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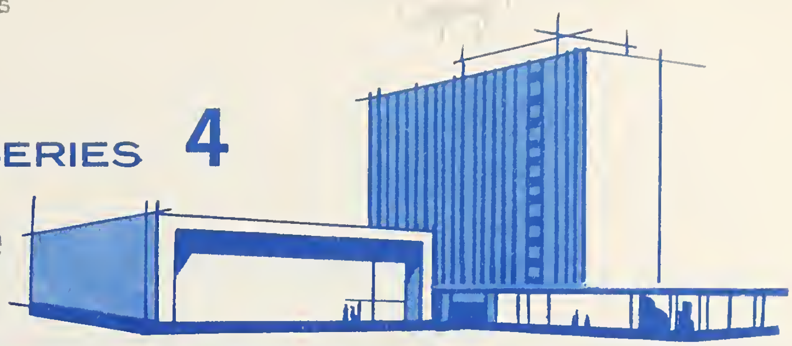

Weather Resistance of Porcelain Enamels

Effect of exposure site and other variables after 7 years

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Weather Resistance of Porcelain Enamels

Effect of Exposure Site and Other Variables After Seven Years

Margaret A. Rushmer and Milton D. Burdick

Building Research Division
Institute for Applied Technology
National Bureau of Standards
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CONTENTS

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Weather Resistance of Porcelain Enamels

Effect of Exposure Site and Other Variables After Seven Years

Margaret A. Rushmer and Milton D. Burdick *

An exposure test of porcelain enamels at seven representative sites in the continental United States was initiated by the National Bureau of Standards and the Porcelain Enamel Institute in 1956. After seven years all specimens were returned to the Bureau and the changes in gloss and color determined. These changes were found to be different at all exposure sites except Pittsburgh and New Orleans. The most severe changes occurred for specimens exposed at Kure Beach, 80 feet from the ocean, while the least change occurred for specimens exposed at Los Angeles. The differences in behavior of the specimens correlated with both the relative humidity and the *p*H of the suspended particulate matter at the different sites.

A direct relation existed between the acid resistance of the enamels and weather resistance. However, enamels of different types, such as enamels on aluminum and steel, having the same acid resistance did not necessarily show the same weather resistance.

Comparison with enamel specimens exposed for seven years in an earlier test showed that porcelain enamels produced after the end of World War II were equally resistant to changes in gloss at the Washington, D.C., site as those produced before the war.

As a group, the regular glossy acid-resistant enamels on steel showed the best weather resistance of the various types tested. No corrosion of the base metal was noted for any specimen on which the initial coverage was complete.

Key words: Acid resistance, color, gloss, *p*H, porcelain enamel, relative humidity, weather resistance.

1. Introduction

The weather resistance of porcelain enamels is important to architects and engineers who have the responsibility of selecting exterior finishes for various types of buildings, as well as to owners who are interested in obtaining a long, maintenance-free life from the finish. That some porcelain enamels have excellent weather resistance is widely recognized from inspection of early installations. It is also recognized that not all enamels have this durability. Exposure test data are needed on new enamel types as they are developed, and, in addition, there is a need for reliable laboratory tests that will predict the weathering behavior of new enamels.

The National Bureau of Standards first recognized these needs of the building industry in 1939. An investigation started at that time resulted in a series of reports issued after exposure periods of 1 [1],** 7 [2], and 15 [3] years. The principle finding of that investigation of porcelain enamels on steel, was that the best enamels showed no objectionable changes in either gloss or color at any of the four selected exposure sites after exposure for 15 years and, further, that the enamels with poor resistance could be eliminated from consideration by relatively simple laboratory tests.

After World War II, several new enamel types were introduced and it became important to determine if these new types followed the same pattern, with respect to weathering, as those produced earlier. Such information was of added importance because of the rapidly expanding use of porcelain enamel in modern architectural design, especially in those buildings employing curtain wall construction. Thus, in 1956, a second test was initiated by the National Bureau of Standards and the Porcelain Enamel Institute Research Associateship at the Bureau. Progress reports of the test have been published after 1 [4] and 3 [5] years' exposure.

The present paper is a progress report after 7 years' exposure. For ease of comparison, the same general format is followed as was used in the 3-year report [5]. Also, as an aid to the reader, the description of specimens and exposure sites is repeated in this paper.

The next inspection of these enamels is tentatively planned after 15 years' exposure.

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**Figures in brackets indicate the literature references at the end of this report.

TABLE 1.—*Optical data and acid resistance of enamels*

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature ° F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR)[a] and color retention (CR)[b] after 7 years' exposure at [c]																Citric [d] acid spot test rating	Acid [e] solubility mg/in²
					Kure Beach, 80 ft		Kure Beach, 800 ft		Washington		New Orleans		Pittsburgh		Dallas		Los Angeles		Average			
					GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR		
Titanium white, glossy enamel on steel—resistant to acid and alkalies																						
A-1	1	a	1,540	64	65.3	98.4	56.7	99.1	84.6	99.3	86.9	99.0	85.3	98.1	92.4	98.9	96.0	99.2	81.0	98.9	AA	1.0
A-2	2	a	1,520	60	79.4	99.3	65.5	98.9	82.4	99.0	85.8	99.4	85.5	98.4	94.3	99.3	98.2	99.6	84.4	99.1	AA	1.1
A-3	3	b	1,525	71	42.4	97.5	93.2	99.3	89.2	99.5	88.5	99.8	86.7	98.0	93.6	99.7	108.9	98.9	86.1	99.0	AA	1.4
A-4	4	b	1,430	62	73.0	98.3	87.5	99.0	86.3	98.9	90.4	99.2	82.7	99.3	86.1	99.0	92.0	99.2	85.4	99.0	AA	0.6
Average					65.1	98.4	75.7	99.1	85.6	99.2	87.9	99.4	85.1	98.5	91.6	99.2	98.7	99.2				
Titanium white, glossy enamel on steel—resistant to acids but not to alkalies																						
B-1	5	a	1,450	60	37.0	95.2	76.2	97.7	69.9	97.9	84.6	98.3	75.6	96.5	89.9	98.5	90.6	99.1	74.8	97.6	B	13.4
B-2	6	a	1,425	63	14.5	95.5	80.8	96.6	63.3	97.4	82.3	96.5	77.5	96.5	88.2	98.4	90.6	98.7	71.0	96.3	B	18.6
B-3	7	b	1,450	60	44.4	96.9	63.4	99.1	74.5	97.9	86.8	97.9	81.0	97.7	93.7	98.2	92.7	97.5	74.5	97.9	A	7.0
B-4	8	b	1,430	60	50.0	97.5	53.2	99.3	71.1	98.3	79.9	98.0	81.7	97.6	88.7	98.2	90.6	98.3	73.6	98.2	B	8.2
Average					36.5	96.3	68.4	98.2	69.7	97.9	83.4	97.7	79.0	97.1	90.3	98.3	91.1	98.4				
Zirconium white, glossy enamel on steel—resistant to alkalies but not to acids																						
C-1	9	a	1,430	65	12.5	98.1	27.4	98.5	23.4	95.8	50.3	97.0	35.5	84.3	78.4	98.4	71.9	97.0	42.8	95.6	C	279.9
C-2	8	a	1,540	70	9.9	97.2	32.7	98.0	29.8	95.1	60.3	96.8	41.6	86.1	77.4	98.8	75.3	98.1	46.7	95.7	C	442.7
C-3	1	b	1,520	64	7.6	97.5	19.8	97.8	28.0	96.7	51.0	96.3	32.0	80.0	71.5	98.3	72.2	95.7	40.3	94.6	D	536.4
C-4	2	b	1,500	65	7.6	97.4	18.1	97.5	24.4	95.2	47.1	96.5	32.4	83.2	69.6	98.4	68.0	95.3	38.2	94.8	D	376.6
Average					9.4	97.6	24.5	98.0	26.4	95.7	52.2	96.7	35.4	83.4	74.2	98.5	71.9	96.5				
Red, glossy enamel on steel—acid-resistant type																						
D-1	10	c	1,500	40	32.7	95.8	48.5	96.2	69.1	96.0	81.1	97.0	86.9	97.1	94.4	96.9	100.3	99.3	73.3	96.9	C	4.7
D-2	11	c	1,520	56	51.6	94.9	71.1	98.8	78.3	99.3	85.8	97.8	79.7	96.9	84.6	98.5	86.5	99.4	76.8	97.9	A	1.4
D-3	12	d	1,480	62	71.4	87.3	62.4	98.6	68.2	99.0	85.7	91.0	73.0	95.9	85.2	98.6	89.9	98.9	76.6	95.6	AA	3.4
D-4	13	d	1,490	62	67.9	94.2	64.1	97.4	63.3	97.4	85.8	91.5	76.3	97.2	86.6	98.4	91.8	98.8	76.5	96.4	AA	4.0
Average					55.9	93.1	61.5	97.8	69.7	97.9	84.6	94.3	79.0	96.8	87.8	98.1	92.1	99.1				
Red, glossy enamel on steel—nonacid resistant type																						
E-1	12	c	1,510	53	43.6	95.7	45.4	98.3	70.8	98.8	77.9	92.5	76.9	98.6	84.4	99.1	84.6	98.8	69.1	97.4	C	1.2
E-2	13	c	1,510	54	38.2	96.5	34.9	96.8	71.5	96.7	81.0	93.2	78.9	97.6	82.1	98.4	85.6	98.0	67.4	96.7	C	3.2
E-3	10	d	1,520	56	24.8	95.8	19.2	95.8	32.7	92.8	71.7	90.5	57.8	95.1	79.1	98.5	81.7	96.0	52.4	94.9	D	20.1
E-4	14	d	1,480	55	29.7	95.6	15.9	96.8	70.8	98.2	70.5	92.3	73.3	98.6	82.3	98.4	85.8	98.2	61.2	96.9	D	22.3
Average					34.1	95.9	28.7	96.9	61.5	96.6	75.3	92.1	71.7	97.5	82.0	98.6	84.4	97.8				

See footnotes at end of table.

TABLE 1.—*Optical data and acid resistance of enamels*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR)[a] and color retention (CR)[b] after 7 years' exposure at [c] Kure Beach, 80 ft		Kure Beach, 800 ft		Washington		New Orleans		Pittsburgh		Dallas		Los Angeles		Average		Citric [d] acid spot test rating	Acid [e] solubility mg/in²
					GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR		
Red, glossy screening paste enamel on steel—acid-resistant type																						
F-1	5	a	1,500	63	5.6	(f)	29.0	75.8	28.5	77.5	72.7	75.0	72.3	61.4	72.9	87.5	76.0	77.9	51.0		C	7.1
F-2	15	a	1,500	61	14.9	(f)	56.6	76.0	43.0	78.1	76.7	78.4	73.5	74.1	78.9	90.0	80.6	75.4	60.6		A	4.4
F-3	16	a	1,500	61	11.1	(f)	48.6	76.8	27.0	81.1	80.7	80.7	76.6	77.6	77.9	88.7	80.1	76.6	57.4		B	6.8
F-4	17	a	1,500	62	3.5	(f)	41.9	78.7	21.4	80.9	75.5	78.5	72.1	76.1	77.8	86.6	78.8	78.6	53.0		C	5.5
Average					8.8		44.0	76.8	30.0	79.4	76.4	7.2	73.6	72.3	76.9	88.2	78.9	77.1				
Red, glossy screening paste enamel on steel—acid-resistant type																						
FA-4	17	a	1,500	53	3.2	(f)	15.4	(f)	31.4	(f)	72.6	(f)	65.2	(f)	77.1	(f)	81.1	(f)	49.4		C	5.1
Average					3.2		15.4		31.4		72.6		65.2		77.1		81.1					
Yellow, glossy screening paste enamel on steel—acid resistant type																						
G-1	5	b	1,500	39	45.5	90.6	62.1	90.5	69.3	92.6	80.3	91.5	91.9	90.3	84.4	95.0	102.4	88.4	76.6	91.3	A	1.5
G-2	15	b	1,500	46	36.2	82.2	64.9	83.0	65.8	85.2	73.9	85.9	77.3	89.3	78.0	93.0	82.5	82.5	68.4	85.9	AA	0.9
G-3	17	b	1,500	40	28.8	88.9	57.0	89.4	62.8	92.5	85.3	91.3	96.6	92.1	84.7	95.0	108.0	89.3	74.8	91.2	A	2.7
G-4	16	b	1,500	45	39.8	88.1	59.2	87.7	67.4	90.4	77.8	88.8	76.2	92.3	78.6	94.6	90.6	88.6	69.9	90.1	A	1.9
Average					37.6	87.5	60.8	89.0	66.3	90.2	79.3	89.4	85.5	91.0	81.4	94.4	95.9	87.2				
Yellow, glossy screening paste enamel on steel—acid resistant type																						
GA-1	5	b	1,500	34	40.0	79.8	64.0	78.6	75.9	78.7	74.7	82.4	75.2	82.8	86.0	84.0	110.7	81.3	75.2	81.1	A	1.7
GA-2	15	b	1,500	45	39.3	77.6	63.9	78.0	78.4	78.2	72.7	81.6	67.1	81.9	81.4	85.5	81.5	80.4	69.2	80.5	A	1.3
GA-3	16	b	1,500	37	36.7	77.8	60.6	77.4	67.3	78.5	74.1	81.2	75.6	82.5	90.4	86.6	111.0	80.8	73.7	80.7	A	2.1
GA-4	17	b	1,500	32	33.1	78.3	68.8	78.0	72.6	79.5	81.5	82.0	80.3	82.2	94.6	85.5	124.0	79.5	79.2	80.7	A	2.1
Average					37.3	78.4	64.3	78.0	73.6	78.7	75.8	81.8	74.6	82.4	88.1	85.4	106.8	80.6				
Black, glossy enamel on steel—acid-resistant type																						
H-1	12	e	1,500	66	44.0	92.0	74.8	98.2	72.4	98.3	79.3	97.9	69.1	96.6	76.9	97.4	83.8	97.7	71.5	96.8	AA	0.5
H-2	13	e	1,510	66	58.3	94.8	61.3	99.0	71.6	98.5	82.5	98.5	69.5	97.5	78.3	97.3	85.5	97.3	72.9	97.6	A	1.7
H-3	14	c	1,480	60	72.2	94.8	70.7	98.8	81.2	99.2	82.9	98.5	78.7	95.8	88.4	99.2	93.8	99.1	81.1	97.9	A	0.9
H-4	10	c	1,500	61	22.4	89.3	42.6	95.1	77.3	98.7	82.4	97.8	76.5	96.0	89.7	98.4	95.6	99.4	69.5	96.4	A	2.1
Average					49.2	92.7	62.4	97.8	75.6	98.7	81.8	98.2	73.5	96.5	83.3	98.1	89.7	98.4				

See footnote at end of table.

TABLE 1.—*Optical data and acid resistance of enamels*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR)[a] and color retention (CR)[b] after 7 years' exposure at [c] Kure Beach, 80 ft		Kure Beach, 800 ft		Washington		New Orleans		Pittsburgh		Dallas		Los Angeles		Average		Citric [d] acid spot test rating	Acid [e] solubility mg/in²
					GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR		
Black, glossy enamel on steel—non-acid-resistant type																						
K-1	12	e	1,500	62	34.8	93.9	34.7	97.1	69.0	99.1	76.2	98.6	71.1	95.5	80.0	97.3	79.3	97.6	63.6	97.0	C	20.9
K-2	13	e	1,510	61	36.9	95.5	27.8	97.2	68.9	98.3	74.6	98.4	73.9	95.8	78.0	98.0	80.1	97.4	62.9	97.2	D	19.2
K-3	14	c	1,480	57	21.1	83.3	45.4	88.4	70.6	89.2	74.2	86.2	77.1	92.8	80.2	98.5	83.0	96.1	64.5	90.6	D	43.8
K-4	10	c	1,500	53	26.9	83.4	49.9	90.0	50.8	76.8	61.3	80.5	72.5	79.0	79.3	93.0	78.0	80.6	59.8	83.3	D	63.9
Average					29.9	89.0	39.5	93.2	64.8	90.9	71.6	90.9	73.7	90.7	79.4	96.7	80.1	92.9				
Titanium pastel yellow, glossy enamel on steel—acid-resistant type																						
L-1	6	b	1,525	62	52.1	96.8	60.2	97.0	72.8	98.0	84.5	98.7	82.9	97.8	89.8	98.6	92.0	98.5	76.3	97.9	A	1.9
L-2	7	b	1,525	60	49.9	95.9	49.9	96.9	72.2	98.2	83.2	98.6	84.0	98.7	90.1	98.0	92.2	97.8	74.5	97.7	A	2.2
L-3	11	c	1,470	67	38.4	93.6	31.1	95.5	66.4	96.9	78.0	98.6	84.8	99.3	89.7	98.0	88.6	91.1	68.2	96.1	A	3.2
L-4	12	c	1,480	62	69.8	97.4	65.5	97.2	73.3	99.2	85.5	93.7	82.0	99.5	88.7	98.2	87.7	98.5	78.9	97.7	AA	0.8
Average					52.6	95.9	51.7	96.7	71.2	98.1	82.8	97.4	83.4	98.8	89.6	98.2	90.1	96.5				
Blue, ground-coat, enamel on steel—acid-resistant type																						
M-1	18	a	1,580	57	64.6	96.7	63.2	99.5	79.1	99.2	82.3	98.3	79.3	97.3	82.5	98.4	83.8	98.3	76.4	98.2	A	2.7
M-2	8	a	1,580	57	28.8	92.0	57.4	96.8	81.1	96.0	80.7	97.8	78.1	96.4	86.0	98.9	80.9	99.0	70.4	96.7	A	2.6
M-3	7	d	1,540	57	66.7	97.8	34.3	98.6	82.3	98.5	80.0	98.5	84.3	97.8	84.0	98.8	94.1	99.3	75.1	98.5	A	1.9
M-4	16	d	1,540	58	61.3	96.6	53.0	95.6	82.2	97.0	77.4	96.5	72.8	95.0	85.8	97.4	92.9	98.6	75.0	96.7	A	2.5
Average					55.4	95.8	52.0	97.6	81.2	97.7	80.1	97.8	78.6	96.6	84.3	98.4	87.9	98.8				
Blue, ground-coat enamel on steel—non-acid-resistant type																						
N-1	4	c	1,540-60	55	34.3	85.1	59.0	88.7	67.0	90.2	68.6	88.3	76.8	94.6	74.9	95.5	73.7	92.7	64.9	90.7	C	21.1
N-2	9	c	1,540-60	52	41.0	82.6	72.1	84.6	64.7	76.1	66.5	82.8	69.2	85.6	83.2	89.9	77.7	88.9	67.8	84.4	D	34.3
N-3	1	d	1,540	55	43.8	93.1	29.2	93.3	71.8	85.5	77.4	97.5	73.0	96.6	80.0	99.2	85.7	98.1	65.9	94.8	C	36.1
N-4	18	d	1,540	55	52.5	91.4	39.8	92.5	73.0	85.2	77.1	98.1	75.1	96.2	79.0	99.3	86.7	99.4	69.0	94.6	C	41.5
Average					42.9	88.1	50.0	89.8	69.1	84.3	72.3	91.7	73.5	93.3	79.3	96.0	81.0	94.8				
Green mat enamel on steel—clear, acid-resistant frit matted with calcined aluminum oxide																						
P-1	2	a	1,510	52	49.4	96.1	78.3	97.9	72.9	98.3	78.1	96.8	74.9	98.7	73.7	98.9	77.6	99.0	72.1	98.0	A	2.2
P-2	6	a	1,520	43	59.7	97.3	78.5	92.3	74.4	98.2	73.1	96.3	75.5	95.9	78.7	99.5	76.2	99.8	73.7	97.0	B	3.7
P-4	7	d	1,480	35	50.1	94.7	63.6	93.6	25.3	91.9	80.6	96.3	81.7	98.2	97.8	93.0	93.2	98.8	70.3	95.2	C	30.1
Average					53.0	95.9	73.4	94.5	57.5	96.0	77.2	96.4	77.3	97.5	83.3	97.0	82.2	99.1				

See footnotes at end of table.

Table 1.—*Optical data and acid resistance of enamels*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR)[a] and color retention (CR)[b] after 7 years' exposure at [c] Kure Beach, 80 ft GR	Kure Beach, 80 ft CR	Kure Beach, 800 ft GR	Kure Beach, 800 ft CR	Washington GR	Washington CR	New Orleans GR	New Orleans CR	Pittsburgh GR	Pittsburgh CR	Dallas GR	Dallas CR	Los Angeles GR	Los Angeles CR	Average GR	Average CR	Citric[d] acid spot test rating	Acid[e] solubility mg/in[2]
Green mat enamel on steel—semiopaque, acid-resistant frit matted with calcined aluminum oxide																						
PA-1	7	a	1,480	30	22.5	94.0	40.0	93.3	56.5	88.8	40.5	98.0	31.6	96.1	104.6	98.4	80.2	98.2	53.7	95.3	D	42.4
PA-2	3	a	1,480	40	25.1	95.1	54.0	95.2	55.2	94.3	53.2	97.9	63.6	97.9	93.4	98.8	93.1	98.8	62.5	96.9	C	56.9
PA-3	2	d	1,480	17	66.0	96.5	73.9	97.2	83.5	97.2	56.0	97.5	98.7	98.0	95.5	97.9	95.3	97.6	81.3	97.4	C	30.5
PA-4	6	d	1,480	13	73.7	96.6	77.5	97.0	85.5	97.1	29.1	97.7	112.3	97.2	92.3	97.7	81.9	96.5	78.9	97.1	C	36.2
Average					46.8	95.6	61.4	95.8	70.2	94.3	44.7	97.8	76.6	97.3	96.4	98.2	87.6	97.8				
Green mat enamel on steel—clear, acid-resistant frit matted with barium metaphosphate																						
R-1	8	a	1,430	18	21.8	94.9	49.9	95.6	56.5	96.0	42.3	97.0	78.2	98.9	73.5	94.9	77.5	96.1	57.1	96.2	B	11.1
R-2	10	a	1,520	19	30.9	94.6	51.1	94.0	55.8	94.7	33.3	96.3	55.2	97.0	71.5	93.9	78.8	96.3	53.8	95.2	B	12.0
R-4	2	d	1,480	30	20.1	95.4	33.7	95.1	44.5	94.9	22.4	93.9	98.5	96.9	46.2	95.6	58.4	95.6	46.3	95.3	B	8.0
Average					24.2	94.9	44.9	94.8	52.2	95.1	32.7	95.6	77.2	97.5	63.7	94.7	71.5	95.9				
Green mat enamel on steel—semiopaque, acid-resistant frit matted with barium metaphosphate																						
RA-1	2	a	1,480	31	43.4	89.1	69.6	91.9	81.0	94.0	74.9	95.6	85.3	96.9	84.5	94.6	77.5	96.7	73.7	94.1	B	17.3
RA-2	18	a	1,480	32	46.0	93.2	50.3	92.6	66.3	93.4	57.7	95.8	67.0	96.3	75.9	95.2	77.9	98.1	63.0	95.0	B	17.0
RA-3	8	d	1,430	21	30.0	96.2	54.9	95.2	79.2	95.2	50.1	97.0	83.9	96.6	88.6	96.6	85.5	98.0	67.5	96.4	B	14.1
RA-4	6	d	1,480	7	37.7	96.1	25.2	95.2	52.4	96.9	0.	93.6	61.9	89.8	62.5	95.1	73.3	94.8	44.7	94.5	B	7.4
Average					39.3	93.7	50.0	93.7	69.7	94.9	45.7	95.5	74.5	94.9	77.9	95.4	78.6	96.9				
Green mat enamel on steel—clear, acid-resistant frit matted by proprietary additive																						
S-1	3	e	1,500	38	36.2	93.8	44.6	92.7	44.3	91.9	50.8	95.3	67.0	97.7	79.2	96.2	103.6	98.4	60.8	95.1	C	24.8
S-2	14	e	1,480	44	19.0	93.5	35.2	92.6	32.0	91.8	31.0	95.1	50.8	96.3	71.1	97.1	82.4	97.8	45.9	94.9	C	30.1
Average					27.6	93.7	34.9	92.7	38.2	91.9	40.9	95.2	58.9	97.0	75.2	96.7	93.0	98.1				
Green mat enamel on steel—semiopaque, acid-resistant frit matted with proprietary additive																						
SA-1	4	e	1,520	38	29.8	94.3	44.0	92.6	49.3	91.2	54.6	94.1	62.0	97.5	81.8	96.1	85.7	97.2	58.2	94.7	C	16.4
SA-2	9	e	1,540	43	24.7	94.9	31.2	91.7	34.9	93.7	39.6	96.1	48.4	98.2	67.3	97.2	79.0	98.6	46.4	95.8	C	14.6
Average					27.3	94.6	37.6	92.3	42.1	92.5	47.1	95.1	55.2	97.9	74.6	96.7	82.4	97.9				

See footnotes at end of table.

Table 1.—*Optical data and acid resistance of enamels*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR) [a] and color retention (CR) [b] after 7 years' exposure at [c] Kure Beach, 80 ft		Kure Beach, 800 ft		Washington		New Orleans		Pittsburgh		Dallas		Los Angeles		Average		Citric [d] acid spot test rating	Acid [e] solubility mg/in²
					GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR		
Green, glossy 1,300 °F enamel on steel																						
T-1	11	f	1,330	57	48.0	96.3	58.1	97.8	80.6	98.6	81.8	99.0	75.5	98.7	83.6	98.6	96.9	99.2	74.1	98.3	B	4.0
T-2	19	f	1,300	58	82.1	97.6	83.0	98.7	87.5	99.3	88.1	99.0	75.0	97.9	89.4	99.2	91.2	99.1	86.0	98.7	AA	3.1
Average					65.1	97.0	70.6	98.2	84.1	98.9	84.9	99.0	75.3	98.3	86.5	98.9	94.1	99.2				
Red, glossy 1,300 °F enamel on steel																						
U-1	11	f	1,320	52	31.0	89.4	72.4	94.3	72.3	94.3	93.6	97.2	91.2	95.5	91.2	97.7	102.7	97.1	79.2	95.1	B	3.9
U-2	19	f	1,300	53	66.9	94.7	70.9	96.2	80.3	96.4	87.0	98.6	91.7	98.2	89.3	98.8	104.5	99.4	84.4	97.5	B	2.1
Average					49.0	92.1	71.7	95.3	76.3	95.4	90.3	97.9	91.5	96.9	90.3	98.3	103.6	98.8				
Yellow, glossy enamel on aluminum—acid-resistant type																						
V-1	20	e	1,000	65	20.8	93.8	41.0	93.1	54.5	95.9	82.9	92.2	74.2	94.1	81.6	95.7	82.3	95.0	62.5	94.4	AA	8.2
V-2	10	e	1,000	70	13.7	89.9	35.0	91.0	52.1	94.4	78.0	91.3	70.9	93.7	77.8	93.0	80.7	93.7	58.3	92.4	AA	12.0
V-3	20	g	1,000	83	4.9	68.0	52.7	73.5	53.6	92.2	68.0	92.1	69.3	92.0	73.8	93.6	83.9	94.3	58.0	86.5	B	11.4
V-4	10	g	1,000	85	4.8	71.4	30.3	76.1	49.6	94.4	76.8	95.4	68.6	87.7	61.8	96.6	86.0	95.2	54.0	88.1	A	10.1
Average					11.0	80.8	39.8	83.4	52.5	94.2	76.4	92.8	70.9	91.9	73.8	94.7	83.2	94.6				
White, glossy enamel on aluminum																						
VA-1	20	a	980	81	6.0	95.1	40.8	94.7	43.4	97.1	75.3	90.0	55.0	92.9	70.4	95.3	87.8	96.6	54.1	94.5	AA	8.2
VA-2	10	a	1,000	81	20.1	93.5	63.6	95.3	46.6	97.6	79.3	96.6	67.0	96.5	74.7	97.2	84.6	96.0	62.3	96.2	AA	6.1
Average					13.1	94.3	52.2	95.0	45.0	97.3	77.3	93.3	61.0	94.7	72.6	96.3	86.2	96.3				
Green, glossy enamel on aluminum—acid resistant type																						
W-1	20	e	980	69	15.8	91.9	27.8	92.3	53.1	93.8	92.2	95.1	73.7	92.7	84.3	95.5	80.3	95.5	61.1	93.8	A	6.2
W-2	10	e	1,000	77	20.8	95.0	65.0	95.5	50.5	97.4	89.4	95.1	56.7	93.1	74.2	97.4	76.0	97.7	61.8	95.9	AA	6.9
W-3	20	g	1,000	82	1.2	77.1	27.1	81.6	69.2	93.5	77.2	91.1	77.8	98.3	76.0	98.1	82.0	98.8	58.7	91.2	A	21.1
W-4	10	g	1,000	81	2.2	78.2	29.7	82.9	62.0	94.8	86.5	91.9	79.3	98.7	66.0	98.1	82.8	98.4	58.4	91.9	A	19.9
Average					10.0	85.6	37.4	88.1	58.7	94.9	86.3	93.3	71.9	95.7	75.1	97.3	80.3	97.6				

See footnotes at end of table.

TABLE 1.—*Optical data and acid resistance of enamels*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial specular gloss [a]	Percentage of initial gloss retained (GR) [a] and color retention (CR) [b] after 7 years' exposure at [c]																Citric [d] acid spot test rating	Acid [e] solubility mg/in²
					Kure Beach, 80 ft		Kure Beach, 800 ft		Washington		New Orleans		Pittsburgh		Dallas		Los Angeles		Average			
					GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	CR		
Green, mat enamel on aluminum																						
X-1	20	e	990	13	69.2	93.0	90.2	97.7	59.1	95.6	13.3	89.0	65.7	95.2	79.8	96.6	73.8	96.9	64.4	94.9	AA	6.5
X-2	10	e	1,000	56	29.8	91.7	101.3	91.4	56.5	96.9	79.3	93.9	78.7	98.9	73.6	99.0	80.4	99.2	71.4	95.9	AA	6.3
X-3	20	g	1,000	4	64.8	90.9	52.8	90.3	73.9	93.5	0	90.3	112.6	96.4	92.7	98.1	78.0	96.8	67.8	93.8	A	20.7
X-4	10	g	1,000	20	22.5	90.6	51.8	91.2	43.1	95.2	42.4	90.0	78.1	96.4	79.8	96.6	70.8	97.7	55.5	93.9	A	8.1
Average					46.6	91.6	74.0	92.7	58.2	95.3	33.8	90.8	83.8	96.7	81.5	97.6	75.8	97.7				
Green, glossy 1,000 °F enamel on steel																						
Y-1	21	e	1,020	70	41.6	91.9	68.8	93.9	59.4	91.1	85.1	95.5	79.1	90.5	81.2	97.5	85.7	97.6	71.6	94.0	AA	2.8
Average					41.6	91.9	68.8	93.9	59.4	91.1	85.1	95.5	79.1	90.5	81.2	97.5	85.7	97.6				
Red, glossy 1,000 °F enamel on steel																						
Z-1	21	e	1,000	47	4.8	39.1	76.0	34.8	69.7	79.2	84.7	91.0	86.8	88.2	96.3	93.8	99.4	95.9	73.9	74.6	B	
Average					4.8	39.1	76.0	34.8	69.7	79.2	84.7	91.0	86.8	88.2	96.3	93.8	99.4	95.9				

[a] 45° specular gloss was measured in accordance with ASTM Designation C346-59.
[b] The Color Retention is 100 minus the color change in NBS units.
[c] Computed from three specimens at each site.
[d] Ratings were made in accordance with "Test for Acid Resistance of Enamels, Part I, Flatware" except the grading of Class A and Class B enamels was modified to conform with the "Specification for Architectural Porcelain Enamel for Exterior Use" (refs. [8] and [9]). Enamels with AA, A or B ratings are considered acid-resistant while those with C and D ratings are considered nonacid resistant.
[e] Acid solubilities determined in accordance with ASTM Designation C283-54.
[f] Because of an almost complete loss of color, meaningful color difference measurements could not be obtained by the methods used in this study.

2. Description of Enamels and Specimens

The 28 types of enamel included in this test were furnished to 21 producers of architectural enamel parts by seven companies who manufacture enamel frits.[1] The producers then applied the enamel to the test specimens. Table 1 not only includes coded identification of the frit suppliers and fabricators, but also lists the types of enamels included. Minor variations in composition of the frit for enamels of the same type, as supplied by different manufacturers, probably occurred. Likewise, in many cases, different producers applying the same enamel may not have achieved an identical finish, because of minor variations in milling and firing. If these variations are taken into consideration, there were, in effect, 94 enamels under study; of which 80 were applied to sheet steel and 14 to sheet aluminum. After 3 years' exposure [5], three of the sccreening paste enamels[2] had become so badly weathered that they were withdrawn from further testing. The 91 remaining enamels are evaluated in this report.

The 4½-inch-square specimens with flanged edges were made from 18 gage sheet metal. A small hanging hole was punched in one corner of each specimen. Each enamel was applied to about 60 specimens; of which 21 were used for exposure testing (3 at each site), 2 were used as reference panels, and the remainder were kept in dry storage to be used in the development of accelerated weathering tests.

3. Exposure Sites

The seven exposure-test locations and the general exposure conditions that each site represents are given in table 2. The sites were selected as being representative of the various exposure conditions in different parts of the United States. The racks at five sites were located in commercial city areas. The remaining two were in a rural seacoast location.

Table 3 summarizes both the weather and the air quality data for each of the sites for the actual period of exposure.

The specimens were loosely mounted in ceramic insulators, which were fastened to the metal stretchers of supporting racks. The supporting racks were constructed of aluminum alloy, except those at the two Kure Beach locations which were made of Monel metal. All specimens were exposed at 45 degrees and faced south, except at the Kure Beach–80 ft station where they faced the ocean at east-southeast. Figure 1 shows a typical installation.

Table 2.—*Exposure test locations*

City	Exposure site	Exposure conditions represented
Kure Beach, N.C.	Ground, 80 ft from ocean	Temperate, sea spray.
Kure Beach, N.C.	Ground, 800 ft from ocean	Temperate, sea air.
Washington, D.C.	Roof, Industrial Bldg., National Bureau of Standards.	Temperate, commercial.
Pittsburgh, Pa	Roof, U.S. Post Office	Temperate, commercial.
New Orleans, La	Roof, U.S. Post Office	Semitropical, commercial.
Dallas, Tex	Roof, U.S. Post Office	Texas, commercial.
Los Angeles, Calif.	Roof, U.S. Post Office	Southern Calif., commercial.

Figure 1. *Exposure test site on the roof of the Industrial Building, National Bureau of Standards, Washington, D.C.*

[1] Frit is the principal ingredient used in preparing porcelain enamel. It is formed by melting suitable glass-forming raw materials and then quenching the molten mass, usually in water.

[2] Screening paste enamels are usually strongly colored enamels of a consistancy which permits their application to a previously fired enamel surface by the silk screen process.

TABLE 3.—*Weather data and air quality measurements for the 7-yr exposure period*

Exposure site	pH [a] [b]	Ave. ann.[c] relative humidity	Ave. ann.[c] temperature	Tot. ann.[c] sunshine	Tot. ann.[c] precipitation	Suspended [a] particulate matter
		Percent	*deg F*	*Hours*	*Inches*	*μg/m³*
Kure Beach [d]	4.9	77	60	2669	58	31
Washington	6.9	67	57	2576	39	108
Pittsburgh	6.7	68	50	2202	34	160
New Orleans	7.2	74	70	2744	63	89
Dallas	7.3	63	66	2911	40	95
Los Angeles	6.4	62	66	3284	11	169

[a] Averages from Air Sampling Network of the Department of Health, Education, and Welfare.
[b] Measured for solutions prepared by refluxing an 8% aliquot of particulate matter from the atmosphere with 50 ml of distilled water and diluting to 80 ml. Values are averages of measurements made at approximately biweekly intervals.
[c] Averages from the U.S. Weather Bureau Records.
[d] Data from Cape Hatteras, N.C., rather than Kure Beach, for which no data were available.

4. Results and Discussion

4.1. Cleaning of Specimens

All specimens were returned to the laboratory for inspection after they had been exposed for 7 years. Upon arrival, each specimen was cleaned with a soft cellulose sponge which had been dampened with a 1 percent, by weight, solution of trisodium phosphate in water. This method of cleaning was sufficient for the specimens exposed at all sites except Los Angeles and Pittsburgh. At Los Angeles, a gumlike film had been deposited on the specimens which was not removed by the trisodium phosphate solution, but which was easily removed with benzene. Hence, the Los Angeles specimens were cleaned first with benzene, and then with the trisodium phosphate solution. The panels exposed at Pittsburgh were covered with a dirt film that appeared to consist mostly of soot and fly ash. In addition, in the process of installing a new roof covering on the Post Office Building in Pittsburgh, some of the specimens had been splattered with small amounts of tar and cement mortar. The tar was removed with benzene, the cement was removed by heating at 200 °C for 24 hr followed by brushing, and finally the specimens were scrubbed with a commercial scouring powder. All specimens, including those from Los Angeles and Pittsburgh, were subjected to the trisodium phosphate solution cleaning process and to two rinses, one with distilled water and one with alcohol. These rinses were required to prevent the formation of drying marks that might interfere with later gloss and color measurements.

4.2. Corrosion of the Base Metal

After the specimens were cleaned, they were examined for corrosion of the base metal. None of the enamels on steel at Washington, Dallas, Pittsburgh, and Los Angeles showed any evidence of corrosion of the base metal. One panel at New Orleans, 10 at Kure Beach–800, and 29 at Kure Beach–80 showed some rusting of the base metal. The rusting was not confined to one enamel type but was present on those particular specimens on which either pinhole defects or blisters were present prior to exposure.

4.3. Changes in Gloss and Color

The degree of weathering was evaluated by changes in both color and 45 deg specular gloss. The gloss [6] is reported as the percentage retained after exposure, and the color is reported as color retention, which is 100 minus the color change in NBS units [7].

The individual gloss and color values for each enamel after 7 years' exposure are given in table 1. In later tables and figures, the white porcelain enamels were not included when computing average color changes, since white enamels normally retain their initial color even after relatively severe surface attack. Also, screening paste enamels were excluded from the averages, because of their abnormally large color changes.

4.4. Changes in Gloss and Color with Exposure Time

The effect of exposure time on gloss and color retention is shown in figures 2 and 3. Both the gloss and color values of the enamels exposed at Pittsburgh and New Orleans have been averaged, since there was no significant difference in the degree of attack on the enamels after 7 years (see sec. 4.5).

Figure 2 shows that the enamels at all the exposure sites lose their gloss most rapidly during the first 3 years' exposure; then, the gloss retained remains nearly constant at the five milder exposure sites, while it continues to decrease at the two more severe sites at Kure Beach. The slight increase in gloss at Los Angeles after the second year may possibly be caused by incomplete removal of the gumlike film. This would cause a doubly reflecting surface, which would increase the gloss readings.

The color change was greatest during the first 2 years of exposure (fig. 3), after which the enamels change in color at a nearly constant, but

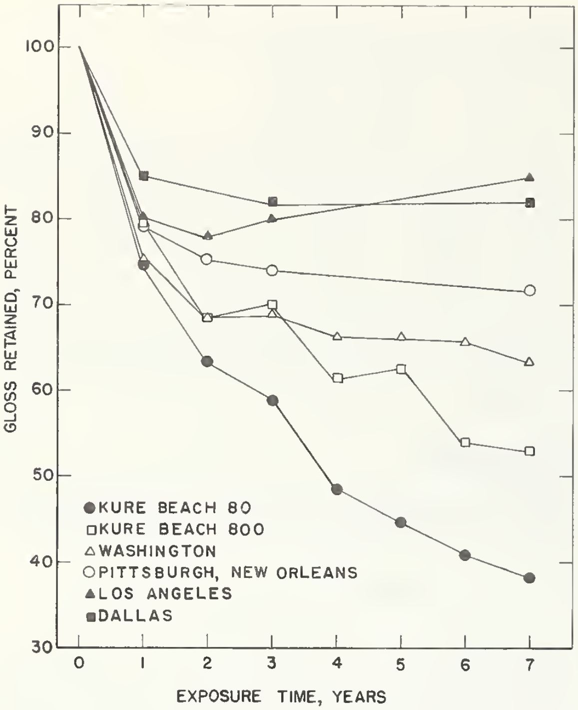

FIGURE 2. *Change in average percentage of gloss retained with exposure time.*

Points are averages for all enamels except screening pastes.

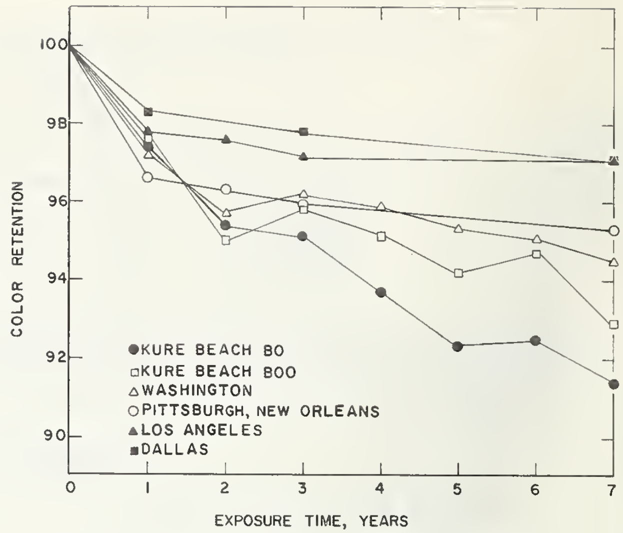

FIGURE 3. *Change in average color retention with exposure time.*

Points are averages for all nonwhite enamels except screening pastes.

different, rate at all seven sites. The lack of any appreciable color change between 3 and 7 years' exposure of the enamels exposed at Pittsburgh and Los Angeles suggests the possibility that adherent films acted as protective coatings on the enamels exposed at these sites.

4.5. Comparison of Exposure Sites

Table 4 gives the average percentage gloss retained and color retention for each exposure site. The gloss values are for all enamels tested, while the color values are for all nonwhite enamels except the screening pastes.

The gloss data in table 1 were ranked to determine if there were significant differences between sites. The analysis showed that such differences (significant at the 5% level)[3] existed between all sites except Pittsburgh and New Orleans. This observation is unusual, since at the 3-year inspection the Pittsburgh site was appreciably more severe than the New Orleans site [5]. The explanation is believed to be associated with the scouring treatment that was necessary to clean the Pittsburgh specimens. This treatment, because of its polishing effect, could have raised the gloss readings above those that would have been obtained had the specimens received only the normal cleaning process.

TABLE 4.—*Average color retention and percentage gloss retained after 7 years' exposure*

Exposure site	Color retention [a]	Percentage gloss retained [b]
Kure Beach-80	91.4	36.4
Kure Beach-800	92.9	53.2
Washington	94.5	62.3
Pittsburgh	95.8	74.2
New Orleans	94.8	70.5
Dallas	97.1	82.0
Los Angeles	97.1	86.4

[a] Color retention is given for all nonwhite enamels except screening pastes.
[b] Percentage gloss retained is given for all enamels.

The differences in the behavior of the enamels exposed at the various sites were undoubtedly caused by differences in the exposure conditions existing at the respective sites. Air pollution by acidic contaminants was found to have an influence on site severity at 3 years [5]. Figures 4 and 5 show that this same effect is active at 7 years. In preparing these figures, gloss and color retention values for the two Kure Beach sites were averaged, since only one value for *p*H was available.[4] It can be seen that at the most severe sites the atmospheric particulates yield more acidic *p*H values, while at the mild sites they give a nearly neutral *p*H. The noncorrelation of the enamels exposed at Pittsburgh and Los Angeles might be explained, at least in part, by the protective action of the adherent films on the specimens exposed at these locations.

Of the various weather parameters listed in table 3, the one that showed the best correlation with changes in both gloss and color was the rela-

[3] Using the sign test for adjacent sites as listed in table 1; see, for example, NBS Handbook 91, Experimental Statistics, ch. 16.

[4] Data from Cape Hatteras, rather than Kure Beach for which no data are available.

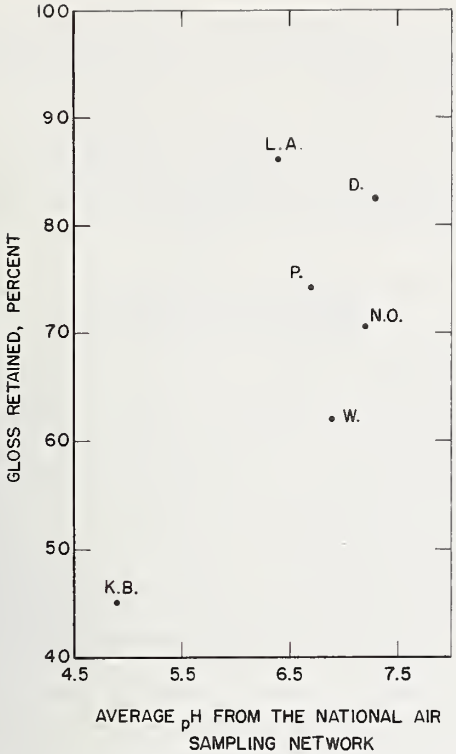

FIGURE 4. *Change in average gloss retention (all enamels) with* pH *of particulate matter collected at the sites.*

Letters adjacent to points indicate the exposure city; D–Dallas, L.A.–Los Angeles, P–Pittsburgh, N.O.–New Orleans, W–Washington, and K.B.–Kure Beach.

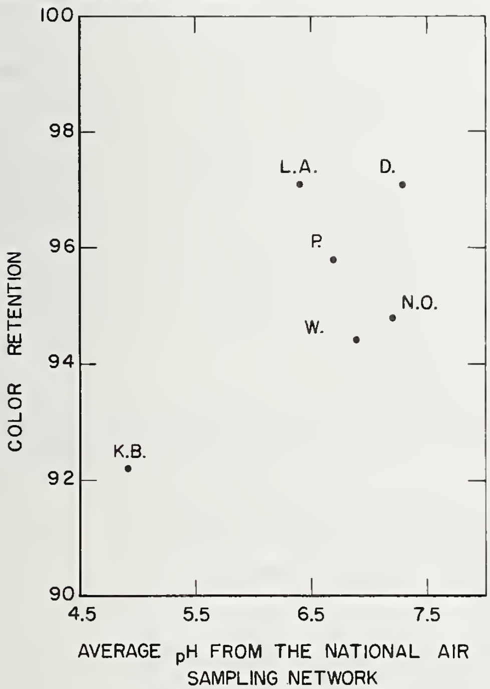

FIGURE 5. *Change in average color retention for all colored enamels (except screening pastes) with* pH *of particulate matter collected at the sites.*

Letters adjacent to points indicate exposure city; D–Dallas, L.A.–Los Angeles, P–Pittsburgh, N.O.–New Orleans, W–Washington, and K.B.–Kure Beach.

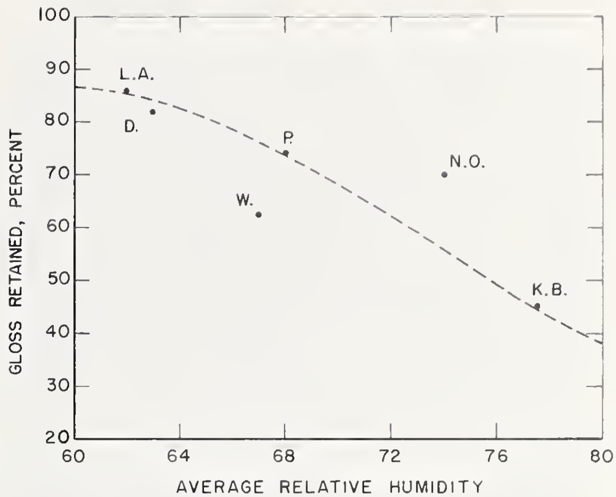

FIGURE 6. *Effect of average site humidity on the average gloss retention values for all enamels.*

Letters adjacent to points indicate exposure city; D–Dallas, L.A.–Los Angeles, P–Pittsburgh, N.O.–New Orleans, W–Washington, and K.B.–Kure Beach.

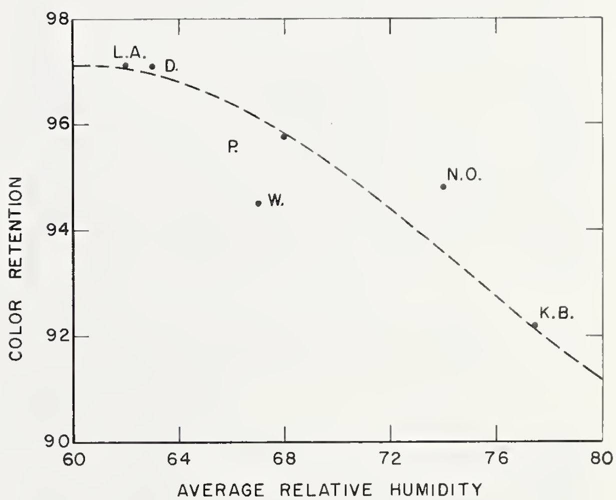

FIGURE 7. *Effect of average site humidity on average color retention for all nonwhite enamels except screening pastes.*

Letters adjacent to points indicate exposure city; D–Dallas, L.A.–Los Angeles, P–Pittsburgh, N.O.–New Orleans, W–Washington, and K.B.–Kure Beach.

tive humidity. This is illustrated in figures 6 and 7. It will be noted that the mild sites, Dallas and Los Angeles, have low relative humidities and the severe sites at Kure Beach have high relative humidities. The averages for Washington and New Orleans do not fall on the curves, but an overall pattern of correlation is evident. A possible explanation of the correlation is that high humidity permits condensation of moisture, as dew, which in turn leaches salts from the particulate matter deposited on the specimens, to give solutions of varying acidities according to the nature of the contaminants.

4.6. Comparison of Enamel Types

The average color and gloss retention at all sites for each enamel type is given in table 5. In this table, enamel types have been ranked according to their color retentions. The glossy acid-resisting enamels on steel had the best color retentions, while the screening paste enamels had the poorest.

Table 6 lists the color retention of the best enamel of each type at the various sites. This table, in effect, gives the best color stability that could be expected at each site if the most durable enamel of each type was selected. Although the gloss retained values are not given, these correlated in most cases with the color change.

Inspection of table 6 and table 1 permits the following observations to be made after 7 years' exposure:

(1) Some enamels on steel had excellent color retentions, even when exposed to the salt-air conditions at Kure Beach.

(2) The best of the enamels on aluminum showed only very small color changes at Dallas, Los Angeles, and Pittsburgh. The color changes for these same enamels at Washington were moderate, while fairly sizable color changes occurred at the two Kure Beach sites and at New Orleans. The cause of the unexpected severity of the New Orleans atmospheric conditions on the aluminum enamels has not been determined. It seems unlikely that the increased attack could be attributed to salt particles carried from the Gulf of Mexico or Lake Pontchartrain since the specimens were exposed on a four-story building several miles from the nearest saltwater. The cause of the increased attack at Kure Beach was tentatively ascribed to chlorides at the time of the 3-year inspection [5].

(3) The color stability of the best of the 1000° enamels on steel and the screening paste enamels was relatively poor at all sites. This is indicated by their low color retentions.

TABLE 5.—*Average color retention and percentage gloss retained for the eight types of enamels*

Enamel type [a]	Color retention	Percent gloss retained
Regular glossy steel, AR	97.2	76.1
1300 °F steel	97.4	80.9
Mat steel	95.8	----------
Mat aluminum	94.6	----------
Regular glossy steel, non-AR	93.2	58.5
Glossy aluminum	91.7	58.8
1000° steel	84.2	72.8
Screening paste steel	----------	63.9

[a] Enamels with citric acid spot test ratings of AA, A, or B are designated as AR (acid-resistant), while those with C and D ratings are designated as non-AR (nonacid-resistant).

4.7. Correlation of Acid Resistance with Weather Resistance

As stated in the introduction, one of the goals of the current investigation was to develop accelerated tests to predict the weather resistance of any given enamel. One test that is currently used is the citric acid spot test [8]. This test assigns the enamels alphabetical ratings of AA, A, B, C, or D. In figure 8, it is evident that the AA and A enamels, which are those recommended for architectural applications [9], had good gloss retentions, while C and D enamels had lower values. The weakness of the spot test is that the correlation existed only when averages were used, but there was a great deal of scatter when individual enamels were considered. This scatter is illustrated in figure 9, which shows the color retentions of the regular glossy enamels on steel exposed at Washington. The scatter is minimal for the AA and A enamels, but it increases appreciably for those with C and D ratings. Unfortunately, from the correlation standpoint, some of the individual C and D enamels showed as high color retentions at Washington as the A and AA enamels.

Figure 10 illustrates that the scatter is even greater when gloss is considered. This increased scatter was especially noticeable for enamels with AA and A ratings. Thus, when considering the good correlation between gloss and acid spot test rating, as shown in figure 8, it must be remembered that this correlation exists only when *averages* are plotted and there are many individual exceptions to the pattern.

Figures 11 and 12 are plots of color and gloss retention, respectively, of these same enamels exposed at Washington, against another measure of

TABLE 6.—*Color retentions for the best non-white enamel of each type after 7 years' exposure*

Enamel type [a]	Kure Beach, 80 ft	Kure Beach, 800 ft	Washington	Pittsburgh	New Orleans	Dallas	Los Angeles
Regular glossy steel, AR	97.4	99.0	99.2	99.3	98.7	98.0	99.4
1300 °F steel	97.6	98.7	99.3	98.2	99.0	99.2	99.2
Mat steel	97.3	97.9	98.3	98.1	97.8	98.8	98.8
Mat aluminum	93.0	97.7	96.9	98.9	93.9	98.1	99.2
Regular glossy steel, non-AR	96.5	98.3	98.8	98.6	98.1	99.3	99.4
Glossy aluminum	95.0	95.5	97.4	98.7	95.1	98.1	98.8
1000° steel	91.9	93.9	91.1	90.5	95.1	97.5	97.6
Screening paste steel	90.6	90.5	92.1	92.1	91.3	95.0	89.3

[a] Enamels with citric acid spot test ratings of AA, A, or B are designated as AR (acid-resistant), while those with C and D ratings are designated as non-AR (nonacid-resistant).

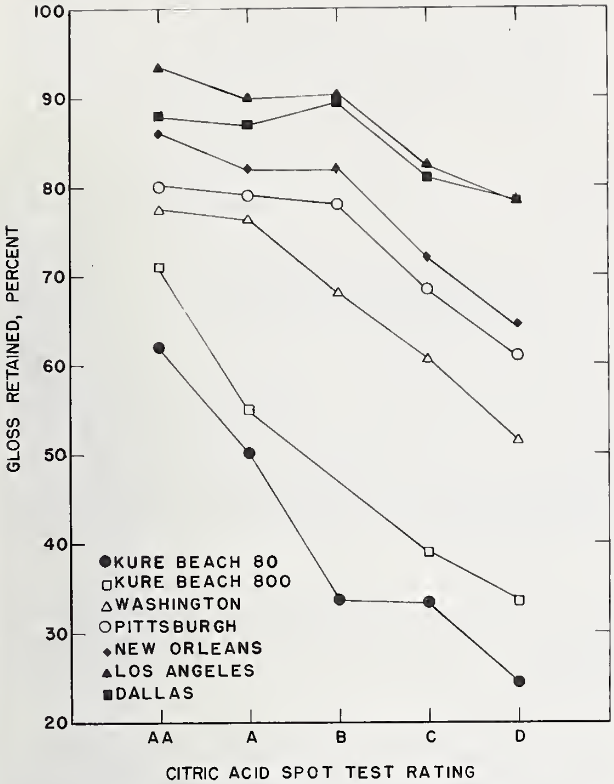

Figure 8. *Correlation of citric acid spot test rating with average of percentage gloss retained for all regular glossy enamels on steel.*

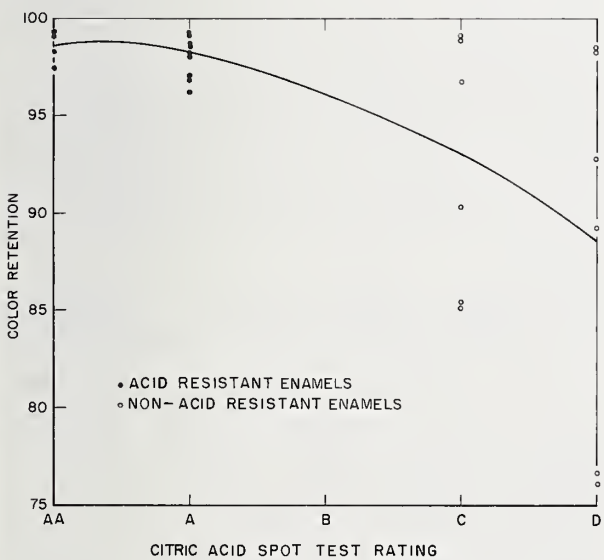

Figure 9. *Color retentions at Washington for regular glossy enamels on steel with different spot test ratings.*

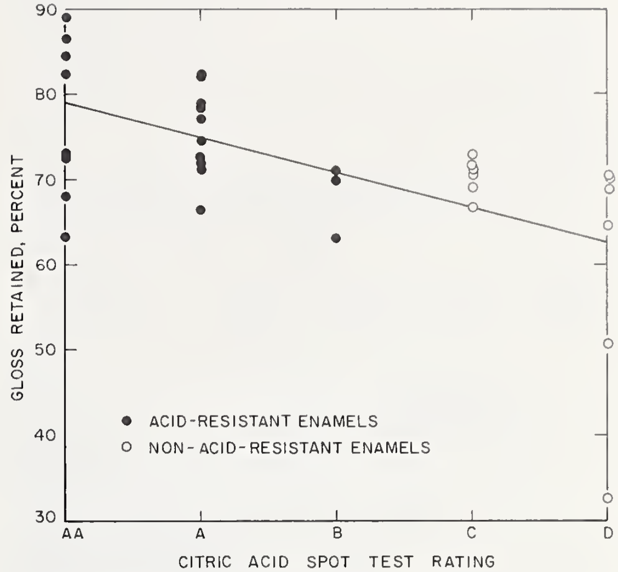

Figure 10. *Gloss retentions at Washington for regular glossy enamels on steel with different spot test ratings.*

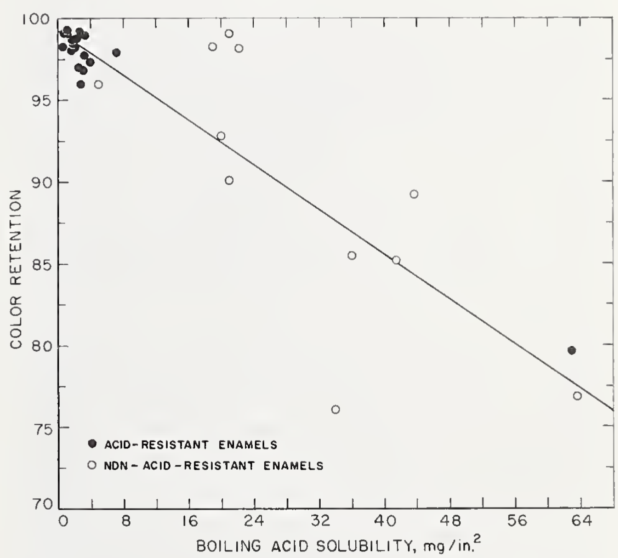

Figure. 11. *Color retentions at Washington for regular glossy enamels on steel plotted against their acid solubilities.*

acid resistance, the boiling acid solubility [10]. This test consists of determining the weight loss, per unit area of specimen, after exposure to a boiling, 6 percent by weight, solution of citric acid for 2½ hours. Since the boiling acid solubility provides a more continuous measure of acid resist-

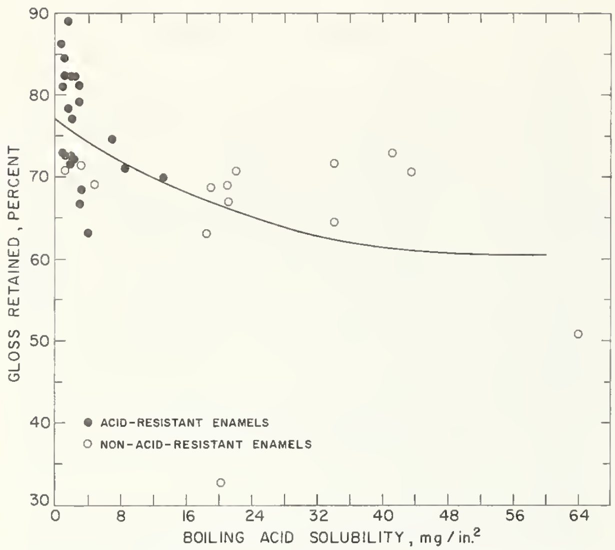

FIGURE 12. *Gloss retentions at Washington for regular glossy enamels on steel plotted against their acid solubilities.*

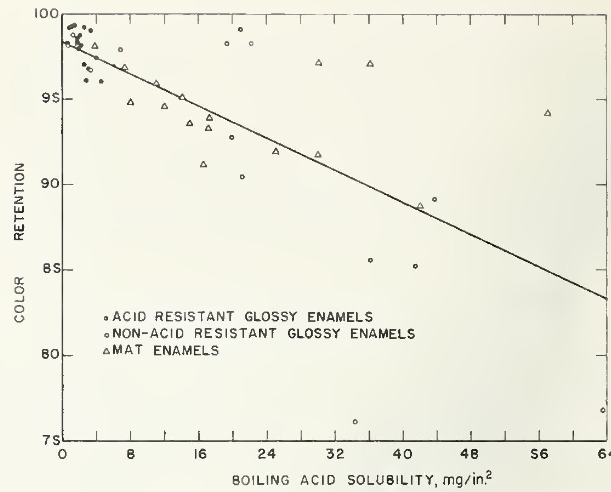

FIGURE 13. *Color retentions at Washington of regular mat and glossy enamels on steel plotted against their boiling acid solubilities.*

ance, the shape of the fitted curves is different from the comparable curves for the acid spot test.

The boiling acid solubility appears to provide a somewhat better correlation with color retention (only 5 enamels more than 2.5 color retention units from the curve) than does the citric acid spot test (11 enamels more than 2.5 units from the curve). Some of the C and D enamels with high color retentions had acid solubilities under 10 mg/in.² as do all the AA and A enamels on steel. Although the gloss retention of these same C and D enamels was relatively low (see fig. 12), it was not lower than some of the AA and A enamels which are now considered as acceptable architectural enamels.

The two gloss curves (figs. 10 and 12) were fitted without considering enamels C–1, C–2, C–3, and C–4 (table 1), because they were of such poor acid resistance and showed such poor gloss retentions that they could not be plotted on a reasonable curve. An inspection of figure 10 will reveal that there were only two C and D enamels that had gloss retentions lower than the AA and A enamels. The wide scatter in gloss retention for the individual acid-resistant enamels indicates that acid resistance, however measured, is not a reliable indicator of gloss retention during weathering. However, from the appearance standpoint, changes in gloss were not as serious as changes in color.

One advantage of the boiling acid solubility test is that, since it works for mat enamels, it overcomes the difficulties that are almost always encountered in assigning spot test ratings to enamels of this type. Figure 13 shows the dependence of color retention on the acid solubility of both mat and glossy enamels on steel which were exposed at Washington. Comparison of this figure with figure 11, which shows this same dependence for the glossy enamels only, reveals no large change in either the scatter or in the slope of the fitted curve.

The improved correlation between color retention of individual enamels and boiling acid solubility and the ease with which the test can be performed on mat enamels indicates that the boiling acid solubility of enamels should be considered in future evaluations of architectural enamels.

Although figures 9 through 13 illustrate the relationship between acid resistance and gloss and color retention only for the enamels exposed at Washington, similar relationships exist for the enamels exposed at the other six sites.

The 7-year exposure data indicate that whether the citric acid spot test or the boiling acid test is used as a measure of acid resistance, enamels of different types, such as enamels on steel and enamels on aluminum, with the same acid resistance, will not necessarily have the same weather resistance.

4.8. Cupric Sulfate Test for Predicting Color Retention of Red and Yellow Enamels

One accelerated test that was developed after the first-year inspection is the cupric sulfate test [11] for enamels pigmented with cadmium-selenium-sulfur complexes. This test has been employed to predict the oftentimes poor color retention of the acid-resistant red, yellow, and orange enamels that contain the cadmium-selenium-sulfide pigments. Enamels that passed this test showed average color retentions of 98.2 or better after 3 years. At 7 years, however, the cupric sulfate test is not as reliable. Although the average color retention of the enamels that passed this test was 95.6, the two glossy red acid-resistant enamels on steel mentioned earlier (D–3 and D–4, in table 1) showed sizable color changes at New Orleans, yet both of these enamels passed the cupric sulfate test. The test has a certain usefulness but, unfortunately, it cannot be considered as completely reliable for all enamels at all sites.

4.9. Comparison of Present-Day Enamels With Those Produced Before World War II

Table 7 compares the gloss retention values of the regular mat and glossy enamels on steel exposed 7 years at Washington, in both the present test and in a test initiated in 1939 [3]. This comparison shows that there is only a two-percent difference in the average gloss retained between the enamels in the two tests. Thus it may be concluded that the enamel types produced after the end of World War II, most of which are opacified with titania, are equally resistant to weathering (as gaged by gloss retention) as those produced before the war. For the most part, these earlier enamels were opacified with either antimony or zirconium oxide.

A similar comparison based on color retentions could not be made, since no color measurements were made at 7 years in the earlier study.

TABLE 7.—*Comparison of 7-year average gloss retentions at Washington, D.C., for regular glossy enamels on steel produced in 1939 with those produced in 1956*

Citric acid spot test rating	1939 test [a]		1956 test [b]	
	Gloss retention	Number of enamels	Gloss retention	Number of enamels
	Percent		*Percent*	
AA	73.7	29	77.5	8
A	69.7	15	76.3	12
B	70.7	3	65.0	11
C	54.9	24	56.1	17
D	44.4	16	52.9	9
Average for all enamels	62.5	87	64.6	58

[a] Data obtained from ref. 3.
[b] Data from present study.

5. Conclusions

The results of the 7-year inspection of porcelain enamels exposed at seven sites indicate that the regular and low-temperature enamels weather at different rates. The regular enamels include all the enamels on steel, except the 1000° enamels, while the low-temperature enamels include the enamels on aluminum, both mat and glossy, and the 1000° enamels on steel. The regular enamels were found to follow the same pattern, with respect to weathering, as those reported by Moore and Harrison [3]. The weatherability of these enamels can be predicted reasonably well by two relatively simple laboratory tests: The citric acid spot test (or the boiling acid test) and the cupric sulfate test. Although the citric acid spot test has proven successful in eliminating enamels with poor weather resistance, the improved correlation between color retention and boiling acid solubility, and the ease with which the acid solubility can be determined on mat enamels, may well lead to this test replacing the acid spot test as a method of predicting weather resistance.

The two acid tests and the cupric sulfate test do not appear to be reliable criteria of weather resistance in the case of the low-temperature enamels, since many of the low-temperature enamels with acid ratings of AA, A, or B (boiling acid solubilities of 22 mg/in.^{2} and lower) showed relatively poor color retentions at most sites. In fact, the only low-temperature specimens that showed reasonably high color retentions were the mat enamels on aluminum exposed at Pittsburgh, Los Angeles, and Dallas. This failure of either of the acid tests (or the cupric sulfate test) to predict with any degree of reliability the weather resistance of the low-temperature enamels means that exposure testing of new enamels of this type will be needed until such time as a more suitable accelerated test can be devised.

The 7-year results confirm the 3-year findings that acidic pollutants and moisture in the atmosphere affect the rate at which an enamel weathers. However, it must be recognized that these are not the only atmospheric conditions that affect the rate of weathering. Undoubtedly, all of the parameters given in table 2 have at least a minor effect. Perhaps it will be possible at some future date to devise a single equation that will, when solved, predict the rate at which an enamel will weather at any given site. This would be invaluable information, not only to architects and engineers, but also to the fabricators, who oftentimes are required to guarantee an installation for prolonged periods.

Although it cannot be said with absolute certainty that enamels that show good resistance to weathering after 7 years will still be good after 15 or 20 years, a comparison of the results at 1, 3, and 7 years shows that the rate of change of both gloss and color is decreasing, at least for the more resistant enamels. This indicates that further changes will be moderate and that further inspections can be scheduled at much longer time intervals. The next inspection is tentatively planned after the enamels have been exposed 15 years.

6. Summary

After 7 years' exposure at Los Angeles, Calif.; Dallas, Texas; New Orleans, La.; Pittsburgh, Pa.; Washington, D.C.; and two sites at Kure Beach, N.C., the changes in gloss, color, and general surface conditions of triplicate specimens of 91 porcelain enamels were determined. A summary of the more important findings follows:

(1) All specimens could be cleaned easily, except those exposed at Pittsburgh and Los Angeles.

(2) No metal corrosion was noted, except for 1 specimen at New Orleans, 10 at Kure Beach–800, and 29 at Kure Beach–80. In most cases, this corrosion occurred on enamels having pinhole defects prior to exposure.

(3) An adherent film on the enamels exposed at Pittsburgh and Los Angeles may have partially protected the enamels from weathering action.

(4) The severity of the exposure conditions on the enamel specimens was found to differ at the various sites, except at Pittsburgh and New Orleans. The sites from mildest to most severe were: Los Angeles, Dallas, New Orleans-Pittsburgh, Washington, Kure Beach–800, and Kure Beach—80.

(5) A good correlation was observed between relative humidity and the gloss and color changes. The gloss and color were also affected by the pH of the suspended particulate matter.

(6) The glossy acid-resistant enamels on steel were found to have the best weather resistance of the seven types of enamels included in the test.

(7) For enamels of similar types, a direct relation existed between the acid resistance, as measured either by the acid spot test or by boiling acid solubility test, and the weather resistance as measured by changes in gloss and color. However, this correlation with the citric acid spot test was evident only when averages were considered.

(8) The boiling acid solubility test was found to be more reliable in predicting the color retention of the regular enamels on steel than was the citric acid spot test.

(9) Comparison with enamel specimens exposed for 7 years in an earlier test showed that porcelain enamels produced after the end of World War II were equally resistant to changes in gloss as those produced before the war.

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