YERINGTON MINE SITE WORKER RADIOLOGICAL DOSE ASSESSMENT

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TABLE OF CONTENTS

		Page
I.	SUMMARY	3
II.	SCOPE	4
III.	BACKGROUND	6
	III.a. Natural Radiation Background	6
	III.b. Verington Mine Site	7
	III.c. Radiological Assessment	9
IV.	DOSE PATHWAY ANALYSIS	13
	IV.a. Inhalation of Suspended, or "Misted," Droplets and Particulates	14
	IV.b. Ingestion of Misted Droplets and Particulates	14
	IV.c. Irradiation by Deposited Evaporator Solids	17
	IV.d. Inhalation, Ingestion, and Irradiation - Sediment Material	17
V.	WORKER DOSE ESTIMATES	17
VI.	CONCLUSIONS	23
VII.	BIBLIOGRAPHY	25

LIST OF TABLES

Table 1.	Worker Annual Committed Effective Doses	3
Table 2.	Effective Dose Equivalents, H_E, from Exposure to Natural Sources	7
Table 3.	Dose Pathways Considered for the Yerington Mine Site Bounding Dose Assessment	14
Table 4.	Soil and Sediment Sample Results, pCi/g dry	19
Table 5.	Worker Time and Motion Data	20
Table 6.	Fractional Integrated Concentrations	21
Table 7.	Worker Total Dose Equivalents by the Evaporator Pathways	22
Table 8.	Inhalation Screening Dose Conversion Factors	23
Table 9.	Worker Sediment Inhalation Doses (H_E, mrem y^{-1})	23
Table 10.	Worker annual committed effective doses (H_E, mrem y^{-1})	24

LIST OF FIGURES

Figure 1.	Examples of a Decrease in Dose with Increasing Distance	12
Figure 2.	EVAP 320 on the left and Turbomist on the right, from the manufacturer web-sites	16

I. SUMMARY

This report conveys the results of a highly conservative radiological dose assessment for workers that performed maintenance and other onsite operations at the Yerington Mine site. The purpose of this study is to determine: 1) whether site workers have been exposed to radiation in the form of technologically enhanced naturally occurring radioactive material (TENORM[1]), and 2) if exposure to radiation occurred, whether the whole body doses estimated as a function of worker environment exceed the regulatory limit for the public (100 mrem in one year[2]). The total effective dose equivalent was determined for each of five workers, for the following years: 2000-2003. This report was prepared with assumptions that are so conservative as to be bounding. **Even so, it can be seen that no worker received an exposure to TENORM at the Yerington Mine site that was in excess of the annual dose limit for the general public through any combination of potential routes for exposure (Table 1).**

Table 1. Worker annual committed effective doses (H_E, mrem y^{-1})

Worker:	2000	2001	2002	2003
A	28	51	31	25
B	26	37	0	0
C	19	47	30	15
D	0	6	32	14
E	0	2	0	0

Because some of the studied, potential routes of exposure occurred in the past, it was necessary to reconstruct the actions and movements of site workers to determine if, where, when, and how much radiation exposure could have occurred. Actions performed as part of this assessment include: determination of possible routes and periods of exposure, the magnitude of the exposure, if any, and the magnitude of the dose a person would have received from the exposure in the context of a total effective dose equivalent (TEDE). Various documents were reviewed,

[1] TENORM is the term used to describe naturally occurring radioactive material that has been altered in concentration and/or location. See III.a. Natural Radiation Background.
[2] The millirem, mrem, is one one-thousandth of a rem. See II. SCOPE

including but not limited to laboratory analytical results of water and soil samples, evaporator technical manuals and operating procedures, worker time and motion data, and historical mine operations documents.

The doses reported in Table 1 are minute. As a point of comparison, each worker will receive up to 300 mrem a year to the whole body (internal and external doses combined) from natural radiation sources in Nevada, or 15,000 mrem in the fifty year commitment period required for regulatory dose estimates (NCRP 1987). Thus, their dose from "Mother Nature" would exceed even the largest total effective dose equivalent listed in Table 1 by up to an order of magnitude. It is quite likely that many workers experienced higher doses in one day from background radiation than they would have conceivably incurred in an average workday at the Yerington Mine site. Finally, it should be noted that, in the context of these bounding dose estimates, actual worker doses were much lower; additional data and effort would be required to estimate actual doses, but such effort is unwarranted, given the small bounding doses estimated in this study.

II. SCOPE

A complete radiological dose assessment involves several steps (See III.b. Radiological Assessment). The most important step is to assess the dose to an individual from all sources of exposure if it is suspected that radiation well in excess of background levels is present. Dose is the index by which the probable risk of all present or future health effects may be postulated. In the health physics profession, an absorbed "dose" is a quantity of energy absorbed by some portion of an organ or tissue of the person in question (Cember 1996, Turner 1995). The *rad* is the traditional unit for quantification of radiation absorbed dose. In the context of ionizing radiation, absorbed dose (usually just referred to as dose) is adjusted for the quality of the radiation, i.e., multiplication by a quality factor[3], and this dose equivalent (traditional unit – *rem*) is used by qualified persons to make a judgment about the potential someone exposed to a particular kind of radiation has for suffering short-term or long-term health effects. If an

[3] Quality factor is a method used in radiation protection to convert absorbed dose quantities to dose equivalent quantities. Quality factors make all radiations equivalent (thus the term dose equivalent) with respect to the expected amount of biological change afforded by a dose.

individual does not receive a dose well in excess of the natural radiation background, then no risk of health effects may be assigned[4].

One standard practice during a radiological dose assessment is to calculate the "bounding" set of doses for a potentially exposed population. A bounding dose estimate is determined in such a highly conservative fashion that a potentially exposed individual could never actually incur such a dose. Bounding dose estimates are usually determined at the outset of a study as an aid in judging whether a more detailed assessment effort is even warranted. If the bounding doses are so low as to be considered negligible from a radiation health standpoint, then the study usually goes no further.

We calculated a set of bounding dose estimates for each of a set of potentially exposed individuals (hypothetical workers) at the Yerington Mine site based on the information reviewed, as discussed above. The bounding conditions we imposed were:

- 2 m s^{-1} wind speed and F-2 atmospheric stability class (stable) 100% of the time, i.e., able to produced higher ground level concentrations than the Yerington site worst-case meteorology,
- all of the material blowing at each worker 100% of the time,
- all uranium was soluble,
- employees worked and remained in the plume at its stagnation point (which occurred more than 30 feet up in the air, where its centerline velocity fell below 10% of its initial velocity, and
- all of the uranium was in respirable size droplets or respirable size dry particles (1 micrometer was assumed for the dose conversion factors used). Additional assumptions as to the worker time of exposure and distance-to-source were taken from provided

[4] It is a commonly held misconception that "there is radiation, therefore there is harm." In actuality, the passage of radiation through living material will produce chemical changes, the majority of which are harmless to the individual as a whole. The International Commission on Radiological Protection (ICRP) distinguished between four terms in an attempt to achieve some clarity on this subject: change, damage, harm and detriment. Changes, which occur naturally thousands of times an hour in the human body, may or not be harmful. Damage represents some degree of deleterious change; however, the damage may be deleterious to the effected region, e.g., a cell, while being completely inconsequential to the organism as a whole (the person with the cell). Harm is used to describe those deleterious changes (damage) that will affect the whole organism or its offspring. Finally, detriment combines probability, severity, and time of expression of harmful effects. It is this final term that receives the most attention in a retrospective radiological dose or risk assessment (ICRP 1990).

employment record synopses and it is our understanding that these are conservatively high-biased, as well. A complete list of all parameters used in the dose assessment is provided in V. WORKER DOSE ESTIMATES.

An additional benefit of bounding calculations is that, as the name implies, bounding calculations "bound" any potential uncertainties associated with more detailed calculations that may be performed. Bounding calculations should not be confused with conservative or "worst case" dose estimates. That is, conservatism in dose estimation is achieved by calculating the highest possible dose that may be achieved using approved methodology and sound professional judgment. In addition to being a responsible health physics practice, this is a directive of several agencies (NRC 1992). Bounding estimates differ from worst-case estimates because it is understood that the bounding dose could never occur. Worst-case scenarios, while highly conservative, do contain some possibility, although highly remote, of occurrence. Worst-case dose estimation is useful for planning purposes, for *a priori* estimation, or dose projection for some process in the future. Such a system of estimation should not be used for *a posteriori* dose assessments, or dose reconstruction after the fact, because actual data exists concerning what, where, how, and when the people in question may have been exposed.

III. BACKGROUND

III.a. Natural Radiation Background

Radiation exposure to all members of the general public occurs continually. People are exposed to three broad categories of radioactive sources: natural radiation, technologically enhanced natural radiation, and anthropogenic (man-made) sources. Natural radiation can be further subdivided into terrestrial, cosmic, and cosmogenic sources. Terrestrial radionuclides include the uranium-, thorium-, neptunium- and actinium-series, as well as a few non-series isotopes, e.g., K-40 and Rb-87, which occur in the air, soil and water throughout the entirety of the earth (NCRP 1987). Cosmic radiation includes those particles and rays, which originate in the solar system and beyond, that reach the earth. Cosmogenic radionuclides are those formed as a result of cosmic radiation interactions in the atmosphere, like H-3, C-14 and Na-22. Finally, TENORM refers to terrestrial NORM that has been concentrated and/or exposed to the

accessible environment through human activities. Annual dose equivalents due to these natural background sources vary from around 300 mrem in the United States (Table 2) to as high as approximately 2,700 mrem in Kerala, India.

Table 2. Effective dose equivalents, H_E, from exposure to natural sources, as averaged over the United States population, per annum (NCRP 1987).

Source:	H_E, mrem y^{-1}:
Terrestrial	28
Cosmic	27
Cosmogenic	1
Inhalation	200
Internal	39
Total:	~300

As can be seen in Table 2, external doses primarily result from exposure to gamma rays of cosmic and terrestrial origin. Internal doses are completely dominated by inhalation of the short-lived progeny of Rn-222 ("inhalation" in the table above). Further internal exposure occurs when the body irradiates itself from materials incorporated into a person's tissues ("internal" in the table above). This is understandable when we consider nuclides such as the H-3 and C-14 (above) are incorporated into the human bodies as a normal part of the metabolism – C-12 and C-14 look like carbon to the body because the human body does not distinguish between nuclei, only atoms.

III.b. Yerington Mine site

The Yerington Mine is located at Weed Heights, in Lyon County, Nevada, approximately 80 miles south-southeast of Reno. Activities that have taken place over the life of this site include exploration, development, and open pit mining of a large, oxidized-copper ore deposit. From 1952 to 1978 mined copper oxide ore was leached with a sulfuric acid solution and the copper was recovered as cement copper. This cement copper was then shipped off to a smelting facility and then to another facility for further refinement.

The industrial facility at the Yerington Mine site consisted of a variety of units. A large open pit mine was the source of the basic ore, which was blasted from its surroundings following removal of overburden. Historically, ore material was then divided into three categories and piled separately: the material containing less than 0.2-percent copper was classified as waste and piled furthest from the plant (to the north of the pit). The rock containing 0.2- to 0.4-percent copper was piled separately, nearer the plant, and the material containing 0.4-0.6-percent copper was stockpiled nearest the plant.

At the plant the ore was milled, starting with the primary crushing machine. Once the initial crushing was completed, the ore was stored in a pile where it was subsequently blended with other grades or ore from other parts of the pit. Ore drawn off this coarse ore-storage pile was delivered to the secondary crushing unit, where it was run over a series of eight screens and then delivered to the leaching vats by a series of three conveyors. Prior to leaching, the ore in each vat underwent agglomeration and bedding to ensure no segregation or channeling of solution or blockage of the circulation of the leaching solution. The process of bedding, leaching, draining the ore, followed by excavation of the residue, was an eight day process and took place in eight 12,000 ton concrete tanks.

The pregnant-copper solution was stored in two 286,000 gallon tanks, and then pretreated and sent to the cementation part of the plant where it was precipitated. The cemented copper was then cleaned and rinsed in several processes and heated to lower the moisture content. Once dry, the cement copper was loaded from a drying hearth into specially designed trucks and hauled off to the smelter.

From 1989 to 1999 copper oxide ores were mined from low grade stock piles, vat leach tailings and the Macarthur pit. The mined copper ores were stacked in heaps on a total of five lined heap leach pads. Copper was extracted from the leach pad heaps with a dilute 1% sulfuric acid solution. The resulting pregnant leach solution (PLS) was collected in catchment ponds at each of the individual heaps. The copper bearing PLS solution was then pumped to a solvent extraction and electrowinning plant (SXEW). Using an organic reagent and kerosene the copper was extracted from the PLS. The copper was then stripped from the organic reagent with a

strong sulfuric acid solution, which produced a copper-bearing electrolyte. The copper was then electrowon from the solution and 99.99 fine copper sheets were produced as a final product. After the copper was extracted from the PLS it was circulated back to the heaps for reuse. This was a zero discharge process.

The copper heap leach and SXEW operation ceased copper production in 1999 and was put on a care and maintenance status. SRK Consulting was contracted by the Nevada Division of Environmental Protection to manage the leach pad drain down fluids at the site. As a part of the fluid management system in 2000, five electric powered evaporators were installed at one of the heap leach pads to enhance fluid evaporation. SRK Consulting has managed the heap leach fluids since January 2000 on a continual basis. It is anticipated that the site will require some level of fluid management over the next several years.

Site historical documents indicate that uranium salts accumulated in the evaporation ponds and that uranium is present in the groundwater at the Yerington Mine site at background levels (SRK 2003). Currently identified mine site-features that have NORM-containing groundwater evaporation salts include the evaporation basins, enhanced evaporation area, and the leach pads. In addition, the pregnant leachate solution (PLS) pond sediments may have a NORM component since groundwater was used for makeup volume in the leach extraction process and the PLS was recycled over the leach pads. The radiological dose assessment conducted for this study included potential exposures to five site workers from the enhanced evaporation operation and the pond sediments.

III.c Radiological Assessment

A radiological dose, D, may be determined by actually measuring and/or assessing the following:

$$STU=D \tag{1}$$

In this expression, S stands for the source term, T the transport factor used to characterize movement of the radioactive source material to the point of interest, and U the usage factor,

which describes the accumulation of a nuclide in a medium to which the person in question has been exposed.

Everything on the left side of the equation expressed above, which is generally described as a dose pathway, requires either measurement or assumption of the values that go into the calculation (NAS NRC 1995). Qualified measurement data should always be used in place of assumptions where those data are available. Thus, inhalation, ingestion and external exposure dose assessments were derived from applicable measurement data, where available. Such data would represent the "S," "T," and even possibly the "U" factors in Equation 1 above, depending on the nature of the measurement.

As indicated above, a radiological dose assessment begins with a determination of the source term. The source term encompasses both the identity and the radioactivity of any radioactive nuclides present at the point of emission. Radioactivity is a term we use to describe an amount of radioactive material. Each different kind of radioactive atom has its own unique rate of decay; thus, the need for determining the identity of any radioactive elements present at the source. This decay rate is used with knowledge (or an assumption) as to the number of radioactive atoms present, to calculate the radioactivity of a source.

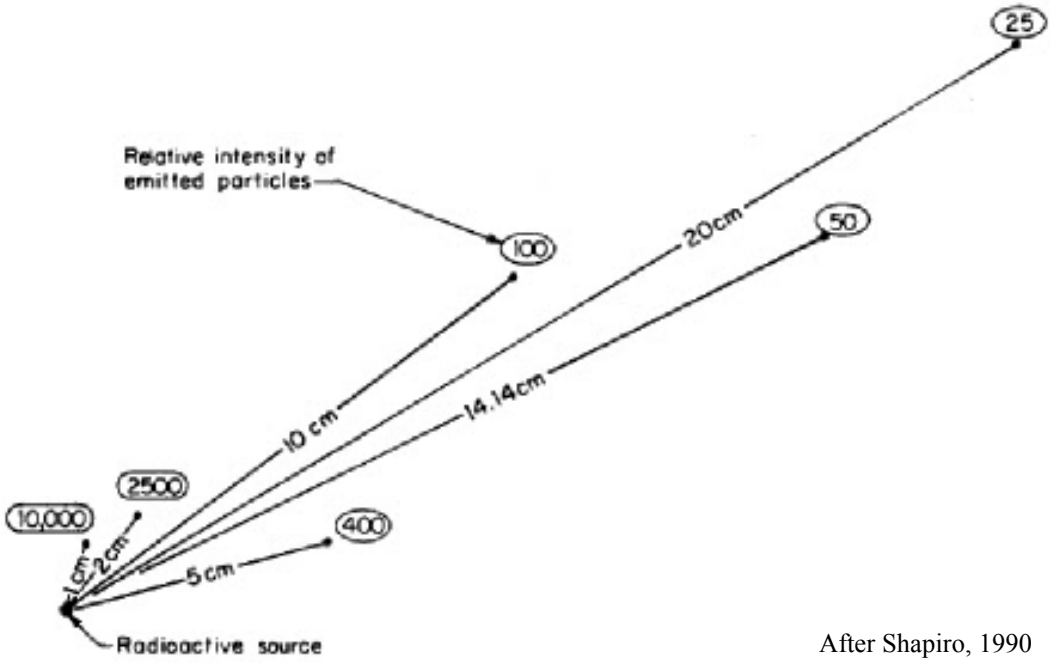
Radioactivity is a very important quantity in dose assessment. How much something might be expected to decay is also a description of how much energy is introduced into the dose pathway, this energy being in the form of radiation as previously discussed. Since a radiological absorbed dose is defined as energy deposited per unit mass it stands to reason that low radioactivity makes for a low energy-introduction rate, which will result in a low-dose-rate.

It should be noted that higher activity does not automatically result in the potential for elevated dose either. For example, Rn-222 (a gas) has such a short half-life, 3.8-days, that it may decay into Po-218 (a solid), prior to diffusing out of a formation, thus rendering the nuclide and any other progeny relatively immobile. This is to say that a radon atom may decay so rapidly as to have effectively removed itself and any further progeny from producing an environmental exposure to humans.

One must also know the identity of any radionuclides posed in an exposure scenario because, as with the aforementioned decay rate, each radioactive nuclide emits a unique combination of particles and energy (radiation). If the emitted radiation poses an insignificant threat to people at the end of the dose pathway, because of low yield, slow decay rate, low particle energy, improper chemical form etc., then it should be excluded from further consideration. Such professional judgment on the part of the radiological dose assessor speaks to the importance of making the correct assumptions when determining which possible dose pathways should be investigated.

Once we know the identity and amount of radioactive material present we must start to determine how much of that material and/or its emitted radiations make it to the point of interest. The distance between the source of radiation and the person in question is a necessary first-step in determining the transport and fate of a nuclide for a given dose pathway.

The distance between a source of radiation and some point beyond the source is important in two ways. First, if the dose is the result of an external irradiation, particles emitted by the radioactive substance (alphas, betas, gammas etc.) must get from point "a" to point "b" in the dose pathway. The number of particles reaching from the source to the receptor falls off very rapidly with distance under most circumstances (Shapiro 1990). Since these particles carry the energy that would become the dose, the dose rate falls off rapidly with distance, as well. This reduction simply happens because the particles are more spread out as one gets further away from the radiation source. Simply geometry illustrates this as shown in Figure 1.



After Shapiro, 1990

Figure 1. Examples of a decrease in dose with increasing distance, i.e., geometric attenuation.

Some radionuclides pose a potential internal hazard rather than an external irradiation hazard; this is the second instance in which distance may factor into a dose assessment. In this case the radioactive atoms, rather than the radiation emitted, must reach the person in question. Distance is once again a critical determinant in the dose pathway because gases and particles must first reach the person at the end of said pathway before they may be of any potential harm. Gases and particles will diffuse and mix convectively into the atmosphere from their point of origin, and will quickly begin to settle out, analogous to the "spreading out" described above for radiation. The distance it takes for a given concentration of radionuclide to settle out will be dominated by meteorological and geological conditions (wind speed, atmospheric stability, thermal gradients, surface roughness, vegetation, rainfall, etc.) and physical properties of the particles such as size, density, shape and charge.

Physical properties of the radioactive atoms under study also determine whether or not the airborne substance poses any internal hazard. For inhalation doses, even when a particle reaches a person it must be of respirable dimension – some particle sizes are more optimal than others for penetrating the human respiratory tract. Put another way, many of the particles a person might be exposed to are too large to be respirable (a term that indicates penetration to the deep lung);

some are even too large to be inhaled (a term that indicates passage through the mouth or nose). Beyond this, properties such as chemical form and half-life again become important. That is, even if a particle reaches the body, and it is of the right size and form to be distributed within the body, it must decay for there to even be a potential for harm. The mere presence of a radioactive atom in the body does not imply that harm has or will be done to that body. Soluble radioactive chemicals, which are those most likely to enter circulation in the body, are also among those most likely to be eliminated from the body. If a radioactive atom passes from the body before it decays then there has been no dose deposited, even though the atom was in the body at some point. Oftentimes, uranium is highly soluble in the body and typically passes through the body quickly, with little absorption (NRC 1986).

In addition to the distance between source and person, the physical nature of emitted radiation will also determine its penetrating ability. As has been stated previously, particles will spread out as they transit away from the source and only some fraction of these radiations will actually be headed in the direction of the receptor. Even though these particles are headed in the "right" direction some will not make it because they will have transferred all the kinetic energy to surrounding materials such as the air, clothing etc. and if no energy is deposited then there can be no radiation absorbed dose.

IV. DOSE PATHWAY ANALYSIS

This chapter contains our pathway analyses and a description of each of the factors above as they pertain to a particular exposure scenario. In general, one has to consider pathways that might release particulate or gaseous radioisotopes to the environment, which may be subsequently inhaled or ingested, as well as direct exposure to gamma and some beta ray-emitting materials. Enhanced evaporation operations were studied for their material release and external radiation exposure potential. In addition, radioactivity concentration results for water and composite samples were investigated for their material release and external radiation exposure potential. Pathways considered in this study are listed in Table 3.

Table 3. Dose pathways considered for the Yerington Mine site bounding dose assessment.

Dose Pathway:	Potential Route of Exposure:
Inhalation of suspended droplets from evaporators	Internal
Ingestion of suspended droplets from evaporators	Internal
Radiation from deposited material (evaporator salts)	External
Inhalation of resuspended sediment	Internal
Incidental ingestion of sediment	Internal
Radiation from sediment material	External

IV.a. Inhalation of suspended, or "misted," droplets and particulates

Radioactive material suspended in the air by the evaporators could be inhaled by workers or others in the vicinity of the evaporators. In the limit of a bounding study, this is the major pathway for the intake of material and is dealt with in-depth in Section V. However, it is our opinion that the actual *uptake* of TENORM as a result of exposure to evaporator mist is by the ingestion pathway, rather than the inhalation pathway, following an inhalation *intake* (see next section). The assumption that radionuclides are taken up by the body by the inhalation pathway following an intake is highly conservative, given the limited biodistribution of soluble uranium in the human gut; thus, actual doses will be much lower than those presented in this report. In calculating reported doses this way, we have bounded the internal dose component of the evaporator exposure pathway because the actual uptake will most likely be some combination of uptake by inhalation and ingestion, with the ingestion pathway dominating given the size of the misted droplets that might reach a receptor (worker).

IV.b. Ingestion of misted droplets and particulates

The injection rate of machines used for production was slightly less than 3 grams of water per cubic meter in the spray plume final volume at a water feed rate of 20 gallons per minute. Air is able to carry water vapor in concentrations ranging from 13 g m^{-3} to 45 g m^{-3} over the temperature range of 60 to 100 °F. If the relative humidity was low, and the radiant heat was sufficiently high, total evaporation of spray droplets within the jetting plume was possible. At a measured concentration smaller than 10 mg uranium per liter of water, the uranium concentration in the air at 10 m downstream from the fan exit plane was less than 0.024 milligrams per cubic

meter of air (mg m^{-3}). At a measured activity smaller than 7,000 pCi per liter of water, the activity in the air was less than 21 pCi per cubic meter of air.

The ACGIH TLV for Uranium is 0.2 mg m^{-3} as uranium for both soluble and insoluble compounds. The OSHA PEL is 0.25 mg m^{-3} as uranium for insoluble compounds and 0.05 mg m^{-3} as soluble compounds (uranyl nitrate and uranium hexaflouride). The NIOSH REL is 0.2 mg m^{-3} with a STEL of 0.6 mg m^{-3} for insoluble compounds as uranium, and 0.05 mg m^{-3} for soluble compounds as uranium. 10 CFR 20 limits the weekly intake of soluble uranium to 10 mg. At a respiration rate of 1.2 m^3 hr^{-1}, and a bounding concentration of 0.024 mg m^{-3}, a 40 hour week involves a bounding uptake less than 1.2 mg wk^{-1}. The in-plume centerline concentration was less than 24 µg m^{-3} of air, well below applicable occupational exposure limits. At ground level and at more distant locations all concentrations would be much lower than this.

On a day with low to moderate relative humidity both the TurboMist and the EVAP320 were capable of generating 20 gallons per minute of water droplets and evaporating most of this to completion. It is reasonable to believe that on a worst case operating day, each machine would evaporate at least 50% of the water that flowed through it in the axial distance between the nozzle and the 10 to 14 meter maximum height reached by the droplet plume. Under this assumption, the distribution of droplets at the peak of the trajectory would contain 370 micrometer droplets, which had shrunk from their original 500 micrometer diameter due to loss by evaporation of half their mass. All initial droplets of diameter smaller than 10 micrometers are assumed to have evaporated in the plume as it rises. However, there will be some droplets that shrink into that size range at the peak altitude achieved by the plume.

Fig 2. EVAP 320 on the left and Turbomist on the right, from manufacturer web-sites.

Droplets larger than 100 micrometers in diameter fall towards the ground, evaporating as they settle. When they reach some size smaller than 50 micrometers, they may be entrained by atmospheric turbulence and cease falling but continue evaporating. The net result is that, within a few 10s of meters from the source, the ground level concentration of droplets is made up of drops similar in size and distribution to those encountered during light to moderate rain.

There is negligible mass in inhalable-size droplets for two reasons. First, each droplet contains very little mass. Second, there are not many such droplets near the ground. The enhanced evaporation field had five to six spray guns that were operated in a fashion that precludes respirable size droplets in the breathing zone of personnel working a few 10s of meters from an operating machine. Personal exposure, if any, would be dominated by droplets much larger than respirable in size. Thus, while one would be able to entrain and inhale some of these large, mist droplets, the droplets would impinge on the respiratory system's walls in the human head and any uptake would probably result from involuntary swallowing of the residue.

The bounding exposures estimated for this study are calculated under the highly conservative assumptions that all uranium was soluble, that employees worked in the plume at its stagnation point, where its centerline velocity fell below 10% of its initial velocity, and that all of the uranium was in respirable size droplets or respirable size dry particles (1 micrometer was

assumed for the dose conversion factors used). This overstates the respirable concentration and it overstates the biological availability of uranium compared with more realistic scenarios.

IV.c. Irradiation by deposited evaporator solids

External exposure from dispersed evaporator solids will be insignificant given the radioactivity concentration values in the provided samples ("SLT" in Table 4). No further consideration was given to this pathway.

IV.d. Inhalation, ingestion, and irradiation – sediment material

Inhalation of sediment material was estimated by using the screening methods from NCRP 129 (NCRP 1999) combined with the radioactive material concentrations in the sediments from the SRK data discussed in Section V. As with the evaporator solids, external exposure from sediment material will be insignificant given the radioactivity concentration values in the provided samples (See Table 4). No further consideration was given to this pathway. Ingestion of this material will be minimal given that the workers are not spending a full work-day in the vicinity of the sediments and are assumed to follow appropriate industrial hygiene practices, such as washing their hands before eating lunch.

V. WORKER DOSE ESTIMATES

The enhanced evaporators, which are modified snow-making machines, entrain pregnant leachate solution (PLS) in an air stream from a fan. Alternatively, another design employed at the Yerington Mine site mixed PLS with compressed air in a venturi. Both evaporator designs will loft the air/water mixture into the air at least 12 m, and possibly as high as 20 m (Turbomist vendor data). Depending on ambient temperature and humidity conditions, between 20% and 96% of the water will evaporate, with 50% evaporation being a reasonable average evaporation rate (Turbomist and 320 Evaporator vendor information). Water that does not evaporate will rain out in the vicinity of the evaporator, within roughly 200 ft. Water that does evaporate will leave behind particulates from the dissolved solids in the water to be transported downwind

depending on ambient meteorological conditions. A simple Gaussian plume model was chosen to calculate this downwind transport and dispersion.

Data provided by SRK were used to determine the operating characteristics of the evaporators (Attachment 1). SRK also provided time and motion data for the workers (Attachment 2), which enabled determination of how long the various workers were in the vicinity of the evaporators. Listed below are the assumptions used in the calculations.

- The evaporators had PLS water flowrates of either 40 gpm or 20 gpm, depending on the time period.
- The uranium concentration in the PLS water was 8.12 mg l^{-1} based on data supplied by SRK.
- The natural uranium inhalation Allowable Limit on Intake is 0.05 µCi (10 CFR 20 Appendix B).
- The natural uranium Derived Air Concentration is 2e-11 µCi ml^{-1} (10 CFR 20 Appendix B).
- On average, 50% of the water pumped through the evaporators evaporates.
- The solid particulates left after evaporation of the water can be treated as originating at a height of at least 12 m since this is the minimum loft height of the evaporators.
- The workers have a breathing rate of 20 l min^{-1}.
- It was assumed that there were 5 evaporators operating in 2000 and 2001. At times there may have been 6 evaporators operating, but the sixth unit was not in operation as much of the time and all of the evaporators were operated less than full-time during the regular work day. During 2002 and 2003, three evaporators were assumed to be operating for the same reasons.
- During 2000 and the first part of 2001, the evaporators were operated at a water flow rate of 40 gpm (2001a in the Tables). After that, the flow rate was decreased to 20 gpm (2001b in the Tables).
- From September 16 2003 through October 16 2003 the pumping rate was increased to 100 gpm combined at 90 psi.

SRK-provided water and soil/sediment sample results were used to calculate the doses from external exposure, inhalation, and ingestion (Attachment 3). Table 4, below, details the results for the soil/sediment samples.

Table 4. Soil and Sediment Sample Results, pCi g^{-1} dry sample

	PHI	PHII	SLT	MEG	YBK	VLT
Ra-226	ND*	ND	5.4 ± 0.3	2.3 ± .02	ND	ND
Bi-214	ND	ND	5.4 ± 0.3	2.3 ± 0.2	ND	ND
Th-234	6.6 ± 1.2	34.3 ± 2.7	9.4 ± 1.5	10.1 ± 1.3	ND	27.6 ± 1.8
Pb-214	2.6 ± 0.2	ND	6.1 ± 0.3	3.1 ± 0.2	2.0 ± 0.2	ND
Ra-228	ND	ND	4.5 ± 0.4	3.6 ± 0.6	ND	ND
Ac-228	ND	ND	4.5 ± 0.4	3.6 ± 0.6	ND	ND
Pb-212	ND	ND	2.6 ± 0.1	ND	ND	ND
K-40	20.1 ± 1.4	ND	22.8 ± 1.4	26.7 ± 1.5	37.9 ± 1.8	ND

ND = Not Detected

The VLT water sample, the water being evaporated, was reported as containing 8.12 mg l^{-1} of natural uranium, 18.8 ± 1.4 pCi l^{-1} of Ra-226, and 7,000 ± 488 pCi l^{-1} of gross alpha activity. Based on these results, the uranium is not in equilibrium with its progeny; there is only 19 pCi l^{-1} of Ra-226 and 8.12 mg l^{-1} of natural uranium is equal to over 2,700 pCi l^{-1} of both U-238 and U-234. For purposes of calculating the dose from inhalation, only the dose from the uranium was considered since it dominates the activity present and is not in equilibrium with its progeny.

Yerington facility workers had four job task-assignments that brought them into the vicinity of the evaporators: checking the water pumps, checking the electrical generators, checking the evaporators, and repairing the evaporators. For this dose reconstruction, these jobs have been combined into two classifications: checks and repairs. The checks are brief "drive-bys" during the day and startup and shutdown of the equipment each day. The repairs are more sustained activity in the vicinity of the evaporators to perform maintenance.

In order to assess the worker dose during the checks, extremely conservative assumptions were made. First, the worker was assumed to be downwind of all of the evaporators during approach and departure from the area while performing the checks. Thus, the worker was exposed to material from all of the evaporators. Second, the worker was treated as being at the optimal

distance downwind in terms of receiving the highest dose for the entire time period of performing the checks. This distance, determined to be 0.6 km, is greater than the actual distance the worker would have been from the evaporators for most of the time while performing equipment checks. Third, during repairs, the worker was assumed to be downwind of the other four evaporators and the evaporators were assumed to be evenly spaced 250 feet apart. These bounding assumptions are extremely conservative because it would not be possible to be downwind of all of the evaporators at once, especially at the optimal distance from each of them. Table 5, below, details the time each worker spent performing each task.

Table 5. Worker Time and Motion Data

Worker	Year of Operation	2000	2001a*	2001b**	2002	2003
A	Total work hours	777	985.5	927.5	1922	1557
	Pump Check	8.051	9.084	9.132	19.011	14.858
	Genset Check	24.25	27.14	27.52	57.29	44.76
	Evap Check	18.199	18.29	18.372	38.247	29.894
	Repair Time	9	9.5	25.5	56	31
B	Total work hours	921	975	583		
	Pump Check	6.889	6.268	5.355		
	Genset Check	20.75	19.37	16.14		
	Evap Check	15.861	12.61	10.773		
	Repair Time	8	10	8		
C	Total work hours	734.5	1069.5	1169	2071.5	1628.5
	Pump Check	5.146	6.719	7.927	14.816	12.534
	Genset Check	15.5	20.26	23.88	44.63	37.76
	Evap Check	10.354	13.529	15.949	29.81	52.218
	Repair Time	2	11	14	30	13
D	Total work hours			36	2213	1606
	Pump Check			2.366	15.772	12.699
	Genset Check			7.13	47.52	38.25
	Evap Check			4.76	31.732	25.551
	Repair Time			5	42	26
E	Total work hours			54		
	Pump Check			1.245		
	Genset Check			3.75		
	Evap Check			2.505		
	Repair Time			0		

*2001 data for evaporator operation at 40 gpm
**2001 data for evaporator operation at 20 gpm

The fractional-integrated concentration of the particulates in air was calculated as a function of distance from the source based on the results of the Gaussian plume modeling effort using the HOTSPOT code (Homann 1994). Table 6 below lists these values for a selection of distances.

Table 6. Fractional Integrated Concentrations.

Distance (km)	(#-s/m^3)
0.076	1.20E-24
0.152	7.00E-09
0.229	4.20E-06
0.305	3.00E-05
0.4	7.10E-05
0.5	9.40E-05
0.6	9.80E-05
0.7	9.40E-05
0.8	8.60E-05
0.9	7.80E-05
1	7.00E-05

The fractional-integrated concentrations can be combined with the mass flow rates through the evaporators, taking credit for 50% evaporation, and the breathing rate of the workers, to determine the amount of material inhaled per unit time. The first four distances were chosen since they are the spacing between evaporators (250 feet each), in meters.

The amount of uranium inhaled during the checks was calculated and then used to determine that the committed effective dose equivalent would be 0.082 mrem hr^{-1}, per evaporator operating at 20 gpm, during the exposure period. This number was then multiplied by the number of evaporators operating, their flow rates, and the length of time each worker was in the vicinity of the evaporators to determine the dose to a given worker.

During the repair time period, the dose rate is lower because the worker is effectively "underneath" the plume of material since the material is thrown up into the air by the evaporators (see IV. DOSE PATHWAY ANALYSIS). The dose rate also varies as a function of the number of evaporators operating and their distance from the worker. Table 7, below, details the dose received by each worker, providing the total annual doses and the breakdown between checks and repairs.

Table 7. Worker total dose equivalents by the evaporator pathways (H_E, mrem y^{-1}).

Worker	Category	2000	2001	2002	2003
A	Total	21	73	14	11
	Checks	21	37	14	11
	Repair		36		
B	Total	18	71		
	Checks	18	24		
	Repair		47		
C	Total	13	34	11	
	Checks	13	29	11	
	Repair		5		
D	Total		4	12	
	Checks		3	12	
	Repair		1		
E	Total		1		
	Checks		1		
	Repair		0		

For calculation of the dose from the inhalation of sediment in the vicinity of the operation, the concentration for the SLT sample, which had the highest amount of radioactive material in it, was used. The methodology of NCRP 129 takes into account the ingrowth of progeny over a finite period (1000 years). From the sample data, the concentration of Th-234 was used as the concentration of U-238, and the Ra-226 and Ra-228 concentrations were used since the other radionuclides present (except K-40) are the progeny of one of these three. Table 8 below lists the median inhalation screening dose-conversion factors for "construction settings" from NCRP 129, which takes into account resuspension by disturbing the ground.

Table 8. Inhalation Screening Dose Conversion Factors

Nuclide	Dose Conversion Factor (mrem hr^{-1} per pCi g^{-1})
U-238	1.7e-3
Ra-226	1.1
Ra-228	1.5e-2

To make a bounding dose assessment, the total time working each year for each of the workers was used with the SLT radioactive material concentrations and the Table 8 dose conversion factors to calculate a bounding dose. Table 9 lists the doses for each worker and each year.

Table 9. Worker Sediment Inhalation Doses (H_E, mrem y^{-1})

Worker	2000	2001	2002	2003
A	7	17	17	14
B	8	14		
C	7	20	19	15
D		3	20	14
E		0.5		

VI. CONCLUSIONS

The total effective dose equivalent was determined for each of 5 workers for the years 2000-2003. Even under conditions that are so conservative as to be bounding, it can be seen that no worker received an exposure to TENORM at the Yerington Mine site that was in excess of the aforementioned annual radiation dose limit for the general public (100 mrem) through any combination of potential routes for exposure. Additionally, bounding exposures to chemical toxicity of uranium were shown to be below the OSHA PEL. It should be noted that, in the context of these bounding dose estimates, actual worker doses were much lower; additional data and effort would be required to estimate actual doses, but we view this as a mathematical

exercise rather than a significant health risk study given the small bounding doses estimated in this study. Table 10 gives the total doses to the workers from every pathway.

Table 10. Worker annual committed effective doses (H_E, mrem y^{-1})

Worker:	2000	2001	2002	2003	Legal Limit
A	28	51	31	25	
B	26	37	0	0	
C	19	47	30	15	100
D	0	6	32	14	
E	0	2	0	0	

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