



ENVIRONMENTAL RESEARCH BRIEF

Atmospheric Acid Deposition Damage to Paints

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Abstract

Available data from laboratory and field studies of damage to paints by erosion have been analyzed to develop an atmospheric acid deposition damage function for exterior house paints containing calcium carbonate or silicate extenders. Regression analysis coefficients associated with sulfur dioxide levels are consistent with the reaction between the SO_2 and calcium carbonate to form soluble calcium sulfate. The effect of sulfuric acid in rain on paint is expected to be similar. Observed actual household painting frequencies prior to 1970 are consistent with the damage functions calculated from the experimental erosion data obtained in the 1950's, 1960's and early 1970's. Changes in both environmental conditions and types of paints that are marketed make it necessary to make assumptions when using the damage functions to estimate costs associated with repainting. The magnitude of the error of these estimates is the same as the estimate. Research is needed to reduce this error and to determine the effects of acid deposition on other mechanisms of paint failure such as peeling from wood and rusting of painted steel.

Introduction

Reducing the rate of atmospheric acid deposition (both wet and dry) will reduce the amount of "weathering" experienced by certain materials. In the case of paints, an economic benefit results from fewer paintings during the life of a structure. Paint life varies considerably with environmental changes. The most significant factors related to paint life are (a) time-of-wetness, (b) temperature, and (c) sunlight (1). Sulfur dioxide, however, contributes to

the erosion of at least those paints containing carbonate or silicate extenders (2,3,4). These effects were observed under several conditions of time-of-wetness, temperature, simulated sunlight, and pollution levels in laboratory controlled environments. All of these studies used erosion of paints on inert substrates as a measure of damage. Field studies conducted in the past have not been adequate to show whether or not there exists a relationship between paint damage and atmospheric acid deposition. Nor has there been an attempt to translate laboratory observations into atmospheric damage functions. This study uses available field and laboratory data to develop functions for exterior house paints damaged by acid deposition at ambient conditions observed in the United States. These relationships can be used to assess the economic benefit that results from fewer paintings associated with reduced acid deposition.

Several controversies have divided the research community on the paint damage function. The controversies are on issues such as:

1. Is weight change due to paint erosion an acceptably precise measure of damage?
2. Is wearing away the surface or is blistering and cracking the more significant mode of damage for painted wood?
3. Is a blistered surface on painted steel sufficient to define the material as damaged and in need of a repair action?
4. What are the essential components of a paint damage function?

This Research Brief is intended to bring information to the scientific community and not to advocate a conclusion on these types of issues.

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Field Data

The results of a comprehensive study in St. Louis, MO, provide the best evidence of the functional shape of the relationship between paint erosion rate and weather variables (1). There was no evidence of SO₂ damage because, (a) the two studied house paints contained no carbonate and relatively low levels of silicates, and (b) the ambient levels and variations between levels of SO₂ were relatively low. The function is:

$$ER = \Psi f + ER_s + \Sigma B_i P_i f \quad (1)$$

where ER = Paint erosion rate - $\mu\text{m}/\text{year}$
 ER_s = Sunlight contribution - $\mu\text{m}/\text{year}$
 $\Sigma B_i P_i f$ = Sum of pollutant contributions - $\mu\text{m}/\text{year}$
 (any set of pollutants)
 Ψ = Temperature factor
 f = Fraction of time-when-wet

The temperature factor (Ψ) is an Arrhenius relationship:

$$\Psi = \text{EXP}(\sigma - \beta/T) \quad (2)$$

where σ and β are regression coefficients (constants)
 T = Average absolute temperature - °K

The fraction of time-when-wet (f) was defined as:

$$f = 1 - \text{EXP}(-0.694(100/RH_s - 0.975)/(100/RH_A - 1)) \quad (3)$$

where RH_A = average relative humidity
 RH_s = relative humidity above which a surface is expected to be wet

A best fit of the St. Louis paint damage data with respect to average relative humidity produced a coefficient corresponding to an RH_s of approximately 87%. Thus:

$$f = 1 - \text{EXP}(-0.121 RH_A/(100 - RH_A)) \quad (4)$$

In St. Louis, the sunlight contributions ER_s were $0.66 \pm 0.10 \mu\text{m}/\text{year}$ and $0.26 \pm 0.10 \mu\text{m}/\text{year}$ for a latex and an oil base house paint, respectively. In each case the contributions amounted to 35.1% and 10.7% of the south facing latex and oil erosion rates, respectively. The sum of the pollutant effects ($\Sigma B_i P_i f$) was relatively insignificant, leaving Ψf the primary effect.

In a contracted study for the U.S. Environmental Protection Agency (EPA) by Sherwin-Williams Co. (2,3) erosion rates of five paints were measured at sites in four different cities. They also reported data they had previously obtained in eight other cities for the same paints. Table 1 lists the cities and their estimated average environmental conditions.

Four of the five exposed paints are of interest in the Sherwin-Williams study: (a) a latex house paint; (b) an oil base paint; (c) a maintenance paint; and (d) a coil coating. The significant compositional differences for these and the EPA St. Louis study paints are given in Table 2.

The previously obtained data in this study were based on calibrated visual ratings. Visual ratings were made on

Table 1. Estimated Environmental Conditions at Paint Exposure Sites

City	Estimated Long-Term Average			
	Relative Humidity ^a (%)	f ^b	Temperature ^a (°C)	SO ₂ ^c ($\mu\text{g}/\text{m}^3$)
Concord/Oakland, CA	77	0.33	13	8
Los Angeles, CA	63	0.19	18	37
Wilmington, DE	66	0.21	13	50
Miami, FL	73	0.28	24	7
Valparaiso, IN	69	0.24	10	20
Chicago, IL	67	0.22	10	97
St. Louis, MO ^d	71	0.26	9	47
Atlantic City, NJ	70	0.24	12	21
Leeds, ND	68	0.22	5	5
Newton, PA	66	0.21	13	61
Palmerton, PA	68	0.23	12	42
Garland, TX	64	0.19	16	7

^aCalculated from long-term normal values from weather stations near each site. Estimated standard deviations on true values are $\pm 3\%$ for relative humidity and $\pm 1^\circ\text{C}$ for temperature.

^bCalculated using equation (4) and average relative humidity (RH_A).

^cCalculated from multi-year annual average data (late 1960's, early 1970's) reported for pollutant measuring stations nearest each site. Estimated standard deviations on the true means are $\pm 20\%$ of the means.

^dAverages for nine sites in St. Louis during the time of the study cited. Included for comparison.

Table 2. Compositional Differences of Paints

Paint	Use	Base	Extender
1	House Paint ^a	Acrylic latex/water	Silicates
2	House paint ^a	Oil	Calcium carbonate/silicates
3	Industrial maintenance ^a	Alkyd	None
4	Coil coating ^a	Alkyd	Calcium carbonate/magnesium silica
5	House paint ^b	Acrylic latex/water	Silicates (11.6%)
6	House paint ^b	Oil/alkyd	Silicates (0.5%)

^aSherwin-Williams study.

^bSt. Louis study.

panels having different measured film thickness. The number of months to reach a visual rating of 7 (sufficient show through to require repainting) was taken as paint life. With these paints, a visual rating of 7 corresponded to a calibration thickness of $18 \mu\text{m}$ (0.7 mils). The desired initial dry film thickness varies with the type of paint. The lowest value for a field applied coating is around $38 \mu\text{m}$ (1.5 mil) for a coverage of about 46.5 m^2 (500 ft²)/gal. Thus, erosion rate

Table 3. Paint Erosion Rates and Estimated Standard Deviations at Four Sites (μ/year)*

Site	Latex House(1)		Oil House(2)		Maintenance(3)		Coil Coating(4)	
	North	South	North	South	North	South	North	South
Los Angeles, CA	0.91 \pm 0.14	0.91 \pm 0.35	3.96 \pm 0.95	4.88 \pm 0.79	1.82 \pm 0.21	2.44 \pm 0.32	3.05 \pm 0.32	3.66 \pm 0.3
Valparaiso, IN	0.61 \pm 0.09	0.61 \pm 0.04	2.44 \pm 0.36	3.05 \pm 0.23	1.52 \pm 0.70	1.83 \pm 0.18	2.49 \pm 0.09	2.74 \pm 0.2
Chicago, IL	0.91 \pm 0.08	0.91 \pm 0.04	3.96 \pm 0.33	4.88 \pm 0.60	1.52 \pm 0.70	1.83 \pm 0.34	3.05 \pm 0.12	3.35 \pm 0.2
Leeds, ND	0.30 \pm 0.08	0.30 \pm 0.08	0.30 \pm 0.14	0.61 \pm 0.22	0.91 \pm 0.20	1.22 \pm 0.37	0.61 \pm 0.09	0.61 \pm 0.17

*Based on weight loss.
Source: Campbell et al. (3).

can be calculated by dividing paint life into 20 μm . Conversely, paint life can be calculated by dividing 20 μm by erosion rate. All the paints were exposed facing south.

During the study, erosion rates were determined by weight loss as a function of time. Dry film paint density was used to calculate thickness loss. Paints were exposed vertically facing both north and south. The results of this field test are given in Table 3.

The differences in the erosion rates of the paints facing south and north average 16.3% of the total. For the individual paints, the values are 0, 20.6, 21.2, and 11.7% for latex, oil, maintenance, and coil coating, respectively.

The visual rating results converted to erosion rates are given in Table 4. These panels faced south, thus, the effect of sunlight could be as much as 20% of the total.

Taking 80 percent of each value in Table 4 and dividing by the fraction of time-when-wet from Table 1 gives the erosion rate when wet and not exposed to the sun. Similar rates can be obtained by dividing the north-facing values of Table 3 by the fraction of time-when-wet. The resulting calculated values using these data are presented in Table 5.

Both weight loss and visual ratings were obtained at Valparaiso, however, they were not the same exposure periods and environmental conditions could have differed from the long term averages. The visual rating results are consistently higher than the weight loss results. The weight loss data are more accurate; however, the visual rating data are more consistent with normal paint life. If the initial thickness of paints on the visual rating samples was actually less than the desired 38 μm , the values from the two methods would be more nearly the same and still be consistent with normal paint life.

The weight loss and visual data were normalized by multiplying the visual data by the ratios of the weight loss to visual values for Valparaiso. The resulting pooled data were least squares fitted to the environmental data in Table 1 using the following functional relationship:

$$ER_w = \text{EXP}(\sigma + \beta/T) + R_1\text{SO}_2 \quad (5)$$

where ER_w = erosion rate when wet
 σ and β are regression coefficients (constants)

Table 4. Paint Erosion Rates and Estimated Standard Deviations Based on Visual Rating Data (μ/year)^a

Site	Latex House(1)	Oil House(2)	Maintenance(3)
Concord/Oakland, CA	--	4.00 \pm 0.75	6.41 ^b
Wilmington, DE	3.95 \pm 0.85	4.90 \pm 0.55	--
Miami, FL	3.60 \pm 0.67	6.10 \pm 1.55	4.80 \pm 0.78
Valparaiso, IN	2.80 \pm 0.55	3.72 \pm 0.77	4.43 ^b
Atlantic City, NJ	--	--	6.25 ^b
Newton, PA	4.00 ^b	--	--
Palmerton, PA	3.10 \pm 0.75	--	--
Garland, TX	--	--	3.53 ^b

^aExposed vertically facing south.

^bSingle value

Source: Campbell et al. (2).

T = average absolute temperature— $^{\circ}\text{K}$
 B_1 = coefficient for SO_2 damage
($\mu\text{m}/\text{year}$)/($\mu\text{g}/\text{m}^3$)
 SO_2 = sulfur dioxide ($\mu\text{g}/\text{m}^3$)

The results are given in Table 6.

The only coefficients that are not significant are for the shaded maintenance paint. With the exception of latex, the unshaded SO_2 coefficients are larger than the shaded SO_2 coefficients, indicating a photochemical interaction with SO_2 damage.

Laboratory Studies

Two controlled environment laboratory studies have demonstrated cause-effect relationships between pollutants and paint damage (3,4). The formulations of the paints evaluated by Sherwin-Williams Co. were the same as those used in their field study. The compositional differences of the paints in the EPA study are given in Table 7.

Both studies used dew-light cycles with xenon arcs as a simulated sunlight source for a total of 1000 h of exposure. In the Sherwin-Williams study, half of the specimens were shaded from the light source. None were shaded in the EPA study. The EPA study used two different input relative humidities. The Sherwin-Williams study had only one. The

Table 5. Paint Erosion Rates and Standard Deviations When Wet and Shaded ($\mu\text{m}/\text{year}$)

Site	Latex House(1)		Oil House(2)		Maintenance(3)		Coil Coating(4)
	Weight Loss	Visual	Weight Loss	Visual	Weight Loss	Visual	Weight Loss
Concord/Oakland, CA	--	--	--	9.70±1.87	--	15.54 ^a	--
Los Angeles, CA	4.84±0.74	--	21.06±5.05	--	9.68±1.11	--	16.22±1.8
Wilmington, DE	--	15.12±3.25	--	18.76±2.11	--	--	--
Miami, FL	--	10.18±1.89	--	17.29±4.38	--	13.57±2.20	--
Valparaiso, IN	2.57±0.38	9.95±1.86	10.30±1.52	12.56±2.60	6.41±1.01	19.95 ^a	--
Chicago, IL	4.16±0.37	--	18.08±1.51	--	6.94±0.91	--	13.93±0.55
St. Louis, MO	4.79±0.10 ^b	--	2.71±0.07 ^b	--	--	--	--
Atlantic City, NJ	--	--	--	--	--	20.75 ^a	--
Leeds, ND	1.35±0.36	--	1.35±0.63	--	4.08±0.90	--	2.74±0.40
Newton, PA	--	15.31 ^a	--	--	--	--	--
Palmerton, PA	--	10.92±2.64	--	--	--	--	--
Garland, TX	--	--	--	--	--	19.76 ^a	--

^aSingle value

^bDifferent formulations included for comparison.

--No data.

1,2,3,4 Number of paint from Table 2.

Table 6. Coefficients and Estimated Standard Deviations for Field-Obtained Paint Damage Functions

Paint	No.	Shaded (North)			Unshaded (South)		
		σ	β	B_1 ($\mu\text{m}/\text{year}$)/($\mu\text{g}/\text{m}^3$)	σ	β	B_1 ($\mu\text{m}/\text{year}$)/($\mu\text{g}/\text{m}^3$)
Latex	1	12.92±3.83*	-3470±1100*	0.027±0.004*	9.19 ±5.83*	-2400±1090*	0.023±0.003*
Oil	2	24.64±5.77*	-6490±1660*	0.154±0.017*	23.77 ±4.77*	-6150±1360*	0.195±0.025*
Maintenance	3	6.46±3.07*	-1310±880	0.020±0.11	9.600±3.11*	-2150± 900*	0.095±0.018*
Coil Coating	4	32.43±4.17*	-8600±1180*	0.067±0.007*	35.86 ±4.53*	-9606±1290*	0.093±0.012*
Latex ^(a)	5	12.30±0.02*	-3040±90*	--	12.43 ±0.02*	-3040±90*	--
Oil ⁽¹⁾	6	27.29±0.03*	-7490±120*	--	27.40 ±0.03*	-7490±120*	--

^(a)From St. Louis study (1), for comparison

*Statistically significant at the 95% confidence level.

environmental conditions are summarized in Table 8. These conditions do not fully simulate actual long term exposures which have rain and freezing but do indicate the effects of the parameters that were controlled.

The erosion rates for the acrylic coil coating (paint 9 from Table 7) were extremely low and not statistically related to any of the environmental factors. All of the others with the exception of the industrial maintenance paint were affected by SO₂. All the erosion rates were divided by the fraction of time-when-wet to get the erosion rate-when-wet. The Sherwin-Williams data were fitted to the equation:

$$ER_w = A + B_1 \cdot SO_2 + B_2 \cdot O_3 \quad (6)$$

where A, B₁, and B₂ are regression coefficients, SO₂ and O₃ are expressed in micrograms per cubic meter.

Table 9 gives the resulting coefficients.

The differences between xenon arc exposed and shaded erosion rates are most significant in this experiment. All of the coefficients appear to be affected, indicating not only a

Table 7. Compositional Differences of Paints in EPA Study

Paint	Use	Base	Extender
7	House paint	Oil/alkyd	Magnesium silicate
8	Coil coating ^a	Vinyl	not known
9	Coil coating ^a	Acrylic	not known

^aFactory applied to aluminum siding.

Table 8. Laboratory Controlled Environment Conditions

Experiment	Cycle Time (min)	Fraction of Time-When-Wet	Shade	Dark (Dew) Temperature °K	Pollutants ($\mu\text{g}/\text{m}^3$)
Sherwin-Williams	120	0.5	1/2	322.0	clean, SO ₂ -262, 2620 O ₃ -197, 1965
EPA low RH	40	0.5175	None	293.6	clean, full two level factorial with
EPA high RH	90	0.6125	None	302.6	SO ₂ -79, 1310 O ₃ -157, 980 NO ₂ -94, 940

Table 9. Laboratory-Obtained Damage Function Coefficients and Standard Deviations from Sherwin-Williams Data

Paint	No ^a	Shaded	$\mu\text{m}/\text{year}$ A	$(\mu/\text{year})(\mu\text{g}/\text{m}^3)$ B ₁	$(\mu/\text{year})(\mu\text{g}/\text{m}^3)$ B ₂
Latex	(1)	Yes	10.43 ± 4.05*	0.0096 ± 0.0039*	-0.0042 ± 0.0044
		No	23.25 ± 1.25*	0.0098 ± 0.0018*	-0.0719 ± 0.0118*
Oil	(2)	Yes	34.13 ± 9.48*	0.0643 ± 0.0184*	0.0014 ± 0.0098
		No	53.67 ± 8.34*	0.1952 ± 0.0336*	0.0327 ± 0.0247
Maintenance	(3)	Yes	43.10 ± 10.08*	0.0056 ± 0.0080	0.0175 ± 0.0341
		No	60.56 ± 11.10*	0.0125 ± 0.0132	0.0278 ± 0.0320
Coil Coating	(4)	Yes	12.49 ± 7.00	0.0266 ± 0.0179	0.0012 ± 0.0103
		No	39.80 ± 4.87*	0.0396 ± 0.0084*	0.0076 ± 0.0068

*Statistically significant at the 95% confidence level

^aNumber from Table 2

direct effect of radiation but also a photochemical interaction with the pollutants. The mean percent of the light effect on coefficients, A, B₁ and B₂, is 47 ± 18%, 39 ± 29%, and 78 ± 28%. The overall average effect on corrosion rate is around 43%. The amount of simulated sun radiation absorbed by the paints in these laboratory experiments is much greater than that absorbed on vertically mounted southfacing paints in the field studies. The average effect in the field was only around 20%.

The EPA laboratory data were multiplied by 0.57 (1-.43) to eliminate the radiation effect and fitted to equation (5) for comparison with the shaded field data and the Sherwin-Williams laboratory data. The results are given in Table 10. Regressions were done including ozone as a variable with the result that B₂ coefficients were not statistically significant. Thus, ozone was excluded in the analysis reported in Table 10.

Although the experimental conditions and paints that were evaluated were different in the two laboratory tests, some comparisons can be made. There was only one ozone coefficient in either study that was statistically significant. The sign for that coefficient was not in the expected direction and probably has no physical significance. Six of the ten SO₂ coefficients are statistically significant. The EPA oil house paint contains silicate extenders while the Sherwin-Williams oil paint contains calcium carbonate. In the shaded condition, the SO₂ coefficient for the latter is about 2.5 times that of the former. Unshaded, the ratio of the two is more than four times.

The Sherwin-Williams experiments were done at only one dew temperature while the EPA study was done at two. The A coefficients from the Sherwin-Williams study are consistent with the σ and β coefficients from the EPA study at comparable temperatures. More important, the σ and β coefficients from the laboratory study are consistent with those in Table 6 obtained from field studies. This field-laboratory consistency is also true for the SO₂ coefficients. The magnitudes are comparable for the same types of paints.

Please refer to the cited literature for details on experimental designs and procedures for both the field and laboratory studies.

Table 10. Damage Function Coefficients and Estimated Standard Deviation from EPA Laboratory Study

Paint	No ^(a)	σ	β	B ₁ $(\mu\text{m}/\text{year})(\mu\text{g}/\text{m}^3)$
Oil	(7)	25.976 ± 5.041*	-6736 ± 1500*	0.0261 ± 0.0044*
Vinyl Coil Coating	(8)	10.630 ± 4.676*	2929 ± 1399*	0.0007 ± 0.0004

*Significance at the 95% confidence level

^(a)Number from Table 7

Actual House Painting Frequency

Individuals paint their houses for several reasons including substrate show through caused by paint erosion. Cracking and peeling from moisture damage, desiring a color change, and soiling are equally as important reasons for painting. Thus, if the acid deposition damage functions developed in this study are to be useful in an economic analysis, erosion must be the mechanism limiting paint life.

Two surveys on soiling effects included house painting frequency as a possible economic effect (5,6). The most detailed survey was done in Philadelphia in 1970 by Booz, Allen and Hamilton, Inc (BAH) (5). Less rigorous surveys had previously been done by Michelson and Tourin (6) in two Ohio cities and in three suburbs of Washington, D C.

In their analysis, BAH never looked at more than two possible causative factors at a time. In some cases, they observed no statistical significance because possible causative factors were negatively covariant, canceling effects. Outside wall painting is an example. The reported results are in Table 11.

The means for all households are negatively correlated with pollution levels, not a realistic expectation. For example, painting outside walls only every 33 years is not typical. That mean frequency (.03) includes a lot of people that do not need to paint. Realistic frequencies are noted for those households that actually performed the task. There is a negative correlation between pollution level and percent of households performing the task. The reason for this relationship becomes apparent when it is noted that the

percent of houses having more than 10% painted wood outside wall area for zones 1 through 4, respectively, was 28.1, 23.8, 8.7, and 3.5 (BAH values adjusted with non-responses prorated). Thus, approximately nine houses in the most polluted zone required painting of outside wooden walls. Apparently, about 17 households in that zone painted masonry. This represents a fairly small sample upon which to make a statistical analysis; however, the standard error indicates it can be done.

One would expect that the ability to do something about a high cost pollution effect would be related to household income. The percent of households with incomes of \$10,000 or more for zones 1 through 4, respectively, was 45, 37, 16, and 14 (BAH values adjusted with non-responses prorated). Thus, there are fewer households in the most polluted zones that have the ability to do anything about it. BAH analyzed all responses by income level but did not further restrict the analysis to only those performing the task. If one makes the assumption that the given percentages of households doing the task apply equally to all income levels, this adjustment can be made. The results are given in Table 12.

The maintenance frequencies for those performing the tasks are reasonable and the effect of pollution is in the expected direction. The small sample sizes in the two most polluted zones, however, make the probability of statistically significant differences very low. There is only a probability of about 0.5 that zones 2 and 4 are different or the same.

In Table 13 these frequencies compare favorably with values reported by Michelson and Tourin (6).

Paint life is the reciprocal of painting frequency and varies from about one to four years. There appears to be a strong

dependence on particulate matter level. Generally, however, in the 1960's particulate matter levels were covariant with SO₂ levels. For example, from modelled isopleths for Philadelphia (7), comparable SO₂ levels for zones 1 through 4, were estimated to be 40, 60, 170, and 240 µg/m³, respectively. Using the field-obtained coefficients for the Sherwin-Williams unshaded oil paint, a critical thickness loss of 20 µm, an average temperature of 12.5°C, a fraction of time-when-wet of 0.21, and the above SO₂ levels, the respective painting frequencies for zones 1 through 4 are calculated to be 0.18, 0.22, 0.44, and 0.58 times per year, respectively. These values are consistent with the survey values. Thus, it is possible that either the aesthetic soiling effect, the physical acid damage, or both could have caused households to repaint.

Significant Market Changes Since 1970

House paints have been improved significantly since the late 1960's and early 1970's; however, cheaper, less durable paints are often used by house builders and painting contractors. Less oil base paints are now being used. In 1980, the ratio of exterior latex to exterior oil sold was 6.5 (8) as compared to 1.375 in 1968 (9). An informal survey of four local paint dealers yielded the data presented in Table 14.

The least durable paints contain significant amounts of calcium carbonate. One dealer referred to them as contractor paints. Significant amounts of silicates are used in all grades of flat latex paints; however, concentration tends to decrease with increasing durability. Silicates have beneficial effects other than as an extender. They contribute to a flat sheen and improve resistance to chipping, checking, and cracking (8).

Table 11. BAH Results of Painting Outside Walls

Zone	Annual Mean TSP (µg/m ³)	Number in Sample	All Households		Households Performing Task		
			Mean Annual Frequency 1/years	Standard Error of Mean	% of all Households	Mean Annual Frequency 1/years	Standard Error of Mean
1	50-74	471	0.11	0.009	38.6	0.28	0.016
2	75-99	421	0.10	0.017	28.5	0.35	0.053
3	100-124	299	0.04	0.008	11.4	0.35	0.041
4	125-151	251	0.03	0.008	10.4	0.29	0.055

TSP—Total Suspended Particulate Matter.

Table 12. Outside Wall Painting Frequency for Households With Income of \$10,000 or More

Zone	Annual Mean TSP (µg/m ³)	Number	All Households		Households Performing Task		
			Mean Annual Frequency	Standard Error of Mean	% of All Households	Mean Annual Frequency	Standard Error of Mean
1	50-74	212	0.14	0.017	82	0.36	0.044
2	75-99	156	0.10	0.016	44	0.35	0.056
3	100-124	48	0.05	0.023	5	0.44	0.202
4	125-151	35	0.05	0.023	4	0.48	0.221

Table 13. Annual Average TSP and Painting Frequency in Different Cities

City	TSP ($\mu\text{g}/\text{m}^3$)	Painting Frequency/Year
Fairfax	60	0.26
Philadelphia - Zone 1	61	0.36
Rockville	75	0.28
Suitland	85	0.34
Philadelphia - Zone 2	86	0.35
Philadelphia - Zone 3	111	0.44
Uniontown	115	0.53
Philadelphia - Zone 4	137	0.48
Steubenville	235	1.14

Table 14. Paint Data from Informal Dealer Survey

Brand	Base/Sheen	Extender	Price per Gallon	Warranty or Estimated Life
A	Latex/Flat	15.6% CaCO ₃	\$ 9.53	3
A	Latex/Flat	22% Silicates	\$11.97	5
A	Latex/Satin	2.5% Silicates	\$14.97	8
A	Latex/Flat	15% Silicates	\$16.97	9
B	Latex/Flat	17% Silicates	\$11.97	3
B	Latex/Flat	18% Silicates	\$15.99	6
B	Latex/Flat	21% Silicates	\$18.99	8
B	Latex/Satin	20% Silicates	\$16.97	9
B	Latex/Flat	19% Silicates	\$21.99	10
B	Latex/Gloss	2% Silicates	\$22.99	10
B	Alkyd/Gloss	2% Silicates	\$23.99	10
C	Latex/Flat	12.9% Silicates	\$16.99	5
C	Latex/Flat	11.5% Silicates	\$16.99	10
C	Latex/Flat	13% Silicates	\$19.99	15
D	Latex/Flat	22% CaCO ₃	\$11.99	3
D	Latex/Flat	5.9% Silicates	\$16.99	9

One dealer confirmed the national figures; in that only about 15% of his sales were oil base paints. His most popular paints were the 8-year warranty latex that outsold the 10-year warranty latex by about 50%. Another dealer sold most of his paints to contractors. His cheapest or contractor grade outsold his best grade by about 2 to 1. One might expect that the more durable paints are bought by homeowners to replace the original lower grade paints purchased by builders and contractors.

Selected Coefficients for a Composite Damage Function

More than 85% of house paints are water base latex. Thus, damage coefficients for latex should be representative. The σ and β coefficients for the latex paint exposed in St. Louis have the least variation and are not significantly different from the Sherwin-Williams latex study. The SO₂ coefficients (B₁) are generally a function of the type of extender. If half of the paint sold contains calcium carbonate and lasts four years and the other half contains silicates and lasts eight years, then there would be a 3 to 1 ratio of silicate to carbonate containing paints on walls at any point in time.

Other ratios could be used. Thus, any analysis should be weighted accordingly. For general application to unknown paint compositions, it may be assumed that the SO₂ coefficients apply equally well to all types of paints. They are summarized in Table 15.

The SO₂ coefficient for the calcium carbonate-containing paints is about what can be calculated for a stoichiometric leaching out of product calcium sulfate, with an SO₂ deposition velocity of 0.7 cm/s. Assuming a deposition velocity of 0.7 cm/s, the coefficient can be expressed in terms of rate of accumulation of SO₂ or acidity and, thus, can be applied to acidity in rain. If SO₂ flux is expressed in micrograms per cubic centimeter per year, the CaCO₃ coefficient is $0.00540 \pm 0.00425 \mu\text{m}/\mu\text{g}/\text{cm}^2$. If rain is expressed in centimeters per year and acidity is due to SO₂, the coefficient is

$$[174 \pm 136] \times 10^{-\text{pH}} \mu\text{m}/\text{cm}$$

Similar coefficients for the silicate-containing paints are

$$0.00088 \pm 0.00045 \mu\text{m}/\mu\text{g}/\text{cm}^2 \text{ and } [27 \pm 15] \times 10^{-\text{pH}} \mu\text{m}/\text{cm}.$$

It should be noted that the estimated standard deviations on all of these coefficients are the same order of magnitude as the mean values with which they are associated. None of the calculated coefficients are statistically significant from zero at the 95% confidence level. We have shown, however, that coefficients for individual paints are statistically significant and the mean SO₂ coefficient for carbonate-containing paints is consistent with theory.

Translating Physical Damage to Economic Loss

The basic assumption in using these data in a cost analysis is that erosion of paint film to substrate show through is the life limiting factor that causes households to repaint. There are other major causes for repainting. Two of the most important are the aesthetic effects of soiling (dirtiness) and peeling of the paint from the substrate. Neither of these damage functions is considered in this study. Both could possibly be life limiting factors.

Undiscounted annual costs are directly proportional to annual painting frequency. The marginal costs associated

Table 15. Summary of Unshaded SO₂ (B₁) Coefficients ($\mu\text{m}/\text{year}$)/($\mu\text{g}/\text{m}^3$)

	Extender	
	Calcium Carbonate	Silicates
Individual values	0.1950±0.0280	0.0098±0.0018
	0.0928±0.0119	0.0261±0.0044**
	0.1952±0.0336	0.0229±0.0029
	0.0396±0.0084	
Weighted geometric mean*	0.1191±0.0939	0.0194±0.0099

*Coefficients and standard deviations converted to log forms, coefficients weighted by the reciprocal of the estimated variation.

**Shaded.

with pollution is a function of the annual additional painting frequency.

In order to estimate annual additional cost as a function of wet and dry deposition, the damage functions should be expressed as annual additional painting frequency:

$$PF = (ER-ER_0)/t_c \quad (8)$$

where PF = additional painting frequency (per year)
 ER₀ = erosion rate for clean conditions (μm/year)
 t_c = critical thickness loss (about 20μ for normal application)

The additional annual cost is:

$$C_A = C_p \Delta ER / t_c \quad (9)$$

where C_p = cost per painting
 ΔER = (ER-ER₀)

Because erosion rate difference is used, only the pollutant coefficients and fraction of time-when-wet are needed to calculate additional costs. For CaCO₃-containing paints assuming a pH of 5.2 and an SO₂ level of zero as clean:

$$\Delta ER/t_c = r[8.7 \pm 6.8][10^{-pH} - 10^{-5.2}] + [0.0060 \pm 0.0045]SO_2 f \quad (10a)$$

and for silicate-containing paints.

$$\Delta ER/t_c = r[1.35 \pm 0.75][10^{-pH} - 10^{-5.2}] + [0.00097 \pm 0.00050]SO_2 f \quad (10b)$$

where r = annual rainfall (cm)
 SO₂ = average sulfur dioxide (μg/m³)
 f = fraction of time-when-wet

The annual additional cost per house for the two paints can be compared. Assume that painting with the cheaper calcium carbonate-containing paint costs \$800 and that painting with the better silicate-containing paint costs \$900. Assume the annual rainfall is 100 cm and the fraction of time-when-wet is 0.2. The calculated additional costs as a function of pollutant level are given in Table 16.

Without pollutants, at an average temperature of 12.5°C, the annual painting costs for the carbonate and silicate paints are estimated to be \$49 and \$55, respectively. From Table 16 it is obvious that it does not take much pollution to make the silicate paint the better buy

Expenditures in the future such as repainting are perceived to not be as important as present expenditures. Thus, they are usually discounted. The amount of the discount depends on how far in the future the expenditure must be made and the expected change in the value of money along with other subjective factors. Discount rates are not necessarily the same as interest rates or inflation rates although these can be used as a guide. Pensioners on low fixed income probably discount future repainting much greater than middle income families that intend to live in their houses for more than ten years. In any case, discounting does reduce the annual additional painting costs associated with wet and dry acid deposition

Table 16. Undiscounted Annual Additional Painting Cost Per House

Pollutant Type	Level	Dollars*			
		Carbonate		Silicate	
		Best Estimate	(Upper 95% Confidence Limit) ^(a)	Best Estimate	(Upper 95% Confidence Limit) ^(a)
SO ₂ (μg/m ³)	20	19	48	3	7
	40	38	96	7	14
	60	58	144	10	21
	80	77	192	14	28
	100	96	240	17	35
Wet deposition (pH)	3	692	1773	121	255
	3.5	216	553	38	79
Wet deposition (pH)	4	65	167	11	24
	4.5	18	45	3	6
	5	3	7	0	1

*To nearest dollar

^(a)(Lower 95% confidence limits for both paints are zero for all levels of pollutants)

Discussion and Conclusions

Erosion of paint films to the point at which the substrate begins to show is one of several mechanisms of paint failure resulting in repainting. There are data available from field and laboratory studies that show this type of failure to be dependent on SO₂ levels. Paints containing calcium carbonate extenders are susceptible to attack by SO₂. The magnitude of the attack is consistent with a mechanism of the formation of soluble CaSO₄. Sulfuric acid deposition in rain is expected to have the same effect. Thus, coefficients for wet and dry acid deposition effects can be calculated for calcium carbonate-containing paints.

The effects of temperature and other additive factors cancel out when the damage function is expressed as additional annual painting frequency. This greatly simplifies its application to areas having different climatic conditions. The annual marginal costs can then be directly related to acid deposition levels.

Just based on the variability of the available data, the magnitude of the error in any economic cost estimate will be the same as the estimate. This means the cost could be zero or twice as much as the estimate. Assumptions in economic analysis increase this error. This information, however, does provide a first-cut basis for estimating the relative magnitude of the problem of acid deposition effects on paints.

Recommendations

This study also shows that much more information is needed to accurately assess the damaging effects of acid deposition on paints.

Research is needed to determine the effects on painted hot rolled steel (bridges, etc.).

Research is needed to determine the mechanism of paint peeling from wood associated with acid hydrolysis.

Surveys are needed to determine the relative magnitude of costs associated with different types of paint failures on different substrates, and to see if there is any association with known environmental differences.

More work is needed on the relatively simple mechanism of erosion to reduce the magnitude of the observed error to an acceptable level.

Literature Cited

1. Haynie, F. H. and Spence, J. W. (1984) Air Pollution Damage to Exterior Household Paints. *J. Air Pollut. Control Assoc.*, 34:941-944.
2. Campbell, G. G., Schurr, G. G., and Slawikoski, D. E. (1972) *A Study to Evaluate Techniques of Assessing Air Pollution Damage to Paints*. Final Report EPA Contract 68-02-0030. Sherwin-Williams Co., Chicago, Illinois. 85 pp.
3. Campbell, G. G., Schurr, G. G., Slawikoski, D. E., and Spence, J. W. (1974) Assessing Air Pollution Damage to Coatings. *J. Paint Technol.*, 46(593):59-71.
4. Spence, J. W., Haynie, F. H., and Upham, J. B. (1975) Effects of Gaseous Pollutants on Paints: A Chamber Study. *J. Paint Technol.*, 4(609):57-63.
5. Booz, Allen and Hamilton, Inc. (1970) *Study to Determine Residential Soiling Costs of Particulate Air* Final Report National Air Pollution Control Administration Contract No. CPA 22-69-103. Washington, DC.
6. Spence, J. W. and Haynie, F. H. (1972) *Paint Technology and Air Pollution: A Survey and Economic Assessment*. Office of Air Programs Publication No. AP-103. U.S. Environmental Protection Agency, Research Triangle Park, NC. 44 pp.
7. Public Health Service. (1968) *Report for Consultation on the Metropolitan Philadelphia Interstate Air Quality Control Region*. Department of Health, Education and Welfare, National Air Pollution Control Administration. 74 pp.
8. Rich, S. (1981) *The Kline Guide to the Paint Industry*; Sixth Edition. Charles H. Kline & Co., Fairfield, NJ. 199 pp.
9. Noble, P. (1969) *Marketing Guide to the Paint Industry*. Charles H. Kline & Co., Fairfield, NJ.