dpm/ 100 cm^2	220 dpm/ 100 cm^2	WRS/ **Appendix A**
Interior Drywall	Class 2	0.025	0.05	3,000 dpm/ 100 cm^2	5,000 dpm/ 100 cm^2	200 dpm/ 100 cm^2	200 dpm/ 100 cm^2	WRS/ **Example 7**

Abbreviations: DQO = data quality objective; LBGR = lower bound of the gray region; $DCGL_W$ = derived concentration guideline level using the Wilcoxon Rank Sum test; σ = standard deviation; α = Type I decision error; β = Type II decision error; Bq = becquerel; kg = kilogram; dpm = disintegrations per minute; cm = centimeter.
[a] $DCGL_W$ is given in units of becquerels per kilogram or disintegrations per minute per 100 square centimeters.
[b] Estimated standard deviation from scoping, characterization, and Remedial Action Support surveys

8.3 Radionuclide Not Present in Background

The statistical test discussed in this section is used to compare each survey unit directly with the applicable release criteria. A reference area is not included because the measurement technique is radionuclide-specific and the radionuclide of concern is not present in background (see **Section 8.2.3**). In this case, the concentrations of residual radioactive material are compared directly with the $DCGL_W$. The method in this section should be used only if the radionuclide is not present in background or is present at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In addition, the Sign test is applicable only if radionuclide-specific measurements are made to determine the concentrations. Otherwise, the method in **Section 8.4** is recommended.

Table 8.7: Final Status Survey Parameters for Example Survey Units for Scenario B

Survey Unit	Type	DQO		AL	DL[a]	Estimated Standard Deviation, σ^b		Test/ Section
		α	β			Survey	Reference	
Exterior Surface Soil	Class 1	0.05	0.05	0 Bq/kg	12 Bq/kg	6 Bq/kg	6 Bq/kg	WRS
Exterior Surface Soil[c]	Class 3	0.05	0.01	0 Bq/kg	12 Bq/kg	6 Bq/kg	6 Bq/kg	WRS

Abbreviations: DQO = data quality objective; DL = discrimination limit; σ = standard deviation; α = Type I decision error; β = Type II decision error; Bq = becquerel; kg = kilogram; WRS = Wilcoxon Rank Sum.
[a] AL is zero.
[b] Estimated standard deviation from scoping, characterization, and Remedial Action Support surveys.
[c] This survey unit is not worked out in further examples.

Reference area samples are not needed when there is sufficient information to indicate that there is essentially no background concentration for the radionuclide being considered. With only a single set of survey unit samples, the statistical test used here is the Sign test. See **Section 5.3.4** for further information appropriate to following the example and discussion presented here.

8.3.1 Sign Test

The Sign test is designed to detect failure of the survey unit to meet release criteria if the radioactive material is distributed across that survey unit. Although the parameter of interest is usually the mean concentration of residual radioactive material in the survey unit, the median is used in the Sign test as an estimate of the mean. This test does not assume that the data follow any particular distribution, such as normal or lognormal.

In Scenario A, the hypothesis tested by the Sign test is as follows:

> Null Hypothesis
> H_0: The median concentration of residual radioactive material in the survey unit is greater than or equal to the $DCGL_W$.
>
> Versus
>
> Alternative Hypothesis
> H_1: The median concentration of residual radioactive material in the survey unit is less than the $DCGL_W$; also defined as H_a.

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. For Scenario A, the null hypothesis states that the probability of a measurement less than the $DCGL_W$ is less than one-half, i.e., the 50th percentile (or median) is greater than the $DCGL_W$.

Because the Sign test uses the median instead of the mean, the null hypothesis in Scenario A may be rejected if the median concentration is less than the $DCGL_W$, even if the mean concentration is greater than or equal to the $DCGL_W$. If the mean concentration is greater than or equal to the $DCGL_W$, the survey unit does not meet the release criteria (see **Table 8.3)** Furthermore, in addition to the Sign test, the $DCGL_{EMC}$ (see **Section 5.3.5**) is compared to each measurement to ensure none exceeds the $DCGL_{EMC}$. If a measurement exceeds the $DCGL_{EMC}$, then additional investigation is recommended, at least locally, to determine the actual areal extent of the elevated concentration.

In Scenario B, the hypothesis tested by the Sign test is as follows:

> <u>Null Hypothesis</u>
> H_0: The median concentration of residual radioactive material in the survey unit is less than or equal to the AL.
>
> Versus
>
> <u>Alternative Hypothesis</u>
> H_1: The median concentration of residual radioactive material in the survey unit is greater than the AL.

Again, the null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. For Scenario B, the null hypothesis states that the probability of a measurement greater than the AL is less than one-half (i.e., the 50th percentile [or median] is less than the AL).

When using the Sign test for both Scenario A and B, it is necessary to show that there are a sufficient number of measurements or samples with concentrations below the $DCGL_W$ or AL, respectively. Under Scenario A, when there are too many measurements or samples with concentrations above the $DCGL_W$, we fail to reject the null hypothesis that the survey unit does not meet the release criteria. Under Scenario B, when there are too many measurements or samples with concentrations above the lower bound of the gray region (LBGR), we reject the null hypothesis that the survey unit does meet the release criteria.

When the values of α and β are selected in the DQO process, an important difference between Scenario A and Scenario B should be considered. For a fixed value of N, a lower value for α is more protective in Scenario A, but is less protective in Scenario B. In both scenarios, a lower value for α requires a higher degree of evidence before the null hypothesis is rejected. In Scenario A, the null hypothesis is that the survey unit exceeds the release criteria, and a lower value for α makes it more difficult to reject this hypothesis. In Scenario B, the null hypothesis is that the survey unit meets the release criteria, and a lower value of α makes it more difficult to reject this hypothesis.

Note that some individual survey unit measurements may exceed the $DCGL_W$ even when the survey unit as a whole meets the release criteria. In fact, a survey unit sample mean that is close to the $DCGL_W$ might have almost half of its individual measurements greater than the $DCGL_W$. Such a survey unit may still not exceed the release criteria. The risk associated with any areas above the DCGL is evaluated by developing a $DCGL_{EMC}$ based on dose or risk modeling. The $DCGL_{EMC}$ is higher than the $DCGL_W$ and consider the size of the elevated area. As long as the concentration in the elevated areas are less than the $DCGL_{EMC}$, the site can be released. See **Section 8.6.1** for additional details.

The assumption is that the survey unit measurements are independent random samples from a symmetric distribution. If the distribution of measurements is symmetric, the median and the mean are the same. If the distribution of measurements is highly skewed, then the efficacy of the statistical tests is reduced because of the underlying homogeneity assumptions inherent in the decision criteria (i.e., DCGL calculations).

The hypothesis specifies release criteria in terms of a $DCGL_W$. The test should have sufficient power ($1 - \beta$, as specified in the DQOs) to detect concentrations of residual radioactive material at the LBGR, which is less than the $DCGL_W$. If σ is the standard deviation of the measurements in the survey unit, then the relative shift (the width of the gray region, which is calculated by $DCGL_W$-LBGR, divided by the standard deviation [Δ/σ]) reflects the difference between the average concentration of radioactive material and the DCGL relative to measurement variability. The procedure for determining Δ/σ is given in **Section 5.3.3.2.**

As stated above, the null hypothesis for Scenario B is that the median concentration of residual radioactive material in the survey unit is less than the LBGR (or AL). To use the Sign test with Scenario B, the concentration of radioactive material in background should be zero or insignificant compared to the LBGR (or AL). In some cases, the LBGR (or AL) may be set equal to zero (e.g., release criteria require that concentrations be indistinguishable from background and the radionuclide is not present in background). In this case, results should be scattered about zero; therefore, if there are too many results with concentrations greater than zero, the null hypothesis should be rejected. Results less than zero are both possible and likely when the concentrations are truly equal to zero and measurements are subject to some random component of measurement method uncertainty.

In this case, the number of positive and negative results are expected to be the same, and the average of all the results is expected to be zero. When analyzing samples where the concentration is very small, the data analysis should be reviewed carefully, because even relatively small systematic errors can result in relatively large differences in the number of positive and negative results.

Some laboratories report results below the lower limit of detection as "< LLD" or below the minimum detectable activity as "< MDA". Under Scenario A, the use for the Sign test of such results is usually not problematic, because the DL is required to be less than the $DCGL_W$, and any values less than the DL will also be less than the $DCGL_W$. However, under Scenario B, in which the DL is greater than the AL, it is difficult to determine if the concentrations reported as

"< LLD" or "< MDA" are greater than or less than the AL. For this reason, the Sign test should be used only for Scenario B when actual concentrations, no matter how small, are reported.

8.3.2 Applying the Sign Test

The Sign test is applied as outlined in the following five steps, and further illustrated by Examples 5 and 6. Separate instructions are given for Scenarios A and B.

<u>Scenario A</u>

1. List the survey unit measurements: x_i, $i = 1, 2, 3, \ldots, N$.

2. Subtract each measurement, x_i, from the DCGL_W to obtain the differences: $D_i = \text{DCGL}_\text{W} - x_i, i = 1, 2, 3, \ldots, N$.

3. Discard each difference that is exactly zero and reduce the sample size, N, by the number of such measurements exactly equal to the DCGL_W.

4. Count the number of positive differences. The result is the test statistic $S+$. (Note that a positive difference corresponds to a measurement below the DCGL_W and contributes evidence that the survey unit meets the release criteria).

5. Large values of $S+$ indicate that the null hypothesis is false. The value of $S+$ is compared to the critical values in **Table I.4.** If $S+$ is greater than the critical value, k, in that table, the null hypothesis is rejected.

<u>Scenario B</u>

1. List the survey unit measurements: x_i, $i = 1, 2, 3, \ldots, N$.

2. Subtract the AL from each measurement, x_i, to obtain the differences: $D_i = x_i - \text{AL}$, $i = 1, 2, 3, \ldots, N$.

3. Discard each difference that is exactly zero and reduce the sample size, N, by the number of such measurements exactly equal to the AL.

4. Count the number of positive differences. The result is the test statistic $S+$. (Note that a positive difference corresponds to a measurement above the AL and contributes evidence that the survey unit does not meet the release criteria.)

5. Large values of $S+$ indicate that the null hypothesis is false. The value of $S+$ is compared to the critical values in Table I.4. If $S+$ is greater than the critical value, k, in that table, the null hypothesis is rejected.

Passing a survey unit without making a single calculation may seem an unconventional approach. However, the key is in the survey design, which is intended to ensure enough measurements are made to satisfy the DQOs. As in the previous example, after the data are collected, the conclusions and power of the test can be checked by constructing a retrospective power curve as outlined in **Appendix M.**

In addition to checking the power of the statistical test, it is also important to ensure that the uncertainty of the measurements met the MQOs for required measurement uncertainty. One final consideration remains regarding the survey unit classification: "Was any definite amount of residual radioactive material found in the survey unit?" This will depend on the MDC of the measurement method. Generally, the MDC is at least three or four times the estimated measurement standard deviation. For example, in **Table 8.9,** the largest observation, 9.3 becquerels/kilogram (Bq/kg; 0.25 picocuries/gram [pCi/g]), is less than three times the estimated measurement standard deviation of 3.8 Bq/kg (0.10 pCi/g). Thus, it is unlikely that any of the measurements could be considered indicative of positive residual radioactive material. This means that the Class 3 survey unit classification was appropriate. **Examples 5 and 6** illustrate how to use the Sign test on Class 2 and 3 exterior soil units.

Example 5: Sign Test for a Class 2 Exterior Soil Survey Unit

Refer back to **Example 4** for background information. For the Class 2 Exterior Soil survey unit, the Sign test is appropriate, because the radionuclide of concern does not appear in background and radionuclide-specific measurements were made. Scenario A is selected.

Table 8.6 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.025$. The $DCGL_W$ is 140 becquerels/kilogram (Bq/kg; 3.8 picocuries/gram [pCi/g]), and the LBGR was selected to be 128 Bq/kg (3.5 pCi/g). The estimated standard deviation of the measurements is σ = 4.0 Bq/kg (0.11 pCi/g). The relative shift was calculated to be 3.0, as shown below:

$$\Delta/\sigma = \frac{\mathrm{DCGL_W} - \mathrm{LBGR}}{\sigma} = \frac{140\ \mathrm{Bq/kg} - 128\ \mathrm{Bq/kg}}{4.0\ \mathrm{Bq/kg}} = 3.0$$

Table 5.3 indicates the number of measurements estimated for the Sign Test, N, is 20 ($\alpha = 0.025$, $\beta = 0.025$, and $\Delta/\sigma = 3$). (**Table I.2** in **Appendix I** also lists the number of measurements estimated for the Sign test.) This survey unit is Class 2, so the 20 measurements needed were made on a random-start triangular grid. When laying out the grid, 22 measurement locations were identified.

The 22 measurements taken on the exterior lawn Class 2 survey unit are shown in the first column of **Table 8.8.** The mean of these data is 129 Bq/kg (3.5 pCi/g), and the standard deviation is 11 Bq/kg (0.30 pCi/g). Since the number of measurements is even, the median of the data is the average of the two middle values (126+128)/2 = 127 Bq/kg (3.4 pCi/g). A quantile plot of the data is shown in **Appendix L, Figure L.3.**

Five measurements exceed the $DCGL_W$ value of 140 Bq/kg: 142, 143, 145, 148, and 148. However, none exceed the mean of the data plus three standard deviations: 129+(3×11) = 162 Bq/kg (4.3 pCi/g). Thus, these values appear to reflect the overall variability of the concentration measurements rather than to indicate an area of elevated activity—*provided* that these measurements were scattered through the survey unit. However, if a posting plot demonstrates that the locations of these measurements are grouped together, then that portion of the survey unit containing these locations merits further investigation.

The middle column of **Table 8.8** contains the differences, $DCGL_W$ - Data, and the last column contains the signs of the differences. The bottom row shows the number of measurements with positive differences, which is the test statistic $S+$. In this case, $S+ = 17$.

The value of $S+$ is compared to the appropriate critical value in **Table I.4.** In this case, for $N = 22$ and $\alpha = 0.025$, the critical value is 16. Because $S+ = 17$ exceeds this value, the null hypothesis that the survey unit exceeds the release criteria is rejected.

Table 8.8: Example Sign Analysis: Class 2 Exterior Soil Survey Unit

Data (Bq/kg)	$DCGL_W$ – Data (Bq/kg)	Sign
121	19	+
143	-3	-
145	-5	-
112	28	+
125	15	+
132	8	+
122	18	+
114	26	+
123	17	+
148	-8	-
115	25	+
113	27	+
126	14	+
134	6	+
148	-8	-
130	10	+
119	21	+
136	4	+
128	12	+
125	15	+
142	-2	-
129	11	+
Number of positive differences $S+$ = 17		

Example 6: Sign Test for a Class 3 Exterior Soil Survey Unit

Refer back to **Example 4** for background information. For the Class 3 exterior soil survey unit, the Sign test is again appropriate, because the radionuclide of concern does not appear in background and radionuclide-specific measurements were made. Scenario A is selected.

Table 8.6 shows that the DQOs for this survey unit include α = 0.025 and β = 0.01. The $DCGL_W$ is 140 becquerels/kilogram (Bq/kg; 3.8 picocuries/gram [pCi/g]), and the LBGR was selected to be 128 Bq/kg (3.5 pCi/g). The estimated standard deviation of the measurements is σ = 4.0 Bq/kg (0.11 pCi/g). The relative shift was calculated to be 3.0, as shown below:

$$\Delta/\sigma = \frac{\mathrm{DCGL_W} - \mathrm{LBGR}}{\sigma} = \frac{140\ \mathrm{Bq/kg} - 128\ \mathrm{Bq/kg}}{4.0\ \mathrm{Bq/kg}} = 3.0$$

Table 5.3 indicates that the sample size estimated for the Sign test, N, is 23 ($\alpha = 0.025$, $\beta = 0.01$, and $\Delta/\sigma = 3$). This survey unit is Class 3, so the measurements were made at random locations within the survey unit. The 23 measurements taken on the exterior lawn are shown in the first column of **Table 8.9.** The mean of these data is 2.1 Bq/kg (0.057 pCi/g), and the standard deviation is 3.3 Bq/kg (0.089 pCi/g). None of the data exceed 2.1 Bq/kg + (3×3.3) Bq/kg = 12.0 Bq/kg (0.32 pCi/g). Because N is odd, the median is the middle (12th-highest) value, namely 2.6 Bq/kg (0.070 pCi/g).

An initial review of the data reveals that every data point is below the $DCGL_W$, so the survey unit meets the release criteria specified in **Table 8.3.** For purely illustrative purposes, the Sign test analysis is performed. The middle column of **Table 8.9** contains the quantity $DCGL_W$ – Data. Because every data point is below the $DCGL_W$, the sign of $DCGL_W$ – Data is always positive. The number of positive differences is equal to the number of measurements, N, and so the Sign test statistic $S+$ is 23. The null hypothesis will always be rejected at the maximum value of $S+$ (which in this case is 23) and the survey unit passes. Thus, the application of the Sign test in such cases requires no calculations and one need not consult a table for a critical value. If the survey is properly designed, the critical value must always be less than N.

Notice that some of these measurements are negative (-0.37 in cell A6). This might occur if an analysis background (*e.g.*, the Compton continuum under a spectrum peak) is subtracted to obtain the net concentration value. The data analysis is both easier and more accurate when numerical values are reported *as obtained* rather than reporting the results as “less than” or not detected.

If one determines that residual radioactive material is definitely present, this would indicate that the survey unit was initially misclassified. Ordinarily, MARSSIM recommends a resurvey using a Class 1 or Class 2 design. In some cases, the original survey may have met the requirements for the Class 1 or 2 design. Section 8.6.3 includes additional discussion on the misclassification of survey units.

For example, if one determines that the survey unit is a Class 2, a resurvey might be avoided if the survey unit does not exceed the maximum size recommended for such a classification. In this case, the only difference in survey design would be whether the measurements were obtained on a random or on a triangular grid. Provided that the initial survey's scanning methodology has sufficient detection capability to detect areas at the $DCGL_W$, versus the higher $DCGL_{EMC}$, the scan would be able to compensate for differences in the survey grid sample locations, and those differences alone would not affect the outcome of the statistical analysis. Therefore, if the above conditions were met, a resurvey might not be necessary.

Table 8.9: Sign Test Example Data for Class 3 Exterior Survey Unit

Sample Number	A Data (Bq/kg)	B $DCGL_W$-Data (Bq/kg)	C Sign
1	3.0	137.0	+
2	3.0	137.0	+
3	1.9	138.1	+
4	0.37	139.6	+
5	-0.37	140.4	+
6	6.3	133.7	+
7	-3.7	143.7	+
8	2.6	137.4	+
9	3.0	137.0	+
10	-4.1	144.1	+
11	3.0	137.0	+
12	3.7	136.3	+
13	2.6	137.4	+
14	4.4	135.6	+
15	-3.3	143.3	+
16	2.1	137.9	+
17	6.3	133.7	+
18	4.4	135.6	+
19	-0.37	140.4	+
20	4.1	135.9	+
21	-1.1	141.1	+
22	1.1	138.9	+
23	9.3	130.7	+
	Number of positive differences $S+$ =		23

8.4 Radionuclide Present in Background

The statistical tests discussed in this section will be used to compare each survey unit with an appropriately chosen, site-specific reference area. Each reference area should be selected on the basis of its similarity to the survey unit, as discussed in **Section 4.6.3.**

8.4.1 Wilcoxon Rank Sum Test and Quantile Test

In Scenario A, the comparison of measurements from the reference area and survey unit is made using the WRS test. In Scenario B, in addition to the WRS test, the quantile test should be used to further evaluate survey units when the WRS test fails to reject the null hypothesis. The recommended tests should be conducted for each survey unit. In addition, the EMC is performed against each measurement to ensure that it does not exceed a specified investigation level (e.g., $DCGL_{EMC}$ for Class 1 survey units). If any measurement in the remediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactive material is uniformly present throughout a survey unit. For Scenario A, the test is designed to detect whether this residual radioactive material exceeds the $DCGL_W$. For Scenario B, it is designed to detect whether this residual radioactive material exceeds the AL.

The advantage of the nonparametric WRS test is that it does not assume that the data are normally or lognormally distributed. The WRS test also allows "less than" measurements to be present in the reference area and the survey units. The WRS test can generally be used with up to 40 percent "less than" measurements in either the reference area or the survey unit. However, the use of "less than" values in data reporting is not recommended, as discussed in **Sections 2.3.5 and 8.3.** When possible, report the actual result of a measurement together with its uncertainty.

The quantile test is a statistical test for non-uniformity in the distribution of the residual radioactive material. The quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey unit. The quantile test is performed only when Scenario B is used and only if the null hypothesis is not rejected for the WRS test. Using the quantile test in tandem with the WRS test results in higher power to identify survey units that do not meet the release criteria than either test by itself.

Using the quantile test in tandem with the WRS test also results in higher probability of Type I errors when the true concentration is equal to the AL. The probability of making a Type I error on at least one of the two tests is approximately $\alpha = \alpha_Q + \alpha_W$ where α_Q and α_W are the values of alpha selected for the quantile and WRS tests, respectively. For this reason, when the quantile test is performed in tandem with the WRS test α_Q and α_W should both be set equal to $\alpha/2$ so that when the true concentration is equal to the AL, the probability of a Type I error of the two tests in tandem is approximately α.

In Scenario A, the hypothesis tested by the WRS test is as follows:

> Null Hypothesis
> H_0: The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by more than the $DCGL_W$.
>
> Versus
>
> Alternative Hypothesis
> H_1: The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by less than the $DCGL_W$.

In Scenario B, the hypothesis tested by the WRS test is as follows:

> Null Hypothesis
> H_0: The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by less than the AL.
>
> Versus
>
> Alternative Hypothesis
> H_1: The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by more than the AL.

Scenario B is used when the goal of remediation is that residual radioactive material in the survey unit be indistinguishable from background activity levels in the reference area (e.g., AL = 0) or when the AL is below some discrimination level.

When the values of α and β are selected in the DQO process, an important difference between Scenario A and Scenario B should be considered. For a fixed value of N, a lower value for α is more protective in Scenario A, and a lower value for α is less protective in Scenario B. In both scenarios, a lower value for α requires a higher degree of evidence before the null hypothesis is rejected. In Scenario A, the null hypothesis is that the survey unit exceeds the release criteria, and a lower value for α makes it more difficult to reject this hypothesis. In Scenario B, the null hypothesis is that the survey unit meets the release criteria, and a lower value of α makes it more difficult to reject this hypothesis. An illustration of this effect is shown in **Example 8** presented in **Section 8.4.3.**

In both scenarios, the null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. One assumes that any difference between the reference area and survey unit concentration distributions is due to a shift in the survey unit concentrations to higher values (i.e., due to the presence of residual radioactive material in addition to background). Note that some or all of the survey unit measurements may be larger than some reference area measurements while still meeting the release criteria. Indeed, some survey unit measurements may exceed some reference area measurements by more than the $DCGL_W$. The result of the hypothesis test determines whether the survey unit as a whole is deemed to meet the release criteria. The EMC is used to screen individual measurements.

Two assumptions underlie this test: (1) Samples from the reference area and survey unit are independent, identically distributed random samples, and (2) each measurement is independent of every other measurement, regardless of the set of samples from which it came.

8.4.2 Applying the Wilcoxon Rank Sum Test

The WRS test is applied as outlined in the following six steps and further illustrated by the examples in **Section 8.4.3** and **Appendix A.** Separate instructions are provided for Scenarios A and B.

Scenario A

1. Obtain the adjusted reference area measurements, z_i, by adding the $DCGL_W$ to each reference area measurement, x_i . $z_i = x_i + DCGL_W$. The m adjusted reference sample measurements, z_i, from the reference area and the n sample measurements, y , from the survey unit are pooled and ranked in order of increasing size from 1 to N, where $N = m + n$.

2. If several measurements are tied (i.e., have the same value), all are assigned the average rank of that group of tied measurements.

3. If there are t "less than" values, all are given the average of the ranks from 1 to t. Therefore, they are all assigned the rank $t(t + 1)/(2t) = (t + 1)/2$, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as "less than" values.[5]

4. Sum the ranks of the adjusted measurements from the reference area, W_r. Note that because the sum of the first N integers is $N(N + 1)/2$, one can equivalently sum the ranks of the measurements from the survey unit, W_s, and compute $W_r = N(N + 1)/2 - W_s$.

5. Compare W_r with the critical value given in **Table I.5** for the appropriate values of n, m, and α. If W_r is greater than the tabulated value, reject the hypothesis that the survey unit exceeds the release criteria.

Scenario B

1. Obtain the adjusted survey unit measurements, z_i, by subtracting the AL from each survey unit measurement, y_i . $z_i = y_i - AL$.

[5] If more than 40 percent of the data from either the reference area or survey unit are "less than," the WRS test *cannot* be used. Such a large proportion of non-detects suggest that the DQO process be revisited for this survey to determine if the survey unit was properly classified or the appropriate measurement method was used. As stated previously, the use of "less than" values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

2. The m adjusted sample measurements, z_i, from the survey unit and the n reference measurements, x_i, from the reference area are pooled and ranked in order of increasing size from 1 to N, where $N = m + n$. (Note: When using **Table I.5** for Scenario B, the roles of m and n are reversed.)

3. If several measurements are tied (i.e., have the same value), all are assigned the average rank of that group of tied measurements.

4. If there are t "less than" values, they are all given the average of the ranks from 1 to t. Therefore, all are assigned the rank $t(t+1)/(2t) = (t+1)/2$, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as "less than" values.

5. Sum the ranks of the adjusted measurements from the survey unit, W_s. Note that because the sum of the first N integers is $N(N+1)/2$, one can equivalently sum the ranks of the measurements from the reference area, W_r, and compute $W_s = N(N+1)/2 - W_r$.

6. Compare W_s with the critical value given in **Table I.5** for the appropriate values of n, m, and α. (Because the quantile test is used in addition to the WRS test, $\alpha/2$ should be used rather than α.) If W_s is greater than the tabulated value, reject the null hypothesis that the survey unit does not exceed the release criteria.

Example 7 illustrates the WRS test in practice for a Class 2 interior drywall survey unit.

Example 7: Wilcoxon Rank Sum Test Example: Class 2 Interior Drywall Survey Unit

Refer to **Example 4** for background information. In this example, the gas-flow proportional counter measures gross beta activity (see **Appendix H**), and the measurements are not radionuclide-specific. The Wilcoxon Rank Sum (WRS) test is appropriate for the Class 2 interior drywall survey unit because background contributes to gross beta activity even though the radionuclide of interest does not appear in background. Scenario A is selected because the derived concentration guideline level using the WRS test ($DCGL_W$) is higher than the discrimination limit. As a result, the quantile test will not be needed for this example.

Table 8.6 shows that the data quality objectives (DQOs) for this survey unit include $\alpha = 0.025$ and $\beta = 0.05$. The $DCGL_W$ is 8,300 becquerels/square meter (Bq/m^2; 5,000 decays per minute [dpm]/100 square centimeters [cm^2]) and the lower bound of the gray region (LBGR) was selected to be 5,000 Bq/m^2 $(3{,}000\ \text{dpm/100 cm}^2)$. The estimated standard deviation, σ, of the measurements is about 830 Bq/m^2 (500 dpm/100 cm^2). The relative shift was calculated to be 4.0, as shown below:

$$\Delta/\sigma = \frac{\text{DCGL}_\text{W} - \text{LBGR}}{\sigma} = \frac{8{,}300\ \text{Bq/m}^2 - 5{,}000\ \text{Bq/m}^2}{830\ \text{Bq/m}^2} = 4.0$$

In **Table 5.2,** one finds that the number of measurements estimated for the WRS test is 11 in each survey unit and 11 in each reference area ($\alpha = 0.025$, $\beta = 0.05$, and $\Delta/\sigma = 4$). (**Table I.3** in **Appendix I** also lists the number of measurements estimated for the WRS test.)

Table 8.10 lists the data obtained from the gas-flow proportional counter in units of counts per minute (cpm). A reading of 160 cpm with this instrument corresponds to the $DCGL_W$ of 8,300 Bq/m^2 (5,000 dpm/100 cm^2). Column A lists the measurement results as they were obtained. The sample mean and sample standard deviation of the reference area measurements are 44 and 4.4 cpm, respectively. The sample mean and sample standard deviation of the survey unit measurements are 98 and 5.3 cpm, respectively. In column B, the code "R" denotes a reference area measurement, and "S" denotes a survey unit measurement. Column C contains the Adjusted Data. The Adjusted Data are obtained by adding the $DCGL_W$ to the reference area measurements (see **Section 8.4.2,** Step 1). The ranks of the adjusted data appear in Column D. They range from 1 to 22, because there is a total of 11+11 measurements (see **Section 8.4.2,** Step 2).

Note that two cases of measurements tied with the same value, at 104 and 205. Each tied measurement is always assigned the average of the ranks. Therefore, both measurements at 104 are assigned rank $(9 + 10)/2 = 9.5$ (see **Section 8.4.2,** Step 3). Also note that the sum of *all* of the ranks is still $22(22 + 1)/2 = 253$. Checking this value with the formula in Step 5 of **Section 8.4.2** is recommended to guard against errors in the rankings.

Column E contains only the ranks belonging to the reference area measurements. The total is 187. This is compared with the entry for the critical value of 156 in **Table I.5** for $\alpha = 0.025$, with $n = 11$ and $m = 11$. Because the sum of the reference area ranks is greater than the critical value, the null hypothesis (i.e., that the mean survey unit concentration exceeds the $DCGL_W$) is rejected.

If some of the values of the survey unit had been higher and had ranked above some of the reference unit samples, then the sum of the reference values would have been lower (because the survey values are not counted and would have displaced downward reference values). This then moves the sum closer to the critical value. If enough survey sample ranks had displaced reference rankings, then the sum would have been below the critical value and the null hypothesis would be accepted.

1 **Table 8.10: WRS Test for Class 2 Interior Drywall Survey Unit in Example 7**

Sample Number	A Data (cpm)	B Unit or Area	C Adjusted Data	D Ranks	E Reference Area Ranks
1	49	R	209	22	22
2	35	R	195	12	12
3	45	R	205	17.5	17.5
4	45	R	205	17.5	17.5

Sample Number	A	B	C	D	E
	Data (cpm)	Unit or Area	Adjusted Data	Ranks	Reference Area Ranks
5	41	R	201	14	14
6	44	R	204	16	16
7	48	R	208	21	21
8	37	R	197	13	13
9	46	R	206	19	19
10	42	R	202	15	15
11	47	R	207	20	20
12	104	S	104	9.5	0
13	94	S	94	4	0
14	98	S	98	6	0
15	99	S	99	7	0
16	90	S	90	1	0
17	104	S	104	9.5	0
18	95	S	95	5	0
19	105	S	105	11	0
20	93	S	93	3	0
21	101	S	101	8	0
22	92	S	92	2	0
		Sum =		253	187

Abbreviation: cpm = counts per minute.

8.4.3 Applying the Quantile Test—Used Only in Scenario B

The quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey units. It should be noted that, in general, this shift is not necessarily the same as the shift used for the WRS test. The quantile test is better at detecting situations in which only a portion of the survey unit contains excess residual radioactive material. The WRS test is better at detecting situations in which any excess residual radioactive material is uniform across the entire survey unit. The quantile test is used only in Scenario B. The quantile test is performed after the WRS test, if the null hypothesis for the WRS test has not been rejected. Using the quantile test in tandem with the WRS test in Scenario B results in higher power to detect survey units that have not been adequately remediated than either test has by itself.

The quantile test is outlined in the six steps below:

1. Calculate α_Q. ($\alpha_Q = \alpha/2$).

2. Obtain the adjusted survey unit measurements, z_i, by subtracting the AL from each survey unit measurement, y_i: $z_i = y_i -$ AL. If the $DCGL_W$ is equal to zero, then this step is not necessary.

3. The n adjusted survey unit measurements, z_i, and the m reference area measurements, x_i, are pooled and ranked in order of increasing size from 1 to N, where $N = m + n$.

4. If several measurements are tied (i.e., have the same value), all are assigned the mean rank of that group of tied measurements.

5. Look up the values for r and k in **Tables I.7–I.10** to be based on the number of measurements in the survey unit (n), the number of measurements in the reference area (m), and α_Q. The operational decision described in the next step is made using the values for r and k.

6. If k or more of the r largest measurements in the combined ranked data set are from the survey unit, the null hypothesis is rejected.

Examples 8–10 illustrate how certain tests can be used under a variety of testing scenarios.

Example 8: Class 2 Interior Survey Example Under Scenario B Using Wilcoxon Rank Sum and Quantile Tests

Refer to **Example 4** for background information. The data for an example Wilcoxon Rank Sum (WRS) test using Scenario B are shown in Column A of **Table 8.11.** In Column B, the label “R” is inserted to denote a reference area measurement, and the label “S” to denote a survey unit measurement. Column C contains the adjusted data obtained by subtracting the lower bound of the gray region (LBGR) of 142 counts per minute (cpm) from just the survey unit measurements (the reference area measurements are not adjusted). The ranks of the adjusted data in Column C are listed in Column D. The ranks range from 1 to 24, because there are 12 + 12 = 24 measurements. The sum of all the ranks is $N(N + 1)/2$ = (24×25)/2 = 300. Column E contains only the ranks belonging to the adjusted survey unit measurements. The sum of the ranks of the adjusted survey unit data is 194.5. From **Table I.5,** for $\alpha = 0.025$ and n = m = 12, the critical value is 184. Because the sum of the adjusted survey unit ranks, 194.5, is greater than the critical value, 184, the null hypothesis that the survey unit concentrations do not exceed the LBGR is rejected (i.e., the site is determined to be dirty). In Scenario B, the true concentration of radioactive material in the survey unit is judged to be in excess of 142 cpm above the background.

For the quantile test, **Table I.8** provides the critical value, k, of the largest r measurements for different values of n, the number of measurements from the survey unit, and m, the number of measurements from the reference area. The same rankings in Column D of **Table 8.11** for the WRS test can be used for the quantile test. If k or more of the r largest measurements in the combined ranked data set are from the survey unit, the null hypothesis is rejected. For a survey unit that has failed the WRS test, as was the case in this example, it is not usually necessary to also perform the quantile test. However, the quantile test is presented for illustrative purposes.

In **Table 8.11,** Columns F and G show the sorted ranks of the adjusted data and the location associated with each rank (i.e., “R” for reference area and “S” for survey unit). In **Table I.8,** the closest entry to n = m = 12 is for n = m = 10. The values of r = 7, k = 6 and α = 0.029 are found. Thus, the null hypothesis is rejected if six of the seven largest adjusted measurements come from the survey unit. From **Table 8.11,** we find that only five of the seven largest adjusted measurements come from the survey unit, so the null hypothesis is not rejected based on the quantile test. The values of n and m that were used are close to, but not equal to, the actual values so the α value will be different from that listed in the table. It is prudent to check a few other entries in **Table I.8** that are near the actual sample size. Additionally, Chapter 7 in NUREG-1505 (NRC 1998a) provides equations to calculate exact and approximate values of the alpha error for the quantile test as a function of n, m, k, and r.

Table 8.11: WRS and Quantile Test Under Scenario B for Class 2 Interior Drywall Survey Unit in Example 8

	A	B	C	D	E	F	G
Sample Number	Data (cpm)	Area	Adjusted Data	Ranks	Survey Unit Ranks	Sorted Ranks	Location Associated with Sorted Ranks[a]
1	47	R	47	18	—	1	R
2	28	R	28	1	—	2	R
3	36	R	36	6	—	3	R
4	37	R	37	7	—	4.5	R
5	39	R	39	9.5	—	4.5	S
6	45	R	45	13	—	6	R
7	43	R	43	11	—	7	R
8	34	R	34	3	—	8	S
9	32	R	32	2	—	9.5	R
10	35	R	35	4.5	—	9.5	R
11	39	R	39	9.5	—	11	R
12	51	R	51	21	—	13	R
13	209	S	67	24	24	13	S
14	197	S	55	23	23	13	S
15	188	S	46	16	16	16	S
16	191	S	49	19	19	16	S
17	193	S	51	21	21	16	S
18	187	S	45	13	13	18	R
19	188	S	46	16	16	19	S
20	180	S	38	8	8	21	R
21	193	S	51	21	21	21	S
22	188	S	46	16	16	21	S
23	187	S	45	13	13	23	S
24	177	S	35	4.5	4.5	24	S
			Sum =	300	194.5	—	—

[a] Measurements from the reference area and the survey unit are denoted by R and S, respectively. The adjusted data and data columns are identical when AL= 0.

Example 9: Example Using NUREG-1505 Kruskall-Wallis Test to Determine Whether Appropriate to Consider Variability from Background under Scenario B

NUREG-1505 (NRC 1998a) provides guidance on methods used to demonstrate indistinguishability from background when Scenario B is deemed appropriate to use (e.g., when the DCGL is close to background considering variability). A difficulty arises in the ability to release a site when variations in mean background among the potential reference areas become comparable in magnitude to the width of the gray region. Because any difference in radioactivity between the reference area and survey unit is assumed to be due to residual radioactivity, and it is not possible to determine if the difference is actually due to differences in background concentrations between the two areas, tests are available to determine the significance of background variability and how this variability can be considered in the statistical tests used to help determine if the site is clean.

The parametric F-test (assumes a normal distribution) and nonparametric Kruskall-Wallis test (does not make an assumption regarding the underlying distribution) can be used to determine if variability between the means of potential reference areas is statistically significant. See data in **Table 8.12** used to determine ranks of reference area measurements used to perform the Kruskall-Wallis test. NUREG-1505 Equation 13-3 is used to calculate a Kruskal-Wallis statistic:

$$K = \frac{12}{N\,(N+1)}\left(\sum_{i=1}^{k}\frac{R_i^2}{n_i}\right) - 3\,(N+1)$$

where *N* is the total number of measurements in all the reference areas *i*=1 to k reference areas; n_i is the number of measurements in a given reference area; and R_i is the sum of the ranks of the measurements in a given reference area.

The test statistic of 14.0 is compared to the critical values provided in NUREG-1505 Table 13.1. In the example, the Kruskall Wallis statistic of 14.0 is above the critical threshold for 4 – 1=3 reference areas that range from 11.3 for an α value of 0.01 to 4.6 for an α value of 0.2. Therefore, the null hypothesis that the variability in the reference area means is zero can be rejected with high confidence (i.e., the null hypothesis is rejected even for very small α or false positive error rates). Although the Kruskall-Wallis test (or F-test) is used to determine if it is appropriate to consider reference area variability in applying Scenario B, NUREG-1505 also indicates that background variability could be given the benefit of the doubt, in which case the Kruskal-Wallis test (or F-test) need not be conducted.

If it is determined that the variability between reference means should be considered, NUREG-1505 Equation 13-13 can be used to calculate the variance, $\widehat{\omega}^2$, which can be used to determine the lower bound of the gray region (LBGR, or action level [AL]) for Scenario B. NUREG-1505 provides an example where the mean square between reference areas, ${s_b}^2$, and mean square within reference areas, ${s_w}^2$, calculated manually using Equation 13-13 or output from ANOVA testing can be used to compute $\widehat{\omega}^2 = ({s_b}^2 - {s_w}^2)/n_0$, where n_0 is equal to the number of measurements per reference area when the number of measurements in each reference area is the same (or see Equation 13-13 in NUREG-1505 when the number of measurements in the reference areas are not the same). Using the ANOVA output in **Table 8.13,**

$$\widehat{\omega}^2 = \frac{{s_b}^2 - {s_w}^2}{n_0} = \frac{6.52 - 0.97}{10} = 0.55$$

As part of the data quality objective process, an agreed-upon value for the LBGR as a multiple of $\widehat{\omega}$ can be selected (e.g., NUREG-1505 states that 3 $\widehat{\omega}$ is a reasonable default [or in the example $\sqrt{55} \times 3 = 0.74 \times 3 = 2.22$ for the LBGR]). Note that the difference in means between reference areas 2 and 4 in Table 13.2 is 1.82, which is similar to the LBGR calculated based on 3 $\widehat{\omega}$. NUREG-1505, Table 13.5 also provides information on the power of the F-test, which is used to approximate the power of the Kruskal-Wallis test, to help determine the number of references areas and the number of measurements that should be taken in each reference area to perform the Kruskal-Wallis test and to estimate $\widehat{\omega}$. In all cases, the regulatory authority should be consulted to determine the acceptability of using Scenario B, as well as determining appropriate values for the test parameters.

Table 8.12: Calculation of $\widehat{\omega}^2$ for Example 9

Sample Number	Measurements				Measurement Ranks				Measurements Squared			
	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4
1	0.27	1.04	2.45	3.77	6	13	27	39	0.07	1.08	6.00	14.21
2	1.87	0.39	0.34	2.63	20	9	8	31	3.50	0.15	0.12	6.92
3	0.97	2.07	3.06	4.05	10	23	37	40	0.94	4.28	9.36	16.40
4	1.01	0.57	2.83	1.72	11	2	35	19	1.02	0.32	8.01	2.96
5	2.08	1.97	1.09	1.50	24	21	14	17	4.33	3.88	1.19	2.25
6	1.62	0.22	0.26	2.47	18	3	5	29	2.62	0.05	0.07	6.10
7	0.30	1.39	2.80	1.42	7	15	34	16	0.09	1.93	7.84	2.02
8	1.98	0.05	2.77	2.47	22	4	33	28	3.92	0.00	7.67	6.10
9	2.18	0.75	2.42	2.76	25	1	26	32	4.75	0.56	5.86	7.62
10	1.02	2.50	2.86	3.35	12	30	36	38	1.04	6.25	8.18	11.22
Sum	13.30	7.87	20.88	26.14	—	—	—	—	22.28	18.50	54.30	75.80
Average	1.33	0.79	2.09	2.61	—	—	—	—	—	—	—	—
Average Squared	1.77	0.62	4.36	6.83	—	—	—	—	—	—	—	—

Table 8.13: Analysis of Variance for Example 9 Data

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Statistic
Between Groups	19.56	3	6.52	6.69
Within Groups	35.08	36	0.97	—

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Statistic
Total	54.65	39	—	—

Example 10: Class 1 Interior Concrete Survey Unit

As in the previous example, the gas-flow proportional counter measures gross beta activity (see **Appendix H**) and the measurements are not radionuclide-specific. The nonparametric statistical test for when the radionuclide is present in background is appropriate for the Class 1 interior concrete survey unit because gross beta activity contributes to the overall background, even though the specific radionuclide of interest does not appear in background.

Appendix A provides a detailed description of the calculations for the Class 1 interior concrete survey unit.

8.4.4 Multiple Radionuclides

The use of the unity rule when there is more than one radionuclide to be considered is discussed in **Section 4.4.** An example application of the use of the unity rule appears in **Examples 11 and 12.**

Example 11: Application of WRS Test to Multiple Radionuclides

Consider a site with both cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs) contamination. ^{137}Cs appears in background from fallout at a typical concentration of about 37 becquerels/kilogram (Bq/kg; 1 picocurie/gram [pCi/g]). Assume that the $DCGL_W$ for ^{60}Co is 74 Bq/kg (2 pCi/g) and for ^{137}Cs is 52 Bq/kg (1.4 pCi/g). In disturbed areas, the background concentration of ^{137}Cs can vary considerably. An estimated spatial standard deviation of 19 Bq/kg (0.5 pCi/g) for ^{137}Cs will be assumed. During remediation, it was found that the concentrations of the two radionuclides were not well correlated in the survey unit. ^{60}Co concentrations were more variable than the ^{137}Cs concentrations, and 26 Bq/kg (0.7 pCi/g) is estimated for its standard deviation. Measurement errors for both ^{60}Co and ^{137}Cs using gamma spectrometry will be small compared to this. For the comparison to the release criteria, the weighted sum of the concentrations of these radionuclides is computed from—

$$T = \frac{^{60}\text{Co concentration}}{^{60}\text{Co DCGL}} + \frac{^{137}\text{Cs concentration}}{^{137}\text{Cs DCGL}}$$
$$= \frac{^{60}\text{Co concentration}}{74\text{ Bq/kg}} + \frac{^{137}\text{Cs concentration}}{52\text{ Bq/kg}}$$

The variance of the weighted sum, assuming that the ^{60}Co and ^{137}Cs concentrations are spatially unrelated, is—

$$\sigma^2(T) = \left[\frac{\sigma\left(^{60}\text{Co concentration}\right)}{^{60}\text{Co DCGL}}\right]^2 + \left[\frac{\sigma\left(^{137}\text{Cs concentration}\right)}{^{137}\text{Cs DCGL}}\right]^2$$
$$= \left[\frac{26\text{ Bq/kg}}{74\text{ Bq/kg}}\right]^2 + \left[\frac{19\text{ Bq/kg}}{52\text{ Bq/kg}}\right]^2 = 0.26$$

Thus, $\sigma = 0.5$. The wide-area derived concentration guideline level ($DCGL_W$) for the weighted sum is 1. The null hypothesis for Scenario A is that the survey unit exceeds the release criterion. During the data quality objective process, the lower bound of the gray region (LBGR) was set at 0.5 for the weighted sum, so that $\Delta = DCGL_W - LBGR = 1.0 - 0.5 = 0.5$, and $\Delta/\sigma = 0.5/0.5 = 1.0$. The acceptable error rates chosen were $\alpha = \beta = 0.05$. To achieve this, 32 samples each are required in the survey unit and the reference area.

The weighted sums are computed for each measurement location in both the reference area and the survey unit. The WRS test is then performed on the weighted sum. The calculations for this example are shown in **Table 8.14.** The $DCGL_W$ for the unity rule (i.e., 1.0) is added to the weighted sum for each location in the reference area. The ranks of the combined survey unit and adjusted reference area weighted sums are then computed. The sum of the ranks of the adjusted reference area weighted sums is then compared to the critical value for $n = m = 32$, $\alpha = 0.05$, which is 1,162 (see formula following **Table I.5**). In **Table 8.14,** the sum of the ranks of the adjusted reference area weighted sums is 1,281. This exceeds the critical value, so the null hypothesis is rejected. In Scenario A, this means the survey unit meets the release criteria. The difference between the mean of the weighted sums in the survey unit and the reference area is 1.86 - 1.16 = 0.7. Thus, the estimated dose or risk due to residual radioactive material in the survey unit is approximately equal to 70 percent of the release criterion.

Example 12: Use of ProUCL for the WRS Test for Multiple Radionuclides

As **Table 8.14** does for **Example 11, Table 8.15** provides sample results for a survey unit with residual radioactive material that includes cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs). Because ^{137}Cs from fallout is found in the background, samples were also collected and analyzed from a reference area. The wide-area derived concentration guideline levels ($DCGL_W$) for ^{137}Cs and ^{60}Co are 1.4 and 2.0 Bq/kg, respectively. The unity rule is used to determine if the survey unit meets the release criteria. Scenario A was selected. To perform the WRS test, ProUCL, Version 5.0 was used. ProUCL is a freeware statistical software program, provided by the U.S. Environmental Protection Agency.

The data can be entered by hand or copied and pasted from another software program. Descriptions can be provided for the column headers by right-clicking the column header and selecting “Header Name.” For this example, the columns were named “Reference” and

"Survey Unit." **Figure 8.4** shows the initial program inputs of the weighted sums of the reference area and survey unit with their column headings.

To perform the WRS test, the two-sample Wilcoxon-Mann-Whitney test was selected. The Wilcoxon-Mann-Whitney test is a nonparametric of the same hypothesis as the WRS test. The two tests use a different test statistic and critical value, but both tests will provide the same conclusion. The test can be selected by first choosing "Two Sample" from the "Hypothesis Testing" menu, and then selecting "Wilcoxon-Mann-Whitney."

Variables are selected by clicking on the variable name in the list of variables, and then clicking the corresponding ">>" button. The Reference Area results are selected as the "Background/Ambient" variable, and the Survey Unit results are selected as the "Area of Concern/Site" variable, as shown in **Figure 8.5.**

Clicking the "Options" in the dialog window shown in **Figure 8.5,** generates another dialog window. This window allows the user to specify the "Confidence Coefficient." The confidence coefficient is equal to $(1 - \alpha)$. For this example, the "Confidence Coefficient" of 95 percent is selected, corresponding to $\alpha = 0.05$. The dialog window also allows the user to specify the form of the hypothesis. For this example, Form 2 is selected, and the value of 1 is entered for the "Substantial Difference." When using Form 2, the unadjusted reference area results should be used instead of the adjusted reference area results.

Clicking the "OK" button shown in **Figure 8.6** saves the changes and closes the dialog window. Clicking the "OK" button shown in **Figure 8.5** closes that dialog window and generates the output sheet shown in **Figure 8.7.** As shown near the bottom of **Figure 8.7,** the null hypothesis is rejected, and the survey unit is demonstrated to pass the statistical test. The elevated measurement comparison would still need to be performed before deciding that the survey unit has met the release criteria.

Table 8.14: Example 11 WRS Test for Two Radionuclides

Sample Number	Reference Area		Survey Unit		Weighted Sum			Ranks	
	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co	Ref	Survey	Adj Ref	Survey	Adj Ref
1	2.00	0	1.12	0.06	1.43	0.83	2.43	1	56
2	1.23	0	1.66	1.99	0.88	2.18	1.88	43	21
3	0.99	0	3.02	0.56	0.71	2.44	1.71	57	14
4	1.98	0	2.47	0.26	1.41	1.89	2.41	23	55
5	1.78	0	2.08	0.21	1.27	1.59	2.27	9	50
6	1.93	0	2.96	0.00	1.38	2.11	2.38	37	54
7	1.73	0	2.05	0.20	1.23	1.56	2.23	7	46
8	1.83	0	2.41	0.00	1.30	1.72	2.30	16	52
9	1.27	0	1.74	0.00	0.91	1.24	1.91	2	24
10	0.74	0	2.65	0.16	0.53	1.97	1.53	27	6
11	1.17	0	1.92	0.63	0.83	1.68	1.83	13	18
12	1.51	0	1.91	0.69	1.08	1.71	2.08	15	32
13	2.25	0	3.06	0.13	1.61	2.25	2.61	47	63
14	1.36	0	2.18	0.98	0.97	2.05	1.97	30	28
15	2.05	0	2.08	1.26	1.46	2.12	2.46	39	58
16	1.61	0	2.30	1.16	1.15	2.22	2.15	45	41
17	1.29	0	2.20	0.00	0.92	1.57	1.92	8	25
18	1.55	0	3.11	0.50	1.11	2.47	2.11	59	35
19	1.82	0	2.31	0.00	1.30	1.65	2.30	11	51
20	1.17	0	2.82	0.41	0.84	2.22	1.84	44	19
21	1.76	0	1.81	1.18	1.26	1.88	2.26	22	48
22	2.21	0	2.71	0.17	1.58	2.02	2.58	29	62
23	2.35	0	1.89	0.00	1.68	1.35	2.68	3	64
24	1.51	0	2.12	0.34	1.08	1.68	2.08	12	33
25	0.66	0	2.59	0.14	0.47	1.92	1.47	26	5
26	1.56	0	1.75	0.71	1.12	1.60	2.12	10	38
27	1.93	0	2.35	0.85	1.38	2.10	2.38	34	53
28	2.15	0	2.28	0.87	1.54	2.06	2.54	31	61
29	2.07	0	2.56	0.56	1.48	2.11	2.48	36	60
30	1.77	0	2.50	0.00	1.27	1.78	2.27	17	49
31	1.19	0	1.79	0.30	0.85	1.43	1.85	4	20
32	1.57	0	2.55	0.70	1.12	2.17	2.12	42	40
Avg	1.62	0	2.28	0.47	1.16	1.86	2.16	sum =	sum =
Std Dev	0.43	0	0.46	0.48	0.31	0.36	0.31	799	1281

Table 8.15: Example 12 WRS Test for Two Radionuclides

Sample Number	Reference Area Results (Bq/kg)		Survey Unit (Bq/kg)		Reference Area (x_i)	Survey Unit (y_i)	Adjusted Reference Area (z_i)
	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co			
1	2.00	0.00	1.12	0.06	1.429	0.830	2.429
2	1.23	0.00	1.66	1.99	0.879	2.181	1.879
3	0.99	0.00	3.02	0.56	0.707	2.437	1.707
4	1.98	0.00	2.47	0.26	1.414	1.894	2.414
5	1.78	0.00	2.08	0.21	1.271	1.591	2.271
6	1.93	0.00	2.96	0.00	1.379	2.114	2.379
7	1.73	0.00	2.05	0.20	1.236	1.564	2.236
8	1.83	0.00	2.41	0.00	1.307	1.721	2.307
9	1.27	0.00	1.74	0.00	0.907	1.243	1.907
10	0.74	0.00	2.65	0.16	0.529	1.973	1.529
11	1.17	0.00	1.92	0.63	0.836	1.686	1.836
12	1.51	0.00	1.91	0.69	1.079	1.709	2.079
13	2.25	0.00	3.06	0.13	1.607	2.251	2.607
14	1.36	0.00	2.18	0.98	0.971	2.047	1.971
15	2.05	0.00	2.08	1.26	1.464	2.116	2.464
16	1.61	0.00	2.30	1.16	1.150	2.223	2.150
17	1.29	0.00	2.20	0.00	0.921	1.571	1.921
18	1.55	0.00	3.11	0.50	1.107	2.471	2.107
19	1.82	0.00	2.31	0.00	1.300	1.650	2.300
20	1.17	0.00	2.82	0.41	0.836	2.219	1.836
21	1.76	0.00	1.81	1.18	1.257	1.883	2.257
22	2.21	0.00	2.71	0.17	1.579	2.021	2.579
23	2.35	0.00	1.89	0.00	1.679	1.350	2.679
24	1.51	0.00	2.12	0.34	1.079	1.684	2.079
25	0.66	0.00	2.59	0.14	0.471	1.920	1.471
26	1.56	0.00	1.75	0.71	1.114	1.605	2.114
27	1.93	0.00	2.35	0.85	1.379	2.104	2.379
28	2.15	0.00	2.28	0.87	1.536	2.064	2.536
29	2.07	0.00	2.56	0.56	1.479	2.109	2.479
30	1.77	0.00	2.50	0.00	1.264	1.786	2.264
31	1.19	0.00	1.79	0.30	0.850	1.429	1.850
32	1.57	0.00	2.55	0.70	1.121	2.171	2.121

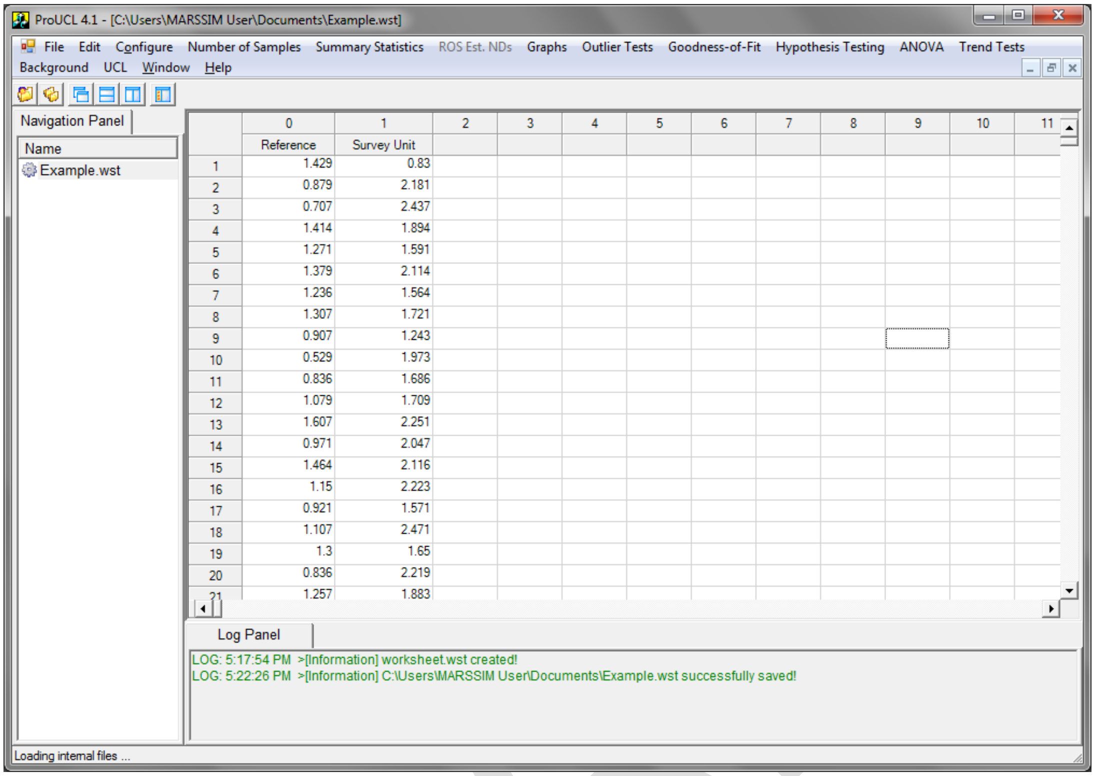


Figure 8.4: ProUCL Worksheet for Example 12

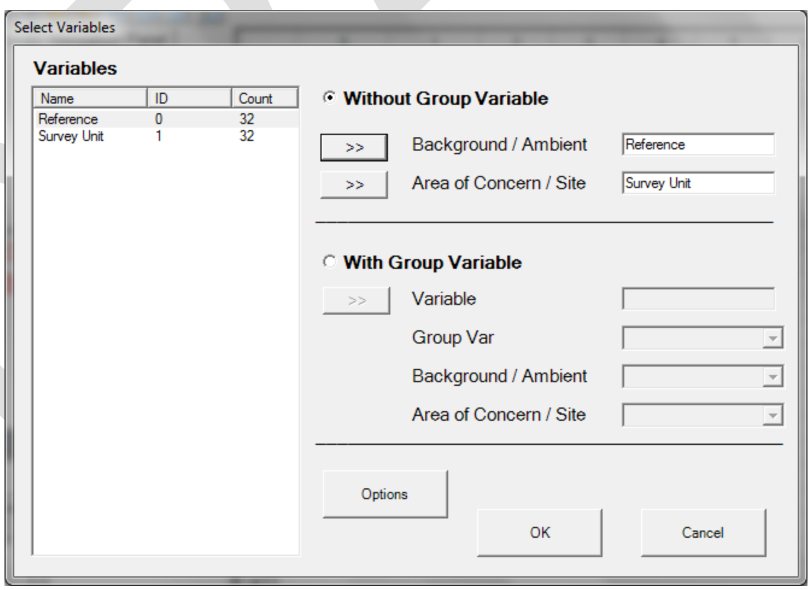


Figure 8.5: ProUCL Select Variables Window for Hypothesis Testing for Example 12

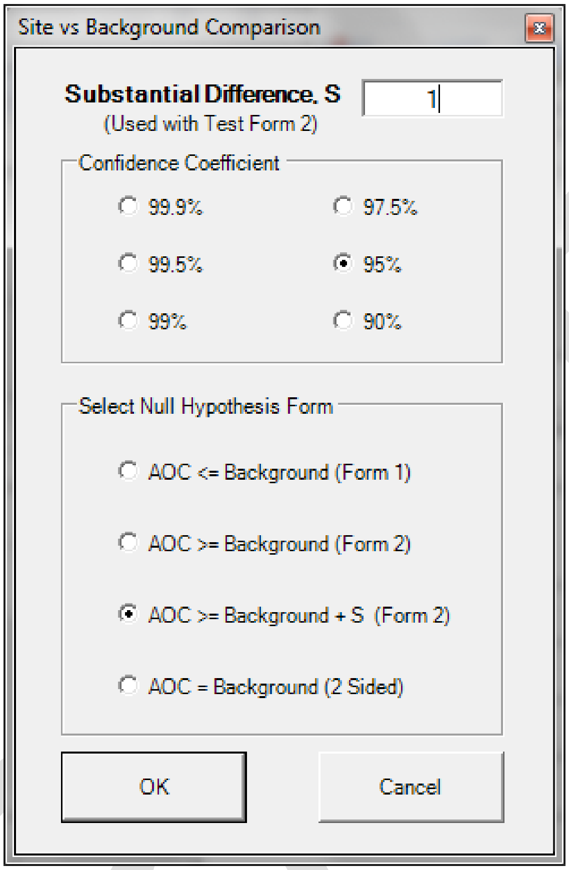


Figure 8.6: ProUCL Hypothesis Testing Options Window for Example 12

	Wilcoxon-Mann-Whitney Site vs Background Comparison Test for Full Data Sets without NDs	
User Selected Options		
From File	C:\Users\MARSSIM User\Documents\Example.wst	
Full Precision	OFF	
Confidence Coefficient	95%	
Substantial Difference	1	
Selected Null Hypothesis	Site or AOC Mean/Median >= Background Mean/Median Plus Substantial Difference, S (Form 2)	
Alternative Hypothesis	Site or AOC Mean/Median Less Than Background Mean/Median Plus Substantial Difference, S	
Area of Concern Data: Survey Unit		
Background Data: Reference		
Raw Statistics		
	Site	Background
Number of Valid Observations	32	32
Number of Distinct Observations	32	29
Minimum	0.83	0.471
Maximum	2.471	1.679
Mean	1.863	1.161
Median	1.907	1.193
SD	0.361	0.308
SE of Mean	0.0638	0.0544
Wilcoxon-Mann-Whitney (WMW) Test		
H0: Mean/Median of Site or AOC >= Mean/Median of Background + 1		
Site Rank Sum W-Stat	799.5	
WMW Test U-Stat	-3.223	
WMW Critical Value (0.050)	-1.645	
P-Value	0.0006354	
Conclusion with Alpha = 0.05		
Reject H0, Conclude Site < Background + 1.00		
P-Value < alpha (0.05)		

Figure 8.7: ProUCL Output for Example 12

8.5 Scan-Only Surveys

The use of the UCL can apply to both Scenario A and B for scan-only surveys where individual results are recorded. When release decisions are made about the estimated mean of a sampled population, the assessment of the survey results is accomplished by comparing a UCL for the mean to the $DCGL_W$ or DL for Scenarios A and B, respectively.

If individual scan-only survey results are recorded, a nonparametric confidence interval can be used to evaluate the results of the release survey. Similarly, a confidence interval can be used to evaluate a series of direct measurements with overlapping fields of view. A one-tailed version of Chebyshev's inequality or software (e.g., EPA's ProUCL software) can be used to evaluate the probability of exceeding the UBGR (i.e., using a UCL). The use of a UCL applies to both Scenario A (where the UBGR equals the $DCGL_W$) and Scenario B (where the UBGR equals the DL).

Chebyshev's inequality calculates the probability that the absolute value of the difference of the true but unknown mean of the population and a random number from the data set is at least a specified value. That is, given a specified positive number (n), a mean (μ), and a random number from the data set (r), then the probability that $[\mu - r]$ is greater than or equal to n is equal to α. In addition, a one-tailed version of the inequality can be used to calculate a UCL for a data set that is independent of the data distribution (i.e., there is no requirement to verify the data are from a normal, lognormal, or any other specified kind of distribution) by letting the inequality equal the UCL. The UCL can be calculated using **Equation 8-3:**

$$\text{UCL} = \mu + \sqrt{\frac{\sigma^2}{n\alpha} - \frac{\sigma^2}{n}} \quad \text{(8-3}$$

The comparison to the UCL is described in the following steps:

1. Calculate the mean (μ) and standard deviation (σ) of the number of results (n) in the data set.
2. For Scenario A, retrieve the Type I error rate (α) used to design the survey. For Scenario B, substitute the Type II error rate (β) used to design the survey for α in **Equation 8-3.**
3. Using Chebyshev's inequality, calculate the maximum UCL using **Equation 8-3.**

If the maximum UCL is less than the UBGR, the survey demonstrates compliance with the disposition criterion (i.e., reject the null hypothesis for Scenario A or fail to reject the null hypothesis for Scenario B).

Chebyshev's inequality must be used with caution when there are very few points in the data set. This is because the population mean and standard deviation in the Chebyshev formula are being estimated by the sample mean and sample standard deviation. In a small data set from a highly skewed distribution, the sample mean and sample standard deviation may be underestimated if the high concentration but low probability portion of the distribution is not captured in the sample data set.

8.6 Evaluate the Results: The Decision

When the data and the results of the tests have been obtained, the specific steps required to achieve survey unit release depend on the procedures instituted by the governing regulatory agencies and site-specific ALARA[6] considerations. The following suggested considerations are

[6] "as low as reasonably achievable"

for the interpretation of the test results with respect to the release limit established for the site or survey unit. Note that the tests need not be performed in any particular order.

8.6.1 Elevated Measurement Comparison

If applicable release criteria for elevated measurements exist, then the EMC consists of comparing each measurement from the survey unit with the investigation levels discussed in **Section 5.3.8.** The EMC is performed both for measurements obtained on the systematic sampling grid and for locations flagged by scanning measurements. Any measurement from the survey unit that is equal to or greater than an investigation level indicates an area of relatively high concentrations that should be investigated, regardless of the outcome of the nonparametric statistical tests.

Under Scenario A, the statistical tests may reject the null hypothesis when only a very few high measurements are obtained in the survey unit, regardless of how high the measurements are. In a similar manner, under Scenario B, the statistical tests might not reject the null hypothesis when only a few high measurements are obtained in the survey unit. The use of the quantile test and the EMC against the investigation levels may be viewed as assurance that unusually large measurements will receive proper attention regardless of the outcome of those tests and that any area having the potential for significant dose or risk contributions will be identified. The EMC is intended to flag potential failures in the remediation process. This should not be considered the primary means to identify whether a survey unit meets the release criteria.

Note that the $DCGL_{EMC}$ is an a priori limit, established both by the $DCGL_{W}$ and by the survey design (i.e., grid spacing and scanning MDC). The true extent of an area of elevated activity can be determined only after performing the survey and taking additional measurements. Upon the completion of further investigation, the a posteriori limit can be established. The area of elevated activity is generally bordered by concentration measurements below the $DCGL_{W}$. An individual elevated measurement on a systematic grid could conceivably represent an area four times as large as the systematic grid area used to define the $DCGL_{EMC}$. This is the area bounded by the nearest neighbors of the elevated measurement location. The results of the investigation should show that the appropriate $DCGL_{EMC}$ is not exceeded. If measurements above the stated scanning MDC are found by sampling or by direct measurements at locations that were not flagged during the scanning survey, then this may indicate the scanning method does not meet the DQOs.

The preceding discussion primarily concerns Class 1 survey units. Measurements exceeding the $DCGL_{W}$ in Class 2 or Class 3 areas may indicate survey unit misclassification. Scanning coverage for Class 2 and Class 3 survey units is less stringent than for Class 1. If the investigation levels of **Section 5.3.8** are exceeded, an investigation should (1) ensure that the area of elevated activity discovered meets the release criteria, and (2) provide reasonable assurance that other undiscovered areas of elevated activity do not exist. If further investigation determines that the survey unit was misclassified with regard to potential for residual radioactive material, then a resurvey using the method appropriate for the new survey unit classification is appropriate.

8.6.2 Interpretation of Statistical Test Results

The result of the statistical test is the decision to reject or not to reject the null hypothesis. Provided that the results of investigations triggered by the EMC were resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criteria in Scenario A. In Scenario B, failure to reject the null hypothesis in both the WRS and quantile tests leads to the decision that the survey unit meets the release criteria, provided that EMC results are acceptable. However, estimating the mean concentration of residual radioactive material in the survey unit may also be necessary so that dose or risk calculations can be made. This estimate is designated by δ. The mean concentration is generally the best estimator for δ. However, only the unbiased measurements from the statistically designed survey should be used in the calculation of δ.

If residual radioactive material is found in an isolated area of elevated activity—in addition to residual radioactive material distributed relatively uniformly across the survey unit—the unity rule (**Section 4.4**) can be used to ensure that the total dose is within the release criteria, as shown in **Equation 8-4:**

$$\frac{\delta}{\mathrm{DCGL_W}} + \frac{(\text{mean concentration in elevated area} - \delta)}{\mathrm{DCGL_{EMC}}} \leq 1 \qquad (8\text{-}4)$$

If there is more than one elevated area, a separate term could be included in **Equation 8-4** for each area. The use of the unity rule for more than one elevated area may imply that a person is centered on each area of elevated radioactive material and exposed simultaneously. This is an impossible situation and represents a very cautious exposure scenario. If there are multiple elevated areas, then alternative approaches may be considered:

1. The MARSSIM user could determine the elevated area (primary area) that contributes the most to the total dose or risk. As shown by Abelquist (2008), the doses from elevated areas other than the primary area can be very small and might be negligible.

2. The dose or risk due to the actual residual radioactive material distribution could be calculated if an appropriate exposure pathway model is available.

Other approaches for handling elevated concentrations of radioactive material may be utilized and should be coordinated with the regulator.

The MARSSIM user should consult with the responsible regulatory agency for guidance on an acceptable approach to address the dose or risk from elevated areas of residual radioactive material. Note that these approaches generally apply only to Class 1 survey units, because areas of elevated activity above the $\mathrm{DCGL_W}$ should not exist in Class 2 or Class 3 survey units.

A retrospective power analysis for the test will often be useful, especially when the null hypothesis is not rejected (see **Appendix M**). When the null hypothesis is not rejected, it may be because it is true, or it may be because the test did not have sufficient power to detect that it is not true. The power of the test will be primarily affected by changes in the actual number of measurements obtained and their standard deviation. An effective survey design will slightly overestimate both the number of measurements and the standard deviation to ensure adequate power. This ensures that a survey unit is not subjected to additional remediation simply because the FSS is not sensitive enough to detect that residual radioactive material is below the $DCGL_W$. When the null hypothesis is rejected in Scenario A, the power of the test becomes a somewhat moot question. Nonetheless, even in this case, a retrospective power curve can be a useful diagnostic tool and an aid to designing future surveys and for other survey units at the site. When the null hypothesis is accepted in Scenario B, the power of the test is of particular importance. If an insufficient number of samples are collected, the null hypothesis that the survey unit meets the release criteria may be accepted simply because of the lack of sufficient power to detect residual radioactive material in the survey unit above the release criteria. If the retrospective power analysis reveals a lack of sufficient power, it may be necessary to revisit the DQO process with the updated estimate of σ.

8.6.3 If the Survey Unit Fails

The systematic planning process included in MARSSIM should include planning for possible survey unit failure. Early discussions with appropriate regulatory personnel about what actions can and should be taken if the survey unit fails may prevent long delays later in the project. However, if the survey unit fails in a way that is not anticipated, agreed upon actions may not be applicable, and discussions will need to take place to address the unanticipated results.

The information provided in MARSSIM is fairly explicit concerning the steps that should be taken to show that a survey unit meets the release criteria. Less has been said about the procedures that should be used if the survey unit fails at any point. This is primarily because there are many different ways that a survey unit may fail the FSS. The mean concentration of residual radioactive material may not pass the nonparametric statistical tests. Further investigation following the elevated measurement comparison may show a large enough area with a concentration too high to meet the release criteria. Investigation levels may have caused locations to be flagged during scanning that indicate unexpected levels of residual radioactive material for the survey unit classification. Site-specific information is needed to fully evaluate all of the possible reasons for failures, their causes, and their remedies.

When a survey unit fails to demonstrate compliance with the release criteria, the first step is to review and confirm the data that led to the decision. Once this is done, the DQO process (**Appendix D**) can be used to identify and evaluate potential solutions to the problem. The concentration of residual radioactive material in the survey unit should be determined to help define the problem. Once the problem has been stated, the decision concerning the survey unit should be developed into a decision rule. Next, determine the additional data, if any, that are needed to document that the survey unit demonstrates compliance with the release criteria. Alternatives to resolving the decision statement should be developed for each survey unit that fails the tests. These alternatives are evaluated against the DQOs, and a survey design that meets the objectives of the project is selected. **Example 13** discusses a Class 2 survey unit with measurements exceeding the $DCGL_W$.

Example 13: Class 2 Survey Unit with Measurements Exceeding the $DCGL_W$

A Class 2 survey unit passes the nonparametric statistical tests but has several measurements on the sampling grid that exceed the derived concentration guideline level determined using the Wilcoxon Rank Sum test ($DCGL_W$). This is unexpected in a Class 2 area, so these measurements are flagged for further investigation. Additional sampling confirms several areas where the concentration exceeds the $DCGL_W$. This indicates that the survey unit was misclassified. However, the scanning technique that was used was sufficient to detect concentrations of residual radioactive material at the derived concentration guideline level determined using the elevated measurement comparison ($DCGL_{EMC}$) calculated for the sample grid. No areas exceeding the $DCGL_{EMC}$ were found. Thus, the only difference between the performed final status survey (FSS) and the required FSS for a Class 1 area is that the scanning may not have covered 100 percent of the survey unit area. In this case, one might simply increase the scan coverage to 100 percent. Reasons the survey unit was misclassified should be noted. If no areas exceeding the $DCGL_{EMC}$ are found, the survey unit essentially demonstrates compliance with the release criteria as a Class 1 survey unit.

If a Class 2 survey unit has been misclassified as a Class 1 survey unit, the size of the survey unit should be considered to determine if the survey unit should be divided into two or more smaller survey units, based on the recommended survey sizes in **Table 4.1** and the concentration of radioactive material in different areas of the survey unit. If the scanning technique was not sufficiently sensitive, it may be possible to reclassify as Class 1 only that portion of the survey unit containing the higher measurements. This portion would be resampled at the higher measurement density required for a Class 1 survey unit, with the rest of the survey unit remaining as Class 2.

Example 14 discusses a Class 1 survey unit with elevated areas.

Example 14: Class 1 Survey Unit with Elevated Areas

Consider a Class 1 Survey unit that passes the nonparametric statistical tests and contains some areas that were flagged for investigation during scanning. Further investigation, sampling, and analysis indicate one area is truly elevated. This area has a concentration that exceeds the derived concentration guideline level determined using the Wilcoxon Rank Sum test by a factor greater than the area factor calculated for its actual size. This area is then remediated. Remediation control sampling shows that the residual radioactive material was removed, and no other areas were affected by residual radioactive material. In this case, one may simply document the original final status survey (FSS), the fact that remediation was performed, the results of the remedial action support survey, and the additional remediation data. In some cases, additional FSS data may not be needed to meet the release criteria.

Example 15 discusses a Class 1 survey unit that fails the statistical test.

> **Example 15: Class 1 Survey Unit Fails the Statistical Test**
>
> Consider a Class 1 area that fails the nonparametric statistical tests. Confirmatory data indicate that the mean concentration in the survey unit exceeds the derived concentration guideline level determined using the Wilcoxon Rank Sum test over a majority of its area. This indicates remediation of the entire survey unit is necessary, followed by another final status survey (FSS). Reasons for performing an FSS in a survey unit with significant amounts of residual radioactive material should be noted.

Examples 13–15 are meant to illustrate the actions that may be necessary to secure the release of a survey unit that has failed to meet the release criteria. The DQO process should be revisited to plan how to attain the original objective, which is to safely release the survey unit by showing that it meets the release criteria. Whatever data are necessary to meet this objective will be in addition to the FSS data already in hand.

8.6.4 Removable Radioactive Material

Some regulatory agencies may require that smear samples be taken at indoor grid locations as an indication of removable surface activity. In addition, the percentage of removable activity assumed in the dose modeling can have a large impact on estimated doses. As such, it might be necessary to confirm this assumption regarding the amount of removable contamination. However, measurements of smears are very difficult to interpret quantitatively. In general, the results of smear samples should be used for determining compliance with requirements that specifically require a smear measurement. In addition, they may be used as a diagnostic tool to determine whether further investigation is necessary.

8.7 Documentation

Documentation of the FSS should provide a complete and unambiguous record of the radiological status of the survey unit relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent evaluation of the results of the survey—including repeating, when possible, measurements at some future time. The documentation should comply with all applicable regulatory requirements. Additional information on documentation is provided in **Chapter 3, Chapter 5,** and **Appendix D.**

Much of the information in the final status report will be available from other decommissioning documents. However, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. This document should describe the instrumentation or analytical methods applied, how the data were converted to DCGL units, the process of comparing the results to the DCGLs, and the process of determining that the DQOs were met.

The results of actions taken as a consequence of individual measurements or sample concentrations in excess of the investigation levels should be reported with any additional data, remediation, or resurveys performed to demonstrate that issues concerning potential areas of elevated activity were resolved. The results of the data evaluation using statistical methods to determine whether release criteria were satisfied should be described. If criteria were not met, or if results indicate a need for additional data, appropriate further actions should be determined by the site management in consultation with the responsible regulatory agency. **Example 16** provides an example of a data interpretation checklist.

Example 16: Example Data Interpretation Checklist

Convert Data to Standard Units

______ Structure activity should be in becquerels/square meter (Bq/m^2) (decays per minute [dpm]/100 square centimeters [cm^2]).

______ Solid media (soil, building surfaces, etc.) activity should be in in Bq/kilogram (kg) (picocuries/gram [pCi/g]).

Evaluate Elevated Measurements

______ Identify elevated data.

______ Compare data with derived elevated area criteria.

______ Determine need to remediate and/or reinvestigate elevated condition.

______ Compare data with survey unit classification criteria.

______ Determine need to investigate and/or reclassify.

Assess Survey Data

______ Review data quality objectives (DQOs), measurement quality objectives (MQOs), and survey design.

______ Verify that data of adequate quantity and quality were obtained.

______ Perform preliminary assessments (graphical methods) for unusual or suspicious trends or results—investigate further as appropriate.

Perform Statistical Tests

______ Select appropriate tests for the radionuclide.

______ Conduct tests.

______ Compare test results against hypotheses.

______ Confirm power level of tests.

Compare Results to Guidelines

______ Determine mean or median concentrations.

______ Confirm that residual activity satisfies guidelines.

Compare Results with DQOs and Measurement Quality Objectives (MQOs)

______ Determine whether all DQOs and MQOs are satisfied.

______ Explain/describe deviations from design-basis DQOs/MQOs.

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