TABLE IV-7. GROSS SOILING DAMAGE COSTS BY MEDIUM SMSA's
(million $)

Medium SMSA's	GSCO1	GSCO2	GSCO3	GSCO4	GSCO5	GSCO6	GSCO7	GSCO8	GSCO9	TGSCO
66. ALB, NM	--	22.8	0.4	7.5	0.1	2.5	1.5	2.5	1.3	38.6
67. ANN, MI	--	16.4	0.3	4.5	--	1.3	0.9	1.6	0.7	25.7
68. APP, WI	--	18.9	0.4	6.2	0.1	2.0	1.2	2.0	1.0	31.9
69. AUG, GA-SC	--	16.7	0.2	0.3	--	1.0	0.8	1.5	0.6	24.8
70. AUS, TX	--	21.6	0.3	5.6	0.1	1.6	1.1	2.0	0.8	33.1
71. BAK, CA	--	25.8	0.6	11.8	0.1	4.4	2.2	3.1	2.3	50.6
72. BAT, LA	--	19.0	0.3	4.4	--	1.1	0.9	1.7	0.6	28.0
73. BEA, TX	--	22.8	0.3	5.1	--	1.3	1.0	2.0	0.7	33.3
74. BIN, NY-PA	--	21.8	0.3	4.8	--	1.2	1.0	1.9	0.6	31.5
75. BRI, CN	--	28.1	0.4	6.1	0.1	1.5	1.2	2.4	0.8	40.6
76. CAN, OH	--	28.2	0.6	10.2	0.1	3.5	2.0	3.2	1.9	49.6
77. CHA, SC	--	19.2	0.2	3.5	--	0.7	0.7	1.7	0.4	26.4
78. CHA, WV	--	18.1	0.4	6.7	0.1	2.3	1.3	2.1	1.2	32.2
79. CHA, NC	--	30.5	0.6	10.7	0.1	3.6	201	3.4	1.9	53.0
80. CHA, TN-GA	--	24.1	0.5	8.9	0.1	3.1	1.7	2.8	1.6	42.8
81. COL. CO	--	16.5	0.3	5.7	--	1.9	1.1	1.8	1.0	28.5
82. COL, SC	--	20.2	0.3	4.8	--	1.3	1.0	1.8	0.6	30.1
83. COL, GA-AL	--	15.5	0.2	3.0	--	0.6	0.6	1.3	0.3	21.7
84. COR, TX	--	19.6	0.4	7.1	--	2.5	1.4	2.2	1.3	34.7
85. DAV, IA-IL	--	28.9	0.7	12.5	0.1	4.6	2.4	3.5	2.4	55.2
86. DES, IA	--	22.4	0.4	7.0	--	2.1	1.3	2.3	1.1	36.8
87. DUL, MN-WI	--	19.9	0.3	5.3	--	1.6	1.0	1.9	0.9	30.9
88. ELP, TX	--	24.4	0.6	11.7	0.1	4.4	2.2	3.0	2.4	49.0
89. ERI, PA	--	19.4	0.4	7.1	0.1	2.5	1.4	2.2	1.3	34.4
90. EUG, OR	--	16.4	0.3	5.1	--	1.6	1.0	1.7	0.9	27.0
91. EVA, IN-KY	--	17.9	0.3	5.0	--	1.5	1.0	1.8	0.8	28.1
92. FAY, NC	--	12.2	0.2	3.0	--	0.8	0.6	1.1	0.4	18.4
93. FLI, MI	0.1	36.2	0.9	16.1	0.1	6.0	3.1	4.4	3.2	70.0
94. FOR, IN	--	20.5	0.3	5.7	0.1	1.7	1.1	2.0	0.9	32.3
95. FRE, CA	--	31.5	0.7	12.5	0.1	4.5	2.4	3.7	2.4	57.9
96. GRE, SC	--	21.7	0.4	0.1	1.8	1.2	1.2	2.2	1.0	34.4
97. HAM, OH	--	16.1	0.3	4.8	--	1.5	0.9	1.6	0.8	26.0
98. HAR, PA	--	31.5	0.5	9.0	0.1	2.7	1.8	3.1	1.4	50.2
99. HUN, WV-KY-OH	--	19.7	0.4	6.8	0.1	2.3	1.3	2.2	1.2	33.9
100. HUN, AL	--	15.3	0.2	3.6	--	1.0	0.7	1.4	0.5	22.7

TABLE IV-7 (Continued)

	GSCO1	GSCO2	GSCO3	GSCO4	GSCO5	GSCO6	GSCO7	GSCO8	GSCO9	TGSCO
101. JAC, MS	--	18.2	0.4	5.7	0.1	2.3	1.3	2.1	1.2	32.3
102. JOH, PA	--	19.8	0.4	7.2	0.1	2.5	1.4	2.3	1.3	35.0
103. KAL, MI	--	13.8	0.2	5.3	--	0.8	0.6	1.2	0.4	20.1
104. KNO, TN	--	21.0	0.6	10.9	0.1	3.7	2.1	3.5	2.0	54.0
105. LAN, PA	--	24.1	0.5	9.1	0.1	3.2	1.8	2.8	1.7	43.2
106. LAN, MI	--	26.5	0.5	7.6	0.1	2.3	1.5	2.7	1.2	42.3
107. LAS, NV	--	21.5	0.4	7.7	0.1	2.6	1.5	1.4	1.4	37.6
108. LAW, MA, NH	--	17.4	0.3	4.2	--	1.1	0.9	1.6	0.6	26.2
109. LITT, AK	--	24.5	0.4	5.7	0.1	2.0	1.3	2.4	1.1	38.4
110. LOR, OH	0.1	19.6	0.6	12.4	0.1	5.1	2.3	2.5	2.7	45.4
111. LOW, MA	--	13.9	0.3	3.7	--	0.6	0.6	1.2	0.3	19.5
112. MAC, GA	--	14.9	0.3	5.4	0.3	1.4	0.9	1.5	0.7	24.1
113. MAD, WI	--	21.2	0.3	5.8	0.1	1.7	1.1	2.1	0.9	33.1
114. MOB, AL	--	26.8	0.6	10.0	0.1	3.5	1.9	3.1	1.8	47.8
115. MON, AL	--	14.6	0.3	5.0	--	1.7	1.0	1.6	0.9	25.2
116. NEW CN	--	26.5	0.4	6.0	0.1	1.5	1.2	2.3	0.8	38.8
117. NEW, CN	--	14.3	0.2	3.3	--	0.9	0.7	1.3	0.5	21.2
118. NEW, VA	--	19.3	0.3	4.0	--	0.9	0.8	1.7	0.5	27.5
119. ORL, FL	--	32.0	0.5	8.8	0.1	2.6	1.8	3.1	1.4	50.3
120. OXN, CA	--	26.4	0.6	10.8	0.1	3.9	2.1	3.1	2.1	49.1
121. PEN, FL	--	17.4	0.4	6.5	0.1	2.3	1.3	2.0	1.2	31.1
122. PEO, IL	--	25.8	0.4	7.3	0.1	2.2	1.4	2.6	1.2	41.1
123. RAL, NC	--	15.9	0.2	3.3	--	0.8	0.7	1.4	0.4	22.7
124. REA, PA	--	24.3	0.5	9.9	0.1	3.6	1.9	2.9	1.9	45.1
125. ROC, IL	--	20.6	0.4	7.6	0.1	2.5	1.5	2.4	1.4	36.6
126 SAG, MI	--	15.8	0.4	7.1	0.1	2.6	1.3	1.9	1.4	30.6
127. SAL, CA	--	17.6	0.4	7.0	0.1	2.5	1.3	2.1	1.3	32.4
128. SAN, CA	--	20.9	0.5	8.6	0.1	3.1	1.6	2.5	1.6	38.9
129. SAN, CA.	--	16.9	0.4	6.9	0.1	2.5	1.3	2.0	1.3	31.5
130. SCR, PA	0.1	20.2	0.6	12.2	0.1	4.9	2.3	2.5	2.6	45.6

TABLE IV-7. (Concluded)

	GSCO1	GSCO2	GSCO3	GSCO4	GSCO5	GSCO6	GSCO7	GSCO8	GSCO9	TGSCO
131. SHR, LA	--	22.3	0.5	8.3	0.1	2.9	1.6	2.6	1.5	39.7
132. SOU, IN	--	20.7	0.3	5.7	0.1	1.7	1.1	2.0	0.9	32.7
133.. SPO, WA	--	22.9	0.5	8.0	0.1	2.7	1.5	2.6	1.4	39.6
134. STA, CN	--	15.0	0.2	3.2	--	0.8	0.7	1.3	0.4	21.6
135. STO, CA	--	21.6	0.3	4.9	--	1.21	1.0	1.9	0.7	31.6
136. TAC, WA	--	29.9	0.6	10.0	0.1	3.3	1.9	3.3	1.8	50.9
137. TRE, NJ	--	22.1	0.4	5.8	0.1	1.7	1.2	2.1	0.9	34.1
138. TUC, AZ	--	27.1	0.5	9.4	0.1	3.2	1.8	3.1	1.7	46.9
139. TUL, OK	--	38.2	0.7	11.5	0.1	3.6	2.3	3.9	1.9	62.3
140. UTI, NY	--	24.5	0.4	6.5	0.1	1.9	1.3	2.3	1.0	37.9
141. VAL, CA	--	17.8	0.3	4.0	--	1.0	0.8	1.6	0.5	26.1
142. WAT, CN	--	15.3	0.3	4.5	--	1.4	0.9	1.6	0.7	24.7
143. WES, FL	--	28.9	0.4	6.7	0.1	1.7	1.4	2.6	0.9	42.7
144. WIC, KS	0.1	31.8	0.8	15.2	0.1	5.8	2.9	3.9	3.1	63.7
145. WIL, PA	--	28.1	0.7	12.2	0.1	4.5	2.3	3.4	2.4	53.8
146 WIL, DE, NJ, MD	0.1	37.3	0.9	16.0	0.1	5.9	3.1	4.5	3.1	71.0
147. WOR, MA	--	25.0	0.4	6.7	0.1	1.9	1.3	2.4	1.0	38.8
148 YOR, PA	--	25.3	0.5	7.7	0.1	2.4	1.5	2.6	1.3	41.4
Total	3.3	1,821.9	34.2	616.3	5.2	198.2	160.3	195.4	105.4	3,204.3

TABLE IV-8. PER CAPITA NET AND GROSS SOILING DAMAGE COSTS ($) BY LARGE SMSA's, 1970

	SMSA	PCNSCO	PCGSCO
1.	AKR, OH	22.83	116.79
2.	ALB, NY	50.49	147.02
3.	ALL, NJ	29.23	128.49
4.	ANA, CA	39.01	132.39
5.	ATL, GA	24.46	119.42
6.	BAL, MD	66.15	156.45
7.	BIR, AL	92.29	184.03
8.	BOS, MA	42.48	137.98
9.	BUF, NY	54.19	147.52
10.	CHI, IL	73.94	166.21
11.	CIN, OH-KY-IN	41.16	135.74
12.	CLE, OH	104.65	196.22
13.	COL, OH	23.03	117.90
14.	DAL, TX	39.46	136.25
15.	DAY, OH	46.35	140.00
16.	DEN, CO	73.86	168.57
17.	DET, MI	70.00	160.00
18.	FOR, FL	12.58	125.00
19.	FOR, TX	31.10	128.61
20.	GAR, IN	38.23	127.65
21.	GRA, MI	18.74	110.95
22.	GRE, NC	27.98	123.51
23.	HAR, CT	23.80	143.22
24.	HON, HI	16.69	98.25
25.	HOU, TX	29.27	123.98
26.	IND, IN	20.45	117.12
27.	JAC, FL	18.34	113.42
28.	JER, NJ	28.24	133.33
29.	KAN, MO-KS	29.19	129.98
30.	LOS, CA	55.18	159.27
31.	LOU, KY-IN	68.08	160.82
32.	MEM, TN-AR	20.91	121.69
33.	MIA, FL	11.83	116.72
34.	MIL, WI	31.27	83.33
35.	MINN, MN	20.34	115.21.
36.	NAS, TN	53.42	148.06
37.	NEW, LA	22.85	116.63
38.	NEW, NY	36.26	138.78
39.	NEW, NJ	60.31	155.09
40.	NOR, VA	41.85	127.75

TABLE IV-8 (Concluded)

	SMSA'S	PCNSCO	PCGSCO
41.	OKL, OK	14,98	117.16
42.	OMA, NE-LA	62.96	154.81
43.	PAT, NJ	6.84	105.22
44.	PHI, PA-NJ	21.59	116.85
45.	PHO, AZ	95.87	186.98
46.	PIT, PA	61.22	156.18
47.	POR, OR-WA	29.83	133.80
48.	PRO, RI-MA	21.62	117.45
49.	RIC, VA	46.72	142.66
50.	ROC, NJ	39.01	124.58
51.	SAC, CA	10.99	110.86
52.	SAI, MO-IL	50.36	144.73
53.	SAL, UT	30.82	118.46
54.	SAN, TX	4.98	93.63
55.	SAN, CA	61.94	157.48
56.	SAN, CA	8.76	106.04
57.	SAN, CA	11.19	124.76
58.	SAN, CA	9.39	104.23
59.	SEA, WA	8.51	112.52
60.	SPR, MC-CT	12.64	109.81
61.	SYR, NY	43.08	135.22
62.	TAM, FL	23.89	127.34
63.	TOL, OH-MI	52.53	145.74
64.	WAS, DC-MD-VA	29.88	127.23
65.	YOU, OH	42.91	135.07

TABLE IV-9. PER CAPITA NET AND GROSS SOILING DAMAGE COSTS ($) BY MEDIUM SMSA'S, 1970

SMSA'S		PCNSCO	PCGSCO
66.	ALB, NM	30.70	122.15
67.	ANN, MI	18.38	109.83
68.	APP, WI	28.52	115.16
69.	AUG, GA-SC	10.67	98.02
70.	AUS, TX	16.22	111.82
71.	BAK, CA	60.49	153.80
72.	BAT, LA	9.47	98.25
73.	BEA, TX	9.49	105.38
74.	BIN, NY-PA	8.25	103.96
75.	BRI, CN	7.71	104.37
76.	CAN, OH	38.71	133.33
77.	CHA, SC	0.99	86.84
78.	CHA, WV	41.74	140.00
79.	CHA, NC	35.70	129.58
80.	CHA, TN-GA	42.30	140.33
81.	COL, CO	32.20	120.76
82.	COL, SC	9.91	93.19
83.	COL, GA-AL	2.93	90.79
84.	COR, TX	35.79	121.75
85.	DAV, IA-IL	56.20	152.07
86.	DES, IA	28.32	128.67
87.	DUL, MN-WI	18.11	116.60
88.	ELP, TX	55.99	136.49
89.	ERI, PA	37.88	130.30
90.	EUG, OR	28.17	126.76
91.	EVA, IN-KY	21.46	120.60
92.	FAY, NC	10.38	86.79
93.	FLI, MI	53.32	140.85
94.	FOR, IN	20.00	115.36
95.	FRE, CA	46.73	140.19
96.	GRE, SC	20.67	114.67
97.	HAM, OH	23.45	115.04
98.	HAR, PA	22.38	122.14
99.	HUN, WV-KY,OH	35.83	133.46
100.	HUN, AL	42.54	99.56

TABLE IV-9 (Continued)

SMSA		PCNSCO	PCGSCO
101.	JAC, MS	37.45	124.71
102 l	JOH, PA	38.401	133.08
103.	KAL, MI	8.42	99.50
104.	KNO, TN	37.50	135.00
105.	LAN, PA	41.56	135.00
106.	LAN, MI	20.90	111.90
107.	LAS, NV	38.83	137.73
108.	ALW, MA-NH	13.36	112.93
109.	LITT, AK	19.81	118.89
110.	LOR, OH	93.77	176.65
1110	LOW, MA	3.29	91.55
112.	MAC, GA	23.79	116.99
113.	MAD, WI	18.97	114.14
114.	MOB, AL	38.46	126.79
115.	MON, AL	33.83	125.37
116.	NEW, CN	9.83	108.99
117.	NEW, CN	10.10	101.92
118.	NEW, VA	5.14	94.18
119.	ORL, FL	20.56	117.52
120.	OXN, CA	62.13	180.51
121.	PEN, FL	39.09	127.98
122.	PEO, IL	22.22	120.18
123.	RAL, NC	6.14	99.56
124.	REA, PA	51.69	152.36
125.	ROC, IL	40.07	134.56
126.	SAG, MI	52.73	139.09
127.	SAL, CA	43.20	129.60
128.	SAN, CA	50.76	147.35
129.	SAN, CA	52.68	153.66
130.	SCR, PA	99.57	194.87
131.	SHR, LA	40.34	134.58
132.	SOU, IN	20.36	116.79
133.	SPO, WA	37.63	137.98
134.	STA, CN	7.77	104.85
135 l	STO, CA	9.66	108.97
136.	TAC, WA	31.63	123.84
137.	TRE, NJ	17.11	112.17
138.	TUC, AZ	36.36	133.24
139.	TUL, OK	27.46	130.61
140.	UTI. NY	26.18	111.47

TABLE IV-9 (Concluded)

SMSA	PCNSCO	PCGSCO
141. VAL, CA	9.24	104.82
142. WAT, CN	23.44	118.18
143. WES, FL	12.32	122.35
144. WIC, KS	67.35	163.75
145. WIL, PA	58.48	157.31
146. WIL, DE, NJ, MD	51.90	142.28
147. WOR, MA	18.02	112.79
148. YOR, PA	27.27	125.45

A summary of the net and gross soiling damages by cleaning operations is contained in Table IV-10. The total net soiling damage as a result of falling suspended particulate for the 148 SMSA's in 1970 amounts to $5 billion. This damage figure is far smaller than the $11 billion and $30 billion national estimate extrapolated from the per capita damage figures reported respectively in the Mellon Institute study and the study by Michelson and Tourin. As noted earlier, the validity of the $11 billion and $30 billion estimates is seriously undermined by the assumptions used in the extrapolation technique. Regarding the gross soiling damage costs, New York, Chicago and Los Angeles had the highest damages among the 148 large SMSA's, about $1.6 billion, $12 billion, and $1.1 billion, respectively, partially because of the relatively high suspended particulate levels and a large number of household units in these three cities. Total gross soiling damage which is the sum of soiling damages attributable to air pollution and other factors amounts to $17.4 billion per year for the 148 SMSA's.

TABLE IV-10. NET AND GROSS SOILING DAMAGE COSTS IN 148 SMSA's BY CLEANING OPERATIONS, 1970

Tasks	Net Soiling Damages (million $)	Gross Soiling Damages (million $)	Net/Gross Soiling Damage Cost
1	11.8	12.8	0.91
2	558.8	9,884.9	0.05
3	454.1	204.0	0.45
4	1,956.3	3,584.1	0.55
5	13.6	30.6	0.44
6	925.7	1,227.9	0.75
7	349.2	691.6	0.50
8	275.1	1,079.2	0.25
9	488.9	652.0	0.75
Total	5,033.0	17,367.1	0.28

TABLE IV-11

TABLE IV-11. SOILING ECONOMIC DAMAGE FUNCTIONS[a,b]

Dependent Variable	MANFV	TSP	PCOL	RHM	DTS	PDS	PAGE	a	R^2
GSC01	66.18	1.128.83	2.377.55	-995.17	271.69	-1.78	764.7	-100.181.3	0.92
	(2.02)*	(147.36)*	(1,288.8)	(538.89)	(193.52)	(3.81)	(1,940.9)	(46,192.6)	
GSC02	42.9	-108.5	2,252.2	670.6		2.2	2.401.1	5,400.0	0.89
	(1.45)*	(105.5)	(915.7)*	(383.4)		(2.7)	(1.392.6)	(32,763.0)	
GSC03	957.6	6,802.6	42.426.0	-14.677.0	1.946.0	12.4	32,626.0	652,046.0	0.93
	(25.9)*	(1.887.5)*	(16,507.0)*	(6,902.0)*	(2.478.0)	(48.9)	(24.859.0)	(591,650.0)	
GSC04	17.2	160.0	727.4	-262.6	42.577		501.9	14,825.0	0.93
	(0.42)*	(33.1)*	(292.3)*	(122.4)*	(43.8)		(439.4)	(10,445.0)	
GSC05	144.3	1,031.6	6,384.9	-2,210.7	294.6	1.85	4,898.9	98,799.0	0,93
	(3.90)*	(284.2)*	(2,485.6)*	(1,039.3)*	(373.2)	(7.36)	(3.743.2)	(89.087.0)	
GSC06	6.12	84.0	236.9	-92.6	20.9	-0.083	116.6	-7.565.5	0.93
	(0.17)*	(12.5)*	(109.9)*	(45.9)*	(16.5)	(0.325)	(165.6)	(3.941.2)	
GSC07	3.29	27.7	142.0	-50.3	7.6	0.025	102.2	-2,607.0	0.93
	(0.08)*	(6.4)*	(56.3)*	(23.5)*	(8.4)	(0.166)	(84.8)	(2,018.7)	
GSC08	4.92	9.07	223.0	-74.8		0.17	212.9	877.7	0.91
	(0.15)*	(10.9)	(94.9)*	(39.7)		(0.28)	(144.4)	(3.396.3)	
GSC09	3.23	44.6	126.9	-48.9	11.2		60.4	4,047.7	0.93
	(0.08)*	(6.5)*	(579.4)*	(24.2)*	(8.6)		(87.0)	(2.070.1)	
TGSCO [b]	78.9	226.4	3.766.0	-1,219.8	90.9	2.3	3,432.3	-25,621.0	0.92
	(2.3)*	(166.9)	(1,460.0)*	(610.7)*	(219.3)	(4.3)	(2,199.5)	(52,347.0)	

[a] All coefficients and standard errors are reduced by a factor of 10^3, except equation GSC01, GSC03 and GSC05. The standard errors are the values below the coefficients, and * indicates that the coefficient is significant at the 1 percent level.

[b] TGSCO denotes the total gross soiling cost for the ith cleaning task, and TGSC0 is the sum of GSC01 over i, i = 1, 2,. . ,9.

The regional soiling damage costs and the national damage cost deduced in this study should be used, however, only as crude estimates. There are uncertainties embodied in the two major assumptions: (1) the physical damage functions for the variety of cleaning tasks estimated on the basis of the Philadelphia study are "representative" of the physical damage functions of the 148 SMSA's; (2) the unit market value figures obtained in the Kansas City area are applicable to other SMSA's.

In order to develop "average" soiling economic damage functions for each of the nine cleaning tasks which can be used for prediction and control purposes, the individual metropolitan damage costs were regressed against not only the SO_2, but also to several socioeconomic, demographic, and climatological characteristics of different regions. The independent variables include MANFV (value of manufacturing), PCOL (percentage of persons 25 or older who have completed 4 years of college), RHM (relative humidity), DTS (number of days with thunderstorm), PDS (population density), PAGE (percentage of population 65 or older) and TSP. The inclusion of these variables is to account for the variations in educational level, economic and age structure and density differentials among the study regions. The stepwise regression technique was used with inputs from the 148 sample observations for the purpose of estimating the economic damage functions. The regression results are summarized in Table IV-11. It is noteworthy that all the coefficients of TSP are of correct signs except the one in the second regression equation. Since the partial correlation coefficient between $\overline{GSC02}$ and $\overline{TSP}$ is positive and equal to 0.18, the negative coefficient obtained for TSP in the regression equation may be attributable to multicolinearity between TSP and other independent variables or other econometric problems or data deficiency.

It is interesting to note that aside from total suspended particulates PCOL, RHM, and MANFV are significant factors in determining the household soiling costs. While the effect of educational level on soiling adjustment cost is ambiguous _a priori_, relative humidity is likely to have a cleansing effect which reduces the soiling costs.

The soiling economic damage functions derived in this study are useful to policymakers at either the local or national level in estimating the marginal and average benefits of implementing a particular pollution abatement program. The responsiveness of gross soiling damages for a particular cleaning task to changes in climatological, demographic, and socioeconomic variables and the concentration level of suspended particulates can be easily estimated. The partial elasticity of the gross soiling costs of, say, cleaning Task 4, i.e., cleaning Venetian blinds and shades, with respect to suspended particulate level, can be estimated by

$$E_{SC4,TSP} = \frac{\partial(SC4)}{\partial(TSP)} \cdot \qquad \text{(IV-3)}$$

where $\partial(SC4)/\partial(TSP)$ is the coefficient of TSP in the soiling economic damage function with GSC04 as the dependent variable, and is equal to 160,000. TSP and $\overline{SC4}$ are respectively the mean values of total suspended particulates and of soiling damage cost associated with cleaning Venetian blinds and shades. Given $\overline{TSP}$ = 94.5 μg/m^3, and $\overline{SC4}$ = \$24.2 million,

$$E_{SC4,TSP} = 0.16 \times (94.5/24.2) = 0.62$$

Thus, for every 1 percent reduction in suspended particulate level, the soiling damage cost of cleaning Venetian blinds would decrease by 0.62 percent, holding other characteristics unchanged. Thus, if the suspended particulate level in the air is lowered by 9.45 μg/m^3 from 94.5 to 85.5 μg/m^3 (i.e., 10 percent reduction), gross soiling damage cost associated with cleaning Venetian blinds alone, would reduce, on the average, by \$1.5 million from \$24.2 to \$22.7 million nationwide. Of particular policy interest is the estimation of possible benefit in terms of the reduction in the overall soiling damage cost as a result of a pollution control program. Note that the coefficient of TSP in the overall soiling economic damage function is 226,400 and the mean value of overall soiling damage cost is \$117.3 million.

$$E_{SC,TSP} = 226400 \times (94.5/117.300000) = 0.18$$

Thus, if the suspended particulate level is lowered, on the average, by 10 percent, from 94.5 to 85.5 μg/m^3, overall gross soiling damage cost would reduce by 1.8 percent or by \$2.1 million, from \$117.3 million to \$115.2 million.

SECTION V

MATERIAL AND AIR POLLUTION

PROBLEMS AND OBJECTIVES

The damaging effects of air pollution to materials have been well recognized by the Air Pollution Control Office of the Environmental Protection Agency for some time. Effects of air pollution on materials range from soiling to chemical alteration. Corrosion of metals has attracted the most attention, while many other important areas were found to have been largely neglected. Most materials exhibit a high degree of chemical resistance to oxides of nitrogen, while sulfur dioxides were found to seriously attack about a third of the materials. And while some materials (such as glass) are highly resistant to chemical attack by most air pollutants, certain plastics and metals are highly susceptible to damage by a number of different commonly encountered air pollutants.

Among the adverse effects of air pollution on material included are the corrosion of metals, the deterioration of rubber, the fading of paint and soiling of materials. Many external factors influence the reaction rate between pollutants and materials, with moisture the most important in accelerating corrosion. Inorganic gases are likely to cause tarnishing and corrosion of metals; they can attack various building materials such as stone, marble, slate, and mortar and may deteriorate a variety of natural and synthetic fibers.

The most noticeable effect of particulate pollutants is soiling of the surfaces on which they are deposited. They may also act as catalysts increasing the corrosive reactions between metals and acid gases. Additional damages to surfaces and textiles are incurred by the wear and tear imposed by the extra cleaning made necessary because of particulate soiling. The true economic damage to materials caused by air pollution is difficult to ascertain because of the difficulty of distinguishing between natural deterioration and deterioration caused by air pollution and the uncertainty regarding indirect costs of early replacement of materials worn out by excessive cleaning.

Some of the material damage estimates attributable to air pollution in this country are as follows: In a pilot study by Uhlig (1950), the total corrosion bill was estimated at $5.4 billion, though air pollution was merely implicated as a causal agent of corrosion. Uhlig's estimate was updated and estimated by the Rust-Oleum Corporation (1974) to be $7.5 billion in 1958. Stickney, Mueller and Spence (1971) estimated that the pollution damage cost of rubber to U.S. consumers amounts to at least $398 million. Haynie (1973) estimated a value of $1.4 billion for the cost of corrosion of galvanized steel. The total damage cost due to air pollution inflicted on textiles and fibers was estimated to be $2 billion annually by Salvin (1970).

Robbins (1970) of Stanford Research Institute conducted one of the first major material damage studies and found that the air pollution damage with respect to electric contacts was not as serious as originally estimated. Two types of major costs were investigated. They are the direct cost associated with the plating of contacts with precious metals and the indirect cost incurred because of the preventive measures of air conditioning and air purification. It was estimated that about $65 million is spent annually on electric contacts because of air pollution.

Economic impact of air pollution on electric components was estimated by International Telephone and Telegraph (ITT) Electro-Physics Laboratories (1971). The damage costs to the following electric components were estimated: semiconductor devices, integrated circuits, television picture tubes, connectors, transformers, relays, receiving tubes, and crystals. Total damages to these categories amounted to $15.5 million.

A most comprehensive study on pollution damage on materials was conducted by Midwest Research Institute (Salmon, 1970). The MRI study presented a systematic analysis of all of the physical and chemical interactions between materials, pollutants and environmental parameters. Fifty-three economically important materials which represent about 40 percent of the economic value of all materials exposed to air pollution were identified and selected for the study. An estimated $100 billion in added cleaning costs would be necessary to keep these materials in polluted areas as clean as they would be in a nonpolluted environment, while deterioration of these materials causes yearly direct damage Losses of approximately $4 billion. Paint and zinc are the two materials most affected by both soiling and deterioration caused by air pollution, accounting for more than half of the total losses in each category. Based on the MRI estimate, Barrett and Waddell (1974) estimated an annual material deterioration damage in the United States to be $4.75 billion.

Some of the methodological procedures for estimating material effect was critically reviewed by Gillette and Upham (1973). It is generally understood that in order to develop reasonable estimates of pollution damages, the following information is very relevant: (1) geographical and temporal distribution of air quality levels and receptors' exposure to various pollution levels; (2) physical damage functions on important receptors; and (3) data on other socio-economic, demographic and environmental factors on a regional basis.

Pollution level varies within any given SMSA. In the absence of population-at-risk information, it is usually assumed that the entire SMSA population was exposed to the same pollution level as recorded by the station(s) which in all probability is (are) Located in the central city of the SMSA. Cost estimates derived under this assumption tend to overestimate the actual damage due to air pollution, since the pollution concentration level is likely to be higher in the central city than in the suburban areas.

Physical damage functions relating material damage to air pollution have recently been derived in a series of in-house experiments. Haynie and his associates (1974, 1975) obtained such physical dose-response relations separately for different kinds of steels, zinc, oil-base house paint and selected fabrics. Economic damage functions for materials which translate material physical loss into monetary terms, however, are still lacking. Although some damage estimates for certain types of materials at the national level are now available, detailed regional cost estimates on material damages due to air pollution are virtually nonexistent. Since the information on such regional damage costs of air pollution is indispensable for providing guidance for establishing pollution controls, it is imperative to develop a set of comparable damage cost estimates for each as well as a system of economic damage functions on different types of materials.

This section represents a first exploratory effort to estimate not only urban material damages attributable to air pollution for all 148 SMSA's with population greater than 250,000, but also the "average" air pollution damage functions on materials for this country. This section contains the following subsections: A Theoretical Framework, Exposition of Methodology, Regional Material Damage Costs, Economic Damage Functions, and A Summary of Material Physical Damage Functions.

A THEORETICAL FRAMEWORK

A theoretical framework is developed in this section for defining and developing urban economic costs and economic damage functions of materials. The economic costs of a material are defined as the decrease in the values of this particular material as a result of increased contamination in the environment. An economic damage function of material which relates the economic costs to a host of relevant variables including pollution, socioeconomic, demographic and climatological variables is also estimated.

It is noteworthy that materials generally do not directly affect an individual's utility or preferences. Thus, materials can be regarded as "pure" intermediate commodities which are differentiable from the traditional interindustry flows. The pure intermediate commodities utilized the primary inputs, i.e., labor and capital, in their production and are themselves solely utilized as inputs in the production of "final" commodities which enter into one's utility function. Interindustry flows, however, refer to those commodities which are intermediate inputs to be used in other industries as well as final outputs for consumers.

The degree of the effect of air pollution on materials depends on a number of factors: (1) the extent of the reduction in the normal service or use life of material; (2) the frequency of maintenance and preventive measures on the part of users; and (3) the changes in the quality and quantity of the services rendered by the product which contains the materials being affected by air pollution.

Let D_i represent the level of physical deterioration of the ith type of material. SL_i will be the service life, SP_i the service performance, ME_i the maintenance effort of the same ith type of material, and A the air pollution concentration level to which the material is being exposed.

Thus, we can write

$$D_i = D_i\left[SL_i(A),\ SP_i(A),\ ME_i(A);\ e\right] \qquad \text{(V-1)}$$

Equation (V-1) states that the deterioration of the ith type of material is functionally related to SL_i, SP_i and ME_i directly. Each of the explanatory variables is, however, being influenced by the prevailing pollution levels.

The plausible signs of the partial derivations are as follows:

$$\frac{\partial D}{\partial (SL)} < 0 \ ; \ \frac{d(SL)}{d(A)} < 0$$

$$\frac{\partial D}{\partial (SP)} < 0 \ ; \ \frac{d(SP)}{d(A)} < 0$$

$$\frac{\partial D}{\partial (ME)} > 0 \ ; \ \frac{d(ME)}{d(A)} > 0$$

Thus, $\frac{\partial D}{\partial (SL)} \cdot \frac{d(SL)}{d(A)} > 0$; $\frac{\partial D}{\partial (SP)} \cdot \frac{d(SP)}{d(A)} > 0$; and $\frac{\partial D}{\partial (ME)} \cdot \frac{d(ME)}{d(A)} > 0$.

Assuming noninteractions among the independent variables, total physical damage of material as a result of an increased pollution is expressed as:[1/]

$$dD = \left[\frac{\partial D}{\partial (SL)}\ \frac{d(SL)}{d(A)} + \frac{\partial D}{\partial (SP)}\ \frac{d(SP)}{d(A)} + \frac{\partial D}{\partial (ME)} \cdot \frac{d(ME)}{d(A)}\right] d(A) \qquad \text{(V-2)}$$

Note that changes in SL and SP of the product represent direct damages attributable to pollution, whereas pollution-induced changes in ME are indirect damages due to pollution.

[1/] The assumption of noninteraction is made for the sake of simplicity. In the real world, it is observed that service life, performance and maintenance effort are interrelated. Increased maintenance should also increase service life and performance.

A simplified and yet commonly adopted formulation of material physical damage function is written as follows:

$$D_i = D_i(A, RHM; u) \qquad (V\text{-}3)$$

where RHM is relative humidity, D and A are the same as in (V-1) and u is the error term.

In order to develop a theoretical framework for estimating economic damage costs of materials, let us assume for the sake of simplicity, but without loss of generality, that there is only one type of material. The initial endowment of this material in a given urban area is M_o . Further, it is assumed that the material stock grows at an exogenously determined rate of r over the planning time horizon. 1/ Thus, total stock of this material in the absence of air pollution in the area at time t is given by:

$$M_g = \int_{t=o}^{t} M_o e^r \, dt \qquad (V\text{-}4)$$

If the area in question is subject to an air pollution level which is above the threshold level, and if the material depreciates at a rate i because of the air pollution, then the net existing material stock at the time t is given by:

$$M_n = \int_{t=o}^{t} M_o e^{(r-i)} \, dt$$

Note that $i = dD/D$ and $D = D(A; RHM)$ with $\partial D/\partial(A) > 0$. $\partial D/\partial(RHM) \gtrless 0$.

The economic damage of this material (ED) is defined to be that portion of the material loss attributable to air pollution evaluated at the prevailing market prices of the material. Let P_m be the market price of the material, which is determined by the supply and demand conditions for this material.

1/ A more realistic approach is to consider that the growth of stock of a material within an area is endogeneously determined. It is determined by the need for that material within an area and the ability to acquire it. One would expect that the stock growth rate to be a function of population growth rate, per capita income growth rate and the change in demand for that material with respect to replacement material.

Thus,

$$ED = P_m(M_g - M_n) = P_m \int_{t=o}^{t} M_o e^{dD/D(A;RHM)} \, dt \qquad (V\text{-}6)$$

It may be remarked that (V-6) reflects the economic damage associated with the air pollution level through a change in demand for the material. It does not reflect the economic damage associated with increased flow of the material through the area caused by pollution-induced decreased service life.

It follows from (V-6) that a general economic damage function for material can be expressed as

$$ED = ED(P_m, A, RHM; u) \qquad (V\text{-}7)$$

Those socioeconomic and other variables which influence P_m could be included in the general economic damage function in addition to A and RHM.

EXPOSITION OF METHODOLOGY

Ideally, the information on the distribution of materials, of pollutants, the value of the products made from the materials, the service life of the products in the absence of pollution and the physical dose-response function should be gathered in order to accurately assess economic costs of material deterioration due to excessive air pollution. Empirical data on the distributions of both materials and pollution are unavailable for most urban areas. However, sketchy estimates for product values and the service life have been derived by Fink _et al_. (1971) by resorting to the annual production figures in the Standard Industrial Classification statistics and product useful life statistics issued by Internal Revenue Service. Dose-response functions for a variety of materials have recently been estimated via the technique of in-house controlled experiments.

In the absence of the relevant material and pollution distribution data, an alternative "top-down" method is developed in this section to derive a consistent set of urban economic costs of material damage as a result of air pollution. The existing valuable information on national material damage and the dose-response functions were obtained through literature survey. The national damage estimates were then allocated down to various SMSA's by utilizing the dose-response functions and other relevant regional data.

For the sake of illustration, but without loss of generality, let the physical dose-response function for the ith type of material be written as:

$$D_i = D_i(A, C) \qquad (V\text{-}8)$$

where D, A and C denote, respectively, the physical damage, the air pollution level and climatological conditions.

Given the physical damage function and the national damage estimates, the regional damage costs for the ith type of material can be estimated by using the following formula:

$$RED_{ij} = NED_i \cdot \frac{D_{ij}}{\sum_{j=1}^{n} D_{ij} \big/ n} \cdot \frac{SE_j}{\sum_{j=1}^{n} SE_j \big/ n} \qquad (V\text{-}9)$$

where RED_{ij} and NED_i are, respectively, the regional and national economic damage costs for the ith type of material. SE_j stands for the relevant socioeconomic characteristics which are thought to affect material damages, e.g., manufacturing establishments and D_{ij} is the dose-response relation for the ith type of material. The subscript j denotes the jth SMSA.

Substituting (V-8) into (V-9) yields:

$$RED_{ij} = NED_i \cdot \frac{D_{ij}(A_j, C_j)}{\sum_j D_{ij}(A_j, C_j)} \cdot \frac{SE_j}{\sum_j SE_j \; n} \qquad (V\text{-}10)$$

Equation (V-10) can be used to derive the regional economic cost for the ith type of material. The data on NED is available from an earlier material damage study conducted by Salmon (1970) at Midwest Research Institute, and A_j, C_j and SE_j can be respectively secured from the *Air Quality Data*, published by the Environmental Protection Agency; *Local Climatological Data,*, published by the National Oceanic and Atmospheric Administration; and 1972 *County and City Data Book*. Substituting the values for NED_i, A_j, C_j, and SE_j into equation (V-10), a series of consistent estimates for material damages for various SMSA's due to air pollution is obtained.

According to the earlier MRI study, material damage as a result of air pollution can be categorized into two major effects: (1) soiling effects attributable to particulate pollutants; and (2) chemical effects attributable to gaseous pollutants. The national soiling cost (SC) and deterioration cost (DC) of various materials were estimated with the aid of the following formulas:

$$SC = SIF \cdot Q \tag{V-11}$$

$$DC = DIF \cdot Q \tag{V-12}$$

$$Q = P \cdot N \cdot F \cdot R \tag{V-13}$$

where SC represents material soiling costs, SIF the soiling interaction factor, Q in-place unprotected material value, DC material deterioration cost, DIF deterioration interaction factor, P annual production value of the material, N economic life of the material based on usage, F weighted average factor for the percentage of the material exposed to air pollution, and R labor factor reflecting the in-place or as-used value of the material.

The rate of soiling interaction factor, SIF, is computed by complex formulas which are different for fibers and nonfibers.1/ The rate of deterioration, DIF, is computed by estimating the difference between the deterioration rate in polluted and, unpolluted environments divided by the average thickness of the material.

Finally, it is noted that two methods are generally feasible for estimating regional damage costs. The first method is the "top-down" technique which is to allocate via weighting and adjusting schemes a national damage estimate down to various regions. The second method is the "bottom-up" technique which involves direct estimation of the regional damages. The bottom-up method, which incorporates uncertainties of the assumptions into regional estimates generated, was used to derive the damage costs for human health and household soiling adjustment in the preceding three sections. The top-down technique was employed, however, in this study to estimate material damage costs because of the lack of distribution information about materials and pollutants and the technical difficulties encountered in direct estimation of the regional damages.

REGIONAL MATERIAL DAMAGE COSTS

This section is concerned with estimating regional material damages by using the top-down method delineated above. In view of the fact that there are virtually infinite categories of materials, and the fact that zinc and paint are most important from an economic point of view, only these two materials were selected for this study. The damage costs of zinc and paint account for over 50 percent of the total economic damage losses of the 53 economically important materials selected in the earlier MRI study (Salmon, 1970).

1/ The formulas are: $SIF_{fibers} = 0.10\,\Delta f/Rw$ and $SIF_{nonfibers} = 0.10\Delta f/Rw\rho t$ where Δf is the increased frequency of cleaning due to pollution, R the labor factor, w the material price per pound, ρ the density and t the average thickness.

The soiling and deterioration costs of paint and zinc, and the percentage of these two costs in terms of total costs, are summarized in Table V-1. 1/ These figures are admittedly artificial because they were calculated on the assumption that the material would be maintained completely clean at all times. In practice, each individual will have an acceptable level of soiling for each material.

TABLE V-1 SOILING AND DETERIORATING COSTS OF PAINT AND ZINC

	Soiling cost (SC) (billion $)	SC/Total SC	Deterioration Cost (DC) (billion $)	DC/Total DC
Paint	35.0	0.35	1.2	0.31
Zinc	24.0	0.24	0.8	0.20
53 Materials	100.0	0.59	3.8	0.51

The physical dose-response functions for zinc and oil-base house paint are obtained from two recent studies by Haynie and Upham (1970), Spence, Haynie and Upham (1975).

$$\text{Zinc - Corrosion} = 0.001028\,(RH - 48.8)\,S0_2 \qquad (V\text{-}14)$$

$$\text{Paint - Erosion} = 14.32 + 0.01506\,S0_2 + 0.3884\,RH \qquad (V\text{-}15)$$

Recalling equation (V-10), and substituting the above physical dose-response function for zinc, and the relevant socioeconomic data into equation (V-10) yields the estimates of soiling and deterioration cost of zinc for the jth SMSA. Thus,

$$RED^*_{zinc_j} = NED^*_{zinc} \cdot \frac{0.001028(RH_j-48.8)SO_{2_j}}{\sum\limits_{j=1}^{148} (0.001028(RH_j-48.8)SO_{2_j}/148)} \cdot \frac{ME_j}{\sum\limits_j ME_j/148} \qquad (V\text{-}16)$$

$$NED^*_{zinc} = NED_{zinc} \cdot \left(\sum_{j=1}^{148} POP_j/POP_{us}\right) \qquad (V\text{-}17)$$

1/ The estimates are taken from Table XII and Table XIII of the MRI research report, "System Analysis of the Effects of Air Pollution on Materials," Kansas City (January 1970).

where $\text{NED*}_{\text{zinc}}$ is the total damage cost of zinc over the 148 SMSA's included for the present study, RH_j and ME_j the relative humidity and manufacturing establishment in the jth SMSA, POP_j and POP_{us} represent, respectively, the population in the jth SMSA and in the whole country.

The earlier MRI study estimated the national soiling and deterioration damage costs of zinc to be $24 billion and $778 million, respectively. Given the ratio of 0.63 which represents the ratio of the 148 SMSA population to the nationwide population in 1974, the soiling and deterioration damage costs of zinc for the 148 SMSA's are calculated as follows:

$$\$24 \times 0.63 = \$15.12 \text{ billion (soiling)}$$

$$\$778 \times 0.63 = \$496 \text{ million (deterioration)}$$

A threshold level of zero $\mu g/m^3$ for SO_2 is implicit in the physical dose-response functions for zinc and paint. Thus, a zero threshold level is used in estimating the regional damage costs of materials. It should be noted that the value of $\text{RED*}_{\text{zinc}}$ as calculated from the weighting scheme expressed by (V-16) can be greater than $\text{NED*}_{\text{zinc}}$. Thus, the damage costs for each SMSA are further adjusted by the ratio $(\text{RED}_{\text{zinc},\ j}\ \overset{j}{j}\ \sum_{j=1}^{148} \text{RED}_{\text{zinc},\ j})$ to preserve the equality between the sum of the regional damage costs obtained via equation (V-16) over the 148 SMSA's and the total damage costs evaluated for the same 148 SMSA's, i.e., NED*.

Similarly, the soiling or deterioration damage costs of paint for the jth SMSA are computed by using the following formula:

$$\text{RED}_{\text{paint},\ j} = \text{NED*}_{\text{paint}} \cdot \frac{(14.3 + 0.01506\ \text{SO}_{2_j} + 0.3884\ \text{RH}_j)}{\sum_{j=1}^{148} (14.3 + 0.01506\ \text{SO}_{2_j} + 0.3884\ \text{RH}_j)/148} \cdot \frac{\text{HU}_j}{\sum_j \text{HU}_j/148} \cdot \frac{\text{YP}_j}{\sum_j \text{YP}_j/148} \qquad \text{(V-18)}$$

$$\text{NED*}_{\text{paint}} = \text{NED}_{\text{paint}} \cdot \left(\sum_{j=1}^{148}\right) \text{POP}_j/\text{POP}_{us} \qquad \text{(V-19)}$$

where NED^*_{paint} is the total cost of zinc over the 148 SMSA's, HU_j and YP_j are housing units and per capita income in the jth SMSA's. POP, SO_2, RH, NED and RED are the same as those in equation (V-15).

The nationwide soiling and deterioration damage costs of paint were estimated in 1970 to be $35 billion and $1.2 billion, respectively. Thus, applying the population ratio of 0.63 to these two estimates, NED* is calculated to be $22 billion and $753 million for soiling and deterioration, respectively. The damage estimates are further adjusted by $RED_{print, j} / (\sum_j RED_{paint, j})$ such that the sum of the damage costs over the 148 SMSA's equals the total damage cost evaluated for these SMSA's by using (V-19).

The soiling and deterioration damage costs of zinc and paint for the 65 large SMSA's and the 83 medium SMSA's are computed by using equations (V-16) through (V-19). The results of the regional damage costs are summarized in Tables V-2 and V-3. Since the national damage figures employed are extremely large because they were estimated on the stringent assumption that the materials would be maintained completely clean at all times, it is not surprising that the top-down method yields relatively large damage figures for the study regions. An examination of the tables reveals that Chicago scores the highest damage costs on zinc among all the 148 SMSA's in both the soiling and deterioration damages (an annual soiling damage of $1.7 billion and deterioration damage of $57 million in 1970). However, regarding the paint damages, New York City, which had an annual soiling and deterioration damage cost of paint of $2.3 billion and $79 million, respectively, surpassed all the SMSA's included in this study.

It should be noted again that the assumptions made in deriving the national damage figures and the physical damage functions in the earlier studies are inherited by this study, especially the theoretically maximum national damage estimates in both categories of soiling and deterioration. Should there be changes in these assumptions, the estimates developed and presented in the table would be modified accordingly. Thus, the results presented in this section are only suggestive and tentative. Given the tentativeness and experimental nature of the methodological and statistical procedures, and the degree of uncertainty associated with the estimates, a great deal of caution should be exercised in using the product of this research.

ECONOMIC DAMAGE FUNCTIONS

In order to develop marginal equivalent economic damage functions which can be used for damage (benefit) prediction and for designing pollution control strategies, the economic costs of material soiling and deterioration are regressed not only against SO_2 and relative humidity, but also against other relevant socioeconomic and climatological variables. The stepwise regression technique was used with inputs from the 148 sample observations for estimating the economic damage functions. The regression results for soiling and deterioration damages of zinc and paint are presented in Table V-4. Consistent with *a priori* expectation, the coefficients of ME, SO_2, TSP, RH, HU and YP are all positive, and the coefficient of SUN has ambiguous signs depending on the type

TABLE V-2. MATERIAL DAMAGE BY LARGE SMSA's, 1970

(in million $)

Large SMSA's	Soiling Damage Cost of Zinc (SDCZ)	Deteriorating Damage Cost of Zinc (DDCZ)	Soiling Damage Cost of Paint (SDCP)	Deteriorating Damage Cost of Paint (DDCP)
1. AKR, OH	108.0	3.533	107.0	3.684
2. ALB, NY	54.0	1.751	121.0	4.141
3. ALL, NJ	16.5	0.537	85.6	2.925
4. ANA, CA	62.6	2.029	279.0	9.542
5. ATL, GA	25.2	0.818	224.0	7.667
6. BAL, MD	190.0	6.166	320.0	10.900
7. BIR, AL	12.9	0.421	98.8	3.374
8. BOS, MA	289.0	9.395	480.0	16.300
9. BUF, NY	32.8	1.064	219.0	7.503
10. CHI, IL	1,770.0	57.600	1,350.0	46.300
11. CIN, OH-KY-IN	134.0	4.372	225.0	7.716
12. CLE, OH	1,110.0	36.000	392.0	13.300
13. COL, OH	91.5	2.969	153.0	5.239
14. DAL, TX	15.3	0.496	273.0	9.343
15. DAY, OH	125.0	4.080	145.0	4.952
16. DEN, CO	--	--	167.0	5.728
17. DET, MI	910.0	29.500	741.0	25.300
18. FOR, FL	8.8	0.284	158.0	5.414
19. FOR, TX	11.9	0.387	127.0	4.352
20. GAR, IN	144.0	4.680	94.0	3.217
21. GRA, MI	29.4	0.955	81.9	2.798
22. GRE, NC	18.8	0.611	86.0	2.937
23. HAR, CT	19.1	0.621	140.0	4.792
24. HON, HI	2.3	0.078	83.7	2.860
25. HOU, TX	28.6	0.929	338.0	11.500
26. IND, IN	79.3	2.572	192.0	6.563
27. JAC, FL	2.1	0.068	70.8	2.418
28. JER, NJ	128.0	4.152	101.0	3.475
29. KAN, MO-KS	122.0	3.956	229.0	7.824
30. LOS, CA	730.0	23.600	1,530.0	52.300
31. LOU, KY-IN	171.0	5.545	127.0	4.345
32. MEM, TN-AR	17.3	0.563	94.5	3.227
33. MIA, FL	24.6	0.800	239.0	8.164
34. MIL, WI	178.0	5.799	247.0	8.435
35. MINN, MN	32.5	1.054	307.0	10.500
36. NAS, TN	12.6	0.411	80.8	2.759
37. NEW, LA	25.6	0.832	147.0	5.035
38. NEW, NY	1,040.0	34.000	2,310.0	79.100
39. NEW, NJ	94.9	3.077	327.0	11.100
40. NOR, VA	10.3	0.335	81.4	2.781

Note: -- denotes damage of value less than $0.5 million.

TABLE V-2 (Concluded)

Large SMSA's	SDCZ	DDCZ	SDCP	DDCP
41. OKL, OK	2.6	0.083	106.0	3.641
42. OMA, NE-IA	13.3	0.434	85.1	2.907
43. PAT, NJ	101.0	3.292	271.0	9.271
44. PHI, PA-NJ	520.0	16.800	767.0	26.200
45. PHO, AZ	--	--	90.5	3.091
46. PIT, PA	504.0	16.300	386.0	13.200
47. POR, OR-WA	36.3	1.780	179.0	6.116
48. PRO, RI-MA	137.0	4.518	140.0	4.798
49. RIC, VA	18.7	0.061	78.7	2.688
50. ROC, NY	57.1	1.852	151.0	5.516
51. SAC, CA	--	--	114.0	3.900
52. SAI, MO-IL	308.0	10.000	411.0	14.000
53. SAL, UT	--	--	58.8	2.011
54. SAN, TX	1.8	0.060	97.2	3.321
55. SAN,CA	12.1	0.393	198.0	6.760
56. SAN, CA	9.8	0.316	224.0	7.670
57. SAN, CA	57.3	1.858	725.0	24.700
58. SAN, CA	26.7	0.868	199.0	6.826
59. SEA, WA	143.0	4.641	293.0	10.000
60. SPR, MC-CT	15.3	0.498	75.6	2.584
61. SYR, NY	40.4	1.311	104.0	3.557
62. TAM, FL	13.3	0.432	175.0	5.975
63. TOL, OH-MI	28.4	0.922	108.0	3.712
64. WAS, DC-MD-VA	38.4	1.246	578.0	19.700
65. YOU, OH	152.0	4.946	84.9	2.900
Total	10,114.4	328.651	18,272.3	624.854

TABLE V-3. MATERIAL DAMAGE BY MEDIUM SMSA's, 1970
(in million $)

Medium SMSA's	SDCZ	DDCZ	SDCP	DDCP
66. ALB, NM	--	--	29.6	1.014
67. ANN, MI	572.0	18.500	46.2	1.580
68. APP, WI	0.0	0.000	39.7	1.357
69. AUG, GA-SC	2.3	0.076	26.5	0.905
70. AUS, TX	3.3	0.107	44.8	1.532
71. BAK, CA	-2.9	-0.095	35.9	1.228
72. BAT, LA	75.8	2.459	38.5	1.317
73. BEA, TX	164.0	5.342	49.1	1.678
74. BIN, NT-PA	93.4	3.030	47.9	1.638
75. BRI, CN	155.0	5.041	70.3	2.404
76. CAN, OH	287.0	9.332	59.0	2.016
77. CHA, SC	3.8	0.122	32.1	1.096
78. CHA, WV	76.6	2.485	33.6	1.148
79. CHA, NC	119.0	3.859	65.1	2.224
80. CHA, TN-GA	96.6	3.134	43.9	1.501
81. COL, CO	--	--	24.8	0.849
82. COL, SC	7.7	0.251	34.8	1.189
83. COL, GA-AL	20.5	0.665	26.5	0.905
84. COR, TX	5.9	0.192	112.0	3.831
85. DAV, IA-IL	34.6	1.123	60.3	2.060
86. DES, IA	28.1	0.912	52.0	1.778
87. DUL, MN-WI	31.4	1.020	43.9	1.501
88. ELP, TX	--	--	24.3	0.830
89. ERI, PA	131.0	3.924	37.0	1.264
90. EUG, OR	41.0	1.332	33.2	1.135
91. EVA, IN-KY	104.0	3.389	34.7	1.186
92. FAY, NC	4.6	0.150	19.1	0.653
93. FLI, MI	0.0	0.0	76.4	2.609
94. FOR, IN	67.2	2.180	46.5	1.591
95. FRE, CA	--	--	46.7	1.596
96. GRE, SC	30.2	0.979	37.6	1.287
97. HAM, OH	22.2	0.722	32.3	1.106
98. HAR, PA	6.7	0.218	62.7	2.143
99. HUN, WV-KY,OH	91.4	2.965	34.8	1.190
100. HUN, AL	38.8	1.260	31.1	1.065
101. JAC, MS	2.7	0.086	28.7	0.980
102. JOH, PA	2.4	0.081	32.3	1.104
103. KAL, MI	45.2	1.466	32.3	1.106
104. KNO, TN	46.9	1.523	55.3	1.889
105. LAN, PA	62.6	2.032	45.0	1.539
106. LAN, MI	118.0	3.839	61.0	2.085
107. LAS, NV	--	--	29.7	1.015
108. LAW, MA-NH	162.0	5.270	42.3	1.444
109. LITT, AK	12.3	0.399	46.2	1.579
110. LOR, OH	17.8	5.771	37.9	1.297

TABLE V-3 (Concluded)

Medium SMSA's	SDCZ	DDCZ	SDCP	DDCP
111. LOW-MA	151.0	4.924	31.2	1.067
112. MAC, GA	2.8	0.089	25.5	0.871
113. MAD, WI	18.5	0.602	49.1	1.678
114. MOB, AL	34.7	1.126	42.8	1.464
115. MON, AL	2.9	0.092	24.7	0.845
116. NEW, CN	66.3	2.152	64.4	2.200
117. NEW, CN	42.8	1.388	32.3	1.106
118. NEW, VA	5.3	0.174	39.8	1.359
119. ORL, FL	18.5	0.601	62.4	2.132
120. OXN, CA	22.5	0.732	57.2	1.954
121. PEN, FL	34.6	1.122	30.3	1.037
122. PEO, IL	240.0	7.782	61.4	2.099
123. RAL, NC	10.9	0.355	30.6	1.046
124. REA, PA	90.6	2.939	48.3	1.650
125. ROC, IL	56.8	1.843	48.3	1.651
126. SAG, MI	56.3	1.828	32.1	1.099
127. SAL, GA	5.0	0.164	36.9	1.261
128. SAN, CA	11.6	0.377	44.8	1.531
129. SAN, CA	14.9	0.485	38.9	1.329
130. SCR, PA	25.8	0.838	31.1	1.065
131. SHR, LA	38.5	1.249	38.3	1.310
132. SOU, IN	154.0	4.993	46.4	1.587
133. SPO, WA	--	--	38.6	1.318
134. STA, CN	84.6	2.744	63.0	2.153
135. STO, CA	--	--	37.8	1.292
136. TAC, WA	35.0	1.137	63.7	2.176
137. TRE, NJ	18.6	0.604	48.3	1.651
138. TUC, AZ	--	--	32.9	1.126
139. TUL, OK	473.0	15.300	97.4	3.328
140. UTI, NY	97.7	3.169	50.7	1.733
141. VAL, CA	11.0	0.357	39.3	1.345
142. WAT, CN	8.7	0.282	31.8	1.087
143. WES, FL	3.8	0.122	79.1	2.702
144. WIC, KS	25.4	0.824	62.5	2.136
145. WIL, PA	60.3	1.956	46.0	1.572
146. WIL, DE-NJ-MD	96.1	3.117	78.0	2.663
147. WOR, MA	201.0	6.537	56.1	1.918
148. YOR, PA	9.7	0.313	49.6	1.695
Total	5,005.5	168.309	3,777.8	127.996

TABLE V-4. ECONOMIC DAMAGE FUNCTIONS ON MATERIALS a/

$$\mathrm{SDCZ} \qquad \underset{(19{,}929)}{-23{,}328.4} + \underset{(3.4)^*}{43.1}\,\mathrm{ME} + \underset{(171.6)^*}{943.3}\,\mathrm{SO_2} + \underset{(356.0)^*}{148.1}\,\mathrm{TSP} - \underset{(1820.4)}{235.0}\,\mathrm{SUN}$$

$$+ \underset{(1{,}750.2)}{2{,}679.3}\,\mathrm{RHM} + \underset{(18.9)}{21.9}\,\mathrm{YP} \qquad R^2 = 0.64 \qquad \text{(V-20)}$$

$$\mathrm{DDCZ} = \underset{(6{,}460.4)}{7{,}562.2} + \underset{(0.1)^*}{1.4}\,\mathrm{ME} + \underset{(5.5)^*}{30.5}\,\mathrm{SO_2} + \underset{(11.5)^*}{47.9}\,\mathrm{TSP} - \underset{(59.0)}{76.2}\,\mathrm{SUN}$$

$$+ \underset{(56.7)}{86.8}\,\mathrm{RHM} + \underset{(615.5)}{712.6}\,\mathrm{YP} \qquad R^2 = 0.63 \qquad \text{(V-21)}$$

$$\mathrm{SDCP} = \underset{(259.861.3)}{-141{,}199.7} + \underset{(3.4)^*}{577.2}\,\mathrm{HU} + \underset{(2.6)^*}{15.2}\,\mathrm{YP} + \underset{(235.3)^*}{911.3}\,\mathrm{RHM} + \underset{(23.2)^*}{69.1}\,\mathrm{SO_2}$$

$$+ \underset{(245.9)}{305.3}\,\mathrm{SUN} \qquad R^2 = 0.995 \qquad \text{(V-22)}$$

$$\mathrm{DDCP} = \underset{(887.2)^*}{-4{,}820.1} + \underset{(0.1)^*}{19.7}\,\mathrm{HU} + \underset{(0.08)^*}{0.5}\,\mathrm{YP} + \underset{(8.0)^*}{31.1}\,\mathrm{RHM} + \underset{(0.8)^*}{2.3}\,\mathrm{SO_2} + \underset{(8.4)}{10.4}\,\mathrm{SUN}$$

$$R^2 = 0.995 \qquad \text{(V-23)}$$

---

a/ The values below the coefficients are standard errors with * to indicate that the coefficients are significant at the 1 percent level. All coefficients and standard errors are reduced by a factor of 10^3.

of material. The coefficients of ME, SO_2, and TSP are significant at the 1 percent level in equations (V-20) and (V-21), whereas the coefficients of HU, YP, RH and SO_2 are significant at the 1 percent level in equations (V-22) and (V-23).

The economic damage functions on zinc and paint summarized in Table V-4 were estimated simply for national decision making They offer some short-cut techniques for rough computations and can be used in determining the marginal as well as average damages (benefits) resulting from a pollution control strategy. To serve as an illustration., an example involving the computation of the partial elasticity of SDCZ with respect to SO_2 , and the associated marginal benefit due to a reduction in SO_2, is presented. Suppose the federal government is contemplating the implementation of a pollution abatement program which is expected to reduce the average SO_2 level in the urban areas by, say, 10 percent. A question arises as to what the dollar benefit will be for the reduction in soiling damage of zinc as a result of the pollution control program. Since the average gross soiling damage due to SO_2 is \$102 million and the average SO_2 level is 55.73 $\mu g/m^3$ among the 148 SMSA's, the partial elasticity of the damage cost with respect to SO_2 is obtained:

$$E_{C,SO_2} = 0.9433 \times (55.73/102) = 0.52.$$

Thus, it is in general expected that a 10 percent decrease in the SO_2 concentration level will result in a 5.2 percent reduction in the soiling damage cost cost of zinc. Since the mean value of the regional damage cost for the 148 SMSA's included in this study is \$102 million, when the SO_2 level decreases from 55.73 $\mu g/m^3$ to 50.16 $\mu g/m^3$, it is also expected that on the average the damage cost will be reduced by the amount of \$102 million x 5.2% = \$5.73 million. Likewise, the elasticities for the other dependent variables with respect to SO_2 and other explanatory variables can be analogously computed and interpreted.

A SUMMARY OF MATERIAL PHYSICAL DAMAGE FUNCTIONS

After a careful review of the literature, some recent publications as well as many unpublished manuscripts were identified as major sources providing useful information for our future on material damage. The damage resulting from air pollution includes corrosion of metals, deterioration of paints and materials, fading of fabric dyes, etc. It is also worth noting that the physical damage functions expressed in equations (V-30) and (V-32) below were utilized in deriving the economic damage estimates in the preceding section.

Major Pollution and Material Interactions

Fred H. Haynie (1974), based on an MRI study, summarized in Table V-5 the relative extent to which effects of pollutants on materials are known. Haynie considered an effect (1) "well established" when evidence was corroborated by several high quality references; (2) "some evidence" in the presence of one or two references; and (3) "suspected" when interactions are based on behavior of material at pollutant level much higher than the ambient level.

TABLE V-5. MAJOR POLLUTANT - MATERIAL INTERACTIONS

	Material				
Pollutants	Metals	Paints	Textile	Elastomers	Plastics
Sulfur dioxide	1	2	1	- -	3
Particulate	2	1	2	- -	- -
Ozone	2	2	1	1	3
Nitrogen dioxide	2	3	1	3	3
Hydrocarbons	- -	3	- -	- -	- -

Metals--

Steel, SO_2 and Photochemical Oxidant--Haynie and Upham (1971) conducted an in-house field study of the effect of atmospheric pollutants on steel corrosion, Good dose-response relationships were estimated as follows:

Carbon steel

$$y = A.013 \left[e^{0.00161\,SO_2} (4.768t)^{0.7512 - 0.00582\,OX} \right] \quad (V\text{-}24)$$

Copper bearing steel

$$y = 8.341 \left[e^{0.00171\,SO_2} (4.351t)^{0.8151 - 0.00642\,OX} \right] \quad (V\text{-}25)$$

Weathering steel

$$y = 8.876 \left[e^{0.0045\,SO_2} (3.389t)^{0.6695 - 0.00544\,OX} \right] \quad (V\text{-}26)$$

Y is the depth of corrosion in microns (m); SO_2 and OX are expressed in $\mu g/m^3$; t is time.

Enameling Steel, Sulfate in Suspended Particulate--Haynie and Upham (1974) in a companion paper <examined correlation between erosion behavior of steel and gaseous SO_2, total suspended particulate, sulfate in suspended particulate, and nitrate in suspended particulate. Multiple linear regression and nonlinear curve fitting techniques were used to analyze the relationship between corrosion of enameling steel and the atmospheric data. The resulting best empirical function has the form:

$$\text{Corrosion} = 183.5 \sqrt{t}\, \text{EXP}\,[0.06421\ \text{Sul} - 163.21/\text{RH}] \qquad \text{(V-27)}$$

where

corrosion = depth of corrosion, µm

t = time, years

Sul = average level of sulfate in suspended particulate ($\mu g/m^3$) or average level of sulfur dioxide ($\mu g/m^3$)

RH = average relative humidity

The statistical analysis shows that differences in average temperature, average total suspended particulate, and average nitrate in suspended particulate exert insignificant effects on steel's corrosion behavior. Covariance between sulfate and SO_2 and the relative accuracies of the two sets of data make it impossible to statistically identify the causative agent. Laboratory experiments suggest that SO_2 is the major cause.

Galvanized Steel and SO_2--In an unpublished paper, Spence, Upham, and Haynie (1975) derived a dose-response relation for galvanized steel, SO_2, NO_2 and Ozone in controlled environmental chambers. Of the three pollutants, SO_2 was shown to be a major factor in determining the corrosion rate of galvanized steel. The corrosion of the galvanized panels fits the relationship:

$$\text{Corr} = (d_0\, SO_2 + e^{b - E/RT})\sqrt{t_w} \qquad \text{(V-28)}$$

where Corr = corrosion in micrometer (µm)

$d_0 = 0.0187,\ b = 41.85,\ E = 23{,}240$

t_w = time of wetness

Weathering Steel, SO_2, Relative Humidity and Temperature--A similar chamber study for weathering steel was conducted by Spence, Haynie, and Upham (1975b) who developed a corrosion function that accounts for 99 percent of the variability for the clean air and pollutant experimental data.

$$\text{Corr} = \left[5.64 \sqrt{SO_2} + e^{(55.44 - \frac{31,150}{RT})}\right]\sqrt{t_w} \qquad \text{(V-28)}$$

where

SO_2 is $\mu g/m^3$

R is 1.9872 Cal/g - mole °K

T is the goemetric mean temperature of the specimen when wet in °K

t_w is time of wetness in years

This chamber has shown that SO_2 is a major factor determining the corrosion of weathering steel.

Zinc and SO_2--Haynie and Upham (1970) have shown that the amount of SO_2 in the air is the major factor in determining the rate of corrosion of zinc. They found that little zinc corrosion would occur in an environment in which SO_2 was not present.

The dose-response relationship between zinc corrosion rate and SO_2 was estimated as follows:

$$Y = 0.00104\ (RH - 49.4)\ SO_2 - 0.00664\ (RH - 76.5) \qquad \text{(V-30)}$$

or alternatively, $Y = 0.001028\ (RH - 48.8)\ SO_2$

where

Y = zinc corrosion rate, μm/year

RH = average relative humidity, percentage

SO_2 = average sulfur dioxide concentration, $\mu g/m^3$

Pitting of Galvanized Steel--J. W. Spence and F. H. Haynie (1974) exposed specimens of galvanized steel to polluted and clean air in controlled environmental chambers. They found that corrosion of the zinc films was essentially a linear function of time for polluted and clean air condition. Uniform corrosion of the zinc occurred in the polluted exposures, whereas pitting corrosion of the zinc was observed in the clean air exposures.

The pitting corrosion, expressed as a uniform thickness loss, fits the relationship:

$$\text{Corr} = t_w \exp \left[30.53 - (16{,}020/RT_m) \right] \qquad \text{(V-31)}$$

where

Corr = amount of pitting corrosion (μm)

t_w = time of wetness, years

T_m = geometric mean specimen temperature when wet, °K

Catastrophic Failure of Metals--Air pollution has contributed to the catastrophic failure of metal structure. John Gerhard and Fred H. Haynie (1974) estimated the loss of metal failure to be between $50 million and $100 million annually for the United States. The dose-response relationship between air pollution and the occurrence of catastrophic failure of metals has not been established in the literature.

Three types of catastrophic failure of metals that are associated with environmental corrosion were identified: (1) stress-corrosion cracking, (2) corrosion fatigue, and (3) hydrogen embrittlement. Notable examples of problem areas involve failure of essential structures, aircraft and aerospace components, and communication equipment.

In the case of a 40 percent reduction in pollution, the per capita cost would drop from the present level of $7.10 to $4.36 by 1980. Assuming a 60 percent reduction in pollution, the per capita cost will drop from $7.10 to $2.20 in 1980.

Air Pollution Corrosion Costs on Metals--Fink, Buttner and Boyd (1971) examined air pollution corrosion costs on metals in the United States from both technical and economic viewpoints. They calculated corrosion costs for the nine major categories which were most sensitive to and most damaged by air pollution corrosion. The grand total cost was estimated at $1.45 billion, or approximately $7.10 per person per year.

Fink, Buttner and Boyd considered SO_2 as the most important pollutant from a corrosion point of view. They projected the damage costs of metals due to SO_2 under a variety of SO_2 concentration levels for 1980. The annual loss would increase from the present $1.45 billion to $2.1 billion by 1980 if there is a 55 percent increase in pollution. A 10 percent increase in SO_2 level would result in an increase in annual loss by $0.3 billion to $1.73 billion in 1980.

Paint

Paint Technology and Air Pollution--

J. W. Spence and F. H. Haynie (1972a) in their recent survey on paint technology and air pollution, identified the characteristics of pollutant attacks on exterior paints, and estimated the annual cost of air pollutant damage to such paints. They assessed the chemical damage of air pollutants for four classes of exterior paints: (1) household, (2) automotive refinishing, (3) coil coating, and (4) maintenance. The cost at the consumer level is more than $0.7 billion annually. Household paints sustain damage representing 75 percent of the total annual dollar loss.

Exterior Paint, SO_2, and Particulates--

Spence and Haynie (1972b) investigated the deterioration of exterior paints due to SO_2 and particulate matter, and the associated potential economic loss to manufacturers and consumers. A breakdown of the damage loss of exterior paints is summarized as follows:

	Loss at Consumer Level (million $)
Coil coating	16
Automotive refinishing	88
Maintenance	60
Household	540
Total	704

Oil Base House Paint, Acrylic Latex House Paint, Vinyl Coil Coating and Acrylic Coil Coating--

A chamber study of the effects of gaseous pollutants on paints was carried out by J. Spence, F. Haynie, and J. Upham (1975c). Regression analysis showed that SO_2 concentration and relative humidity accounted for 61 percent of the variability in the case of oil base house paint which experienced the highest erosion rates. Vinyl and acrylic coil coatings experienced very low erosion rates.

The multiple linear regression of oil base house paint on SO_2 concentration and relative humidity gave the relationship:

$$\text{erosion rate} = 14.323 + 0.01506\ SO_2 + 0.3884\ RH \qquad \text{(V-32)}$$

where erosion rate is $\mu m/year$

SO_2 is $\mu g/m^3$

RH is percent relative humidity

In the case of vinyl and acrylic coil coating, the regression equations are respectively given by:

$$\text{erosion rate} = 2.511 \pm 1.597 \times 10^{-5}\ RH \times SO_2 \qquad \text{(V-33)}$$

and

$$\text{erosion rate} = 0.159 + 0.000714\ O_3 \qquad \text{(V-34)}$$

where O_3 is in $\mu g/m^3$.

Fabric Fading

Selected Drapery Fabrics and NO_2--

Upham, Haynie and Spence (1975) have studied and assessed the fading characteristics of three drapery fabrics after exposure to air pollutants and other environmental factors in the chamber. The experimental results indicated that NO_2 is a major factor in determining the fading rate for one of the fabrics, a plum-colored cotton duck material. The other two fabrics did not fade significantly in the presence of the air pollutants.

The dose-response relationship for the plum fabric was estimated as follows:

$$\Delta E = 30 \left[1 - EXP(-(257 + 3.38 \times 10^{-5} M \times NO_2)t) \right] \qquad \text{(V-35)}$$

where

ΔE = amount of fading, fading units

M = amount of moisture, $\mu g/m^3$, at 25°C and one atmosphere

$NO_2 = \mu g/m^3$

t = exposure time, year

$R^2 = 0.70$

Dyed Fabrics, NO_2, Ozone, SO_2 and Nitric Oxide--

Beloin (1973) assessed 20 dye-fabric combinations which were exposed to two levels each of NO_2, ozone, SO_2 and nitric oxide, at four combinations of temperature and humidity for a period of 12 weeks. The study showed that NO_2, ozone and, to a lesser extent, SO_2, can cause appreciable dye fading, and that nitric oxide has little or no effect. In an earlier article, Beloin (1972) evaluated the color fastness of 67 dye-fabric combinations exposed to atmospheric gases. Multiple regression analysis of pollutant concentrations indicated that SO_2, NO_2 and ozone are major factors determining fabric fading.

Rubber, Ozone, Nitrogen

Stickney, Mueller and Spence (1971) estimated the yearly cost of air pollution damage to rubber industry. The total estimated cost at the consumer level is at least $500 million yearly. Of this, $398 million can be accounted for in detail. Mueller and Stickney (1970) identified ozone as the only major pollutant to shorten the life of rubber products. SO_2 is not known to have harmful effects on rubber products.

Soiling and Suspended Particulates

Beloin and Haynie (1975) studied the soiling of building materials. Six building materials were exposed at five sites in Birmingham, Alabama, to determine the rate of soiling by different levels of suspended particulate. Excellent dose-response relationships were obtained for the white-surfaced painted cedar siding and asphalt shingles. Similar regressions for brick can account for 34 to 50 percent of variability. Poor correlations were obtained for concrete, limestone, and window glass. The regression results are summarized in Table V-6.

Material Damage

Material Damage From SO_2--

An overall assessment of material damage from SO_2 was made by Gillette and Upham (1973) and is summarized as follows:

Metals--Corrosion of metals by acids derived from airborne SO_2 is most important. Zinc and steel are particularly vulnerable to attack by atmospheric SO_2.

Cotton Fabrics--Not significant since most cotton fabrics are not exposed continuously to the external environment.

Synthetic Fabrics and Blends--Not significant with the exception of nylon hosiery.

Dye Fading--Unimportant at present SO_2 concentrations.

Paper and Leather Products--Strongly influenced by SO_2, tend to disintegrate or discolor after prolonged exposure to relatively high levels of SO_2.

Plastics--Little is known about the effects of SO_2 on plastics.

Concrete, Marble, Roofing Slate, Mortar and Other Limestone--Subject to attack from acids derived from SO_2. Most of the concrete and limestone used in the construction of highways and buildings in the United States is not seriously affected by the present level of atmospheric SO_2.

In assessing the damage loss resulting from SO_2, the following observations are noteworthy:

- Most materials are not substantilly damaged when pollution levels are less than 250 $\mu g/m^3$.

TABLE V-6. RESULTS OF REGRESSION ANALYSIS FOR SOILING OF BUILDING MATERIALS AS A FUNCTION OF SUSPENDED PARTICULATE DOSE

Material	Independent variable	N	A	B	S^2_A	S^2_B	S^2_E	R^2	Remarks
Oil Base Paint	$\sqrt{SP(\mu g/m^3) \times t(\text{months})}$	400	89.43	−0.2768	0.0641	0.000069	7.6510	0.745	Excludes all data beyond 12 months
Tint Base Paint	Ditto	400	86.13	−0.2618	0.0571	0.000061	6.8265	0.738	Ditto
Sheltered Acrylic Emulsion Paint	"	400	91.54	−0.593	0.1156	0.000123	13.8143	0.880	"
Acrylic Emulsion Paint	"	720	90.79	−0.4131	0.0497	0.000026	8.3791	0.902	
Shingles	$\frac{SP(\mu g/m^3) \times t(\text{years})}{10}$	48	41.69	−0.331	0.1895	0.000312	3.8685	0.884	Excludes 2 24 month Tarrant readings
Shingles	$\sqrt{SP(\mu g/m^3) \times t(\text{months})}$	48	43.50	−0.199	0.5771	0.000258	7.6992	0.769	Ditto
Concrete	Ditto	160	41.45	−0.0458	0.1338	0.000080	7.5011	0.143	
Coated Limestone	"	80	44.57	+0.0779	0.2464	0.000164	6.9046	0.347	
Uncoated Limestone	"	80	46.99	−0.0503	0.1500	0.000089	4.2035	0.266	
Coated Red Brick	"	80	12.95	−0.0296	0.0223	0.000013	0.6255	0.459	
Uncoated Red Brick	"	80	14.88	−0.0374	0.0331	0.000020	0.9274	0.477	
Coated Yellow Brick	"	80	45.05	−0.1133	0.5337	0.000317	14.9533	0.342	
Uncoated Yellow Brick	"	80	43.21	−0.1133	0.2740	0.000168	7.6773	0.503	
Glass	"	45	0.2806	+0.0314	0.008077	0.000007	0.6851	0.340	Haze readings includeing 3 periods for right panes prior to 12 months

N	Number of data sets (dependent upon the number of controlled variables in the factorial experiment)
A	Intercept of linear regression
B	Slope of linear regression
S^2_A	Estimated variance of intercept
S^2_B	Estimated variance of slope
S^2_E	Residual variance (error)
R^2	Correlation index (fraction of variability accounted for by regression)
SP	Suspended particulate

- Given the present SO_2 levels, damage to most materials other than certain ferrous and nonferrous metals is probably not significant.

- The only important materials adversely affected by SO_2 are iron, steel and zinc products.

- There are two important factors determining the corrosion rate for galvanized products: (1) relative humidity, and (2) SO_2 level.

- The relationship between SO_2 and damage to paint is not as clear as it is between SO_2 and corrosion to galvanized products.

- The threshold or minimum level of SO_2 required to produce an economic loss $\geq$ (10 $\mu g/m^3$). For lack of better data, it is reasonable to assume a threshold level of 20 $\mu g/m^3$ before any loss is achieved.

Finally, to recapitulate, the various physical dose-response relationships for metals, paints, fabrics, and building materials are summarized in Table V-7.

TABLE V-7. PHYSICAL DAMAGE FUNCTIONS FOR MATERIALS

Material	Dose - Response Relationships	R^2
1. Metals		
A. Steel - Carbon steel	$Y = 9.013 \left[e^{0.00161\ SO_2}\right] \left[(4.768t)^{0.7512 - 0.00582\ OX}\right]$	0.91
Copper-bearing steel	$Y = 8.341 \left[e^{0.00171\ SO_2}\right] \left[(4.351t)^{0.8151 - 0.00642\ OX}\right]$	0.91
Weathering steel A	$Y = 8.876 \left[e^{0.0045\ SO_2}\right] \left[(3.389t)^{0.6695 - 0.00544\ OX}\right]$	0.91
Weathering steel B	$corr = \left[5.64 \sqrt{SO_2} + e^{(55.44 - 31{,}150/RT)}\right] \sqrt{t_w}$	0.91
Enameling steel A	$corr = 183.5 \sqrt{t} e^{[0.06421\ Sul - 163.21/RH]}$	
Enameling steel B	$corr = 325 \sqrt{t} e^{[0.00275\ SO_2 - (163.2/RH)]}$	
Galvanized steel	$corr = \left[0.0187\ SO_2 + e^{41.85 - 23{,}240/RT}\right] \sqrt{t_w}$	0.91
B. Zinc	$Y^* = 0.001028\ (RH - 48.8)\ SO_2$	0.92
2. Paints		
A. Oil base house paint	erosion rate = $14.323 + 0.01506\ SO_2 + 0.3884\ RH$	0.61

TABLE V-7 (Concluded

B. Vinyl coil coating	$\text{erosion rate} = 2.511 \pm 1.597 \times 10^{-5}\ RH \times SO_2$	0.34
C. Acrylic coil coating	$\text{erosion rate} = 0.159 + 0.000714\ O_3$	
3. Fabrics - Plain fabric	$\Delta E = 30 \left[1 - e^{-(2.57 + 3.38 \times 10^{-5}\ M \times NO_2)t} \right]$	0.70
4. Soiling of Building Material		
A. Oil base paint	$\text{Reflectance} = 89.43 - 0.2768 \sqrt{SP \times t^*}$	0.74
B. Tint base paint	$\text{Reflectance} = 86.13 - 0.2618 \sqrt{SP \times t^*}$	$R^2 = 0.738$
C. Sheltered acrylic emulsion paint	$\text{Reflectance} = 91.54 - 0.593 \sqrt{SP \times t^*}$	$R^2 = 0.88$
D. Acrylic emulsion paint	$\text{Reflectance} = 90.79 - 0.4131 \sqrt{SP \times t^*}$	$R^2 = 0.902$
E. Shingles	$\text{Reflectance} = 43.50 - 0.199 \sqrt{SP \times t^*}$	$R^2 = 0.769$
F. Coated yellow brick	$\text{Reflectance} = 43.21 - 0.1133 \sqrt{SP \times t^*}$	$R^2 = 0.503$

where Y = depth of corrosion in microns (µ)
SO_2 = µg/m^3
OX = µg/m^3
t = time, years
corr = depth of corrosion in micrometer (µm)
sul = average level of sulfate in suspended particulate (µg/m^3)
RH = average relative humidity, percent
tw = time of wetness
R = 1.9872 cal/g - mole °K
T = geometric mean temperature of the specimen when wet in °K
Y* = Zinc corrosion rate, µm/year
Erosion rate = µm/year
O_3 = Ozone, µg/m^3
ΔE = amount of fading, fading units

M = amount of moisture, µg/m^3 at 25°c and one atmosphere
NO_2 = µg/m^3
Reflectance = a measure of soiling, percent
SP = suspended particulate (µg/m^3)
t* = time, months