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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Weather Resistance of Porcelain Enamels—15-Year Inspection of the 1956 Exposure Test

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Contents

The Weather Resistance of Porcelain Enamels — 15-Year Inspection of the 1956 Exposure Test

Margaret A. Baker*

In 1956, an exposure test of porcelain enamels at 4 urban and 2 ocean shore sites in the continental United States was initiated by the National Bureau of Standards and the Porcelain Enamel Institute. After fifteen years, all exposed specimens were returned to the Bureau and the changes in gloss and color determined. The gloss changes were found to be significantly different at all exposure sites except Pittsburgh, Los Angeles and Dallas. The most severe changes occurred at the Kure Beach, North Carolina, site nearest the ocean, while the least changes occurred at Pittsburgh, Los Angeles and Dallas. The differences in behavior of the specimens correlated with both the average relative humidity and the pH of the suspended particulate matter at the different sites.

A correlation appeared to exist between the acid resistance of the enamels and changes in gloss and color. The regular, glossy, acid-resistant enamels on steel showed the best weather resistance of the various types tested.

Comparison with enamel specimens exposed for fifteen years in an earlier test showed that porcelain enamels produced in the early 1950's were equally resistant to changes in gloss and color as those produced in the late 1930's.

Key words: Acid resistance; color; gloss; pH; porcelain enamel; relative humidity; weather resistance.

1. Introduction

The weather resistance of any building material used in exterior applications is important to building designers and to those responsible for maintenance. As early as 1939, the Enameled Metals Section of the National Bureau of Standards and the Porcelain Enamel Institute recognized the need for accelerated laboratory tests for porcelain enamels that would correlate with weathering data. The study of the weatherability of porcelain enamels on steel begun in 1939 has resulted in a series of reports issued after exposure periods of 1 [1],[1] 7 [2], 15 [3], and 30 [4] years. The principal finding of this study was that the best enamels showed no objectionable changes in gloss or color after 30 years' exposure at Washington, D.C. and the enamels with poor weather resistance could be determined by relatively simple laboratory tests.

In the early 1950's, several new enamel types including low-temperature enamels for steel and aluminum, and titania-opacified enamels, were developed. It was important to determine whether these new enamel types followed the same general pattern with respect to weathering as those tested earlier. Therefore, a new exposure test was initiated in 1956. Progress reports of this test have been published after 1 [5], 3 [6], and 7 [7] years' exposure. The present paper is a progress report after 15 years' exposure. For ease of comparison, the same general format is followed as was used in the 3 year report. Also, as an aid to the reader, the description of the specimens and exposure sites is repeated in this paper.

The next inspection of these enamels is tentatively planned after 30 years' exposure.

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. The producers then applied the enamels to the test specimens. Table 1 includes coded identification of the frit suppliers and fabricators, and also lists the types of enamels. Minor variations in composition of the frit [2] for enamels of the same type as supplied by the different manufacturers probably occurred. Likewise, 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 these 80 were applied to sheet steel and 14 to sheet aluminum. After 3 years' exposure, three of the screening paste enamels [3] had become so badly weathered that they were withdrawn from further testing. The 91 remaining enamels are evaluated in this report.

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*Research Associate from the Porcelain Enamel Institute at the National Bureau of Standards, Washington, D.C., 1964 to 1973.

[1] Figures in brackets refer to literature references at the end of this paper.

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

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

TABLE 1. *Initial data and summary of gloss and color retention data for enamels exposed for 15 years.*

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial gloss [a]	Percentage gloss retention for enamels exposed at: [b]						Color retention for enamels exposed at: [c]						Citric acid spot test rating [d]	Acid solubility [e]
					Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas	Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas		
Titanium white, glossy enamel on steel—resistant to acid & alkalies																		
A-1	1	a	1,540	64	33.8	44.3	74.4	85.7	86.9	89.5	98.4	99.0	98.0	97.0	99.4	98.6	AA	1.0
A-2	2	a	1,520	60	52.9	47.8	73.8	92.7	89.0	87.6	99.5	99.4	98.5	96.4	99.1	99.3	AA	1.1
A-3	3	b	1,525	71	21.8	74.0	73.6	90.5	101.9	91.0	98.9	98.8	98.8	98.9	99.4	99.5	AA	1.4
A-4	4	b	1,430	62	58.7	73.8	71.4	90.0	86.1	91.3	99.1	99.0	98.4	99.2	99.4	98.8	AA	0.6
Average					41.8	60.0	73.3	89.7	91.0	89.9	99.0	99.1	98.4	97.9	99.3	99.1		
Titanium white, glossy enamel on steel—resistant to acids but not to alkalies																		
B-1	5	a	1,450	60	5.3	74.1	49.8	78.1	79.8	83.6	92.0	96.8	94.5	98.2	98.8	98.2	B	13.4
B-2	6	a	1,425	63	1.6	58.8	85.1	79.3	76.8	73.0	55.5	95.9	93.2	96.3	97.0	97.5	B	18.6
B-3	7	b	1,450	60	23.6	46.5	63.3	83.0	86.7	91.4	94.6	96.7	97.0	97.0	97.6	98.2	A	7.0
B-4	8	b	1,430	60	33.8	36.1	59.4	83.8	82.7	86.3	94.4	96.4	96.7	97.4	98.1	91.3	B	8.2
Average					16.1	53.9	64.4	81.1	81.5	83.6	84.1	96.5	95.4	97.2	97.9	96.3		
Zirconium white, glossy enamel on steel—resistant to alkalies but not to acids																		
C-1	9	a	1,430	65	6.6	6.0	17.5	20.1	56.4	73.2	96.9	98.1	92.4	82.8	95.7	98.2	C	279.9
C-2	8	a	1,540	70	7.2	7.8	24.9	15.6	57.3	72.5	95.4	97.2	91.5	74.5	95.0	96.9	C	442.7
C-3	1	b	1,520	64	6.2	6.6	15.6	20.3	55.3	63.9	98.2	99.0	92.3	78.5	90.4	95.5	D	536.4
C-4	2	b	1,500	65	6.9	7.7	19.1	14.3	56.2	66.1	96.8	96.9	93.0	79.2	90.7	95.7	D	376.6
Average					6.7	7.0	19.3	17.6	56.3	68.9	96.8	97.8	92.3	78.8	93.0	96.6		
Red, glossy enamel on steel—acid-resistant type																		
D-1	10	c	1,500	40	14.9	16.4	66.5	104.1	95.2	94.0	90.1	90.2	95.7	95.9	96.4	94.0	C	4.7
D-2	11	c	1,520	56	33.6	60.7	73.6	85.8	79.5	87.1	93.3	98.6	98.7	98.4	98.7	98.7	A	1.4
D-3	12	d	1,480	62	38.1	78.5	64.4	79.4	83.5	85.1	89.5	98.5	98.0	96.2	98.6	98.1	AA	3.4
D-4	13	d	1,490	62	39.6	78.2	63.5	82.5	85.9	85.3	91.1	98.3	98.2	97.9	99.0	98.6	AA	4.0
Average					31.6	58.5	67.0	88.0	86.0	87.9	91.0	96.4	97.6	97.1	98.2	97.4		
Red, glossy enamel on steel—non-acid resistant type																		
E-1	12	c	1,510	53	27.2	20.6	70.0	82.3	80.2	78.9	95.4	97.0	98.8	99.0	99.0	99.3	C	1.2
E-2	13	c	1,510	54	20.6	20.3	66.4	82.6	81.7	82.9	95.2	96.5	98.0	98.2	97.7	98.7	C	3.2
E-3	10	d	1,520	56	13.4	2.8	26.6	55.7	73.1	78.9	91.9	92.0	91.6	93.8	96.5	98.1	D	20.1
E-4	14	d	1,480	55	21.3	4.4	67.8	75.9	81.5	83.2	93.1	93.1	97.0	96.5	98.8	98.3	D	22.3
Average					20.6	12.0	57.7	74.1	79.1	81.0	93.9	94.7	96.4	96.9	98.0	98.6		

See footnotes at end of table.

TABLE 1. *Initial data and summary of gloss and color retention data for enamels exposed for 15 years.*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial gloss[a]	Percentage gloss retention for enamels exposed at:[b]						Color retention for enamels exposed at:[c]						Citric acid spot test rating[d]	Acid solubility[e]
					Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas	Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas		
Red, glossy screening paste enamel on steel—acid-resistant type																		
F–1	5	a	1,500	63	.....	42.7	27.5	74.5	70.8	69.6	.....	77.2	87.2	88.4	73.3	87.5	C	7.1
F–2	15	a	1,500	61	.....	32.0	36.9	77.1	73.3	74.8	.....	83.2	88.4	85.5	84.5	87.3	A	4.4
F–3	16	a	1,500	61	.....	31.9	25.3	79.3	77.3	74.5	.....	82.7	88.9	88.3	84.1	89.3	B	6.8
F–4	17	a	1,500	62	.....	14.6	24.8	73.2	73.3	74.6	.....	79.7	88.1	89.5	86.1	88.2	C	5.5
Average					.....	30.3	28.6	76.0	73.7	73.4	.....	80.7	88.2	87.9	82.0	88.1	.....	.....
Red, glossy screening paste enamel on steel—acid-resistant type																		
FA–4	17	a	1,500	53	.....	6.0	35.8	69.1	71.8	70.4	.....	62.7	68.1	72.4	70.6	64.4	C	5.1
Average					.....	6.0	35.8	69.1	71.8	70.4	.....	62.7	68.1	72.4	70.6	64.4	.....	.....
Yellow, glossy screening paste enamel on steel—acid resistant type																		
G–1	5	b	1,500	39	.....	31.1	69.8	130.9	100.4	91.0	.....	88.9	91.4	88.3	89.6	94.7	A	1.5
G–2	15	b	1,500	46	.....	43.9	64.0	88.3	74.8	73.2	.....	83.0	82.9	86.1	82.9	89.2	AA	0.9
G–3	17	b	1,500	40	.....	23.1	55.8	111.0	105.5	92.0	.....	88.7	89.5	90.2	89.8	94.5	A	2.7
G–4	16	b	1,500	45	.....	28.1	62.1	106.1	89.9	92.0	.....	85.5	88.1	90.4	89.1	94.0	A	1.9
Average					.....	31.6	62.9	109.1	92.7	87.1	.....	86.5	88.0	88.8	87.9	93.1	.....	.....
Yellow, glossy screening paste enamel on steel—acid resistant type																		
GA–1	5	b	1,500	34	.....	88.0	79.0	92.7	109.5	84.7	.....	80.2	79.0	82.9	84.0	83.1	A	1.7
GA–2	15	b	1,500	45	.....	49.1	78.6	85.8	81.2	80.7	.....	78.6	78.4	81.4	84.6	82.2	A	1.3
GA–3	16	b	1,500	37	.....	28.6	65.9	107.4	124.2	91.7	.....	78.0	77.8	81.5	83.2	82.9	A	2.1
GA–4	17	b	1,500	32	.....	32.5	73.2	119.0	77.1	98.9	.....	78.3	78.3	81.9	82.4	82.2	A	2.1
Average					.....	49.6	74.2	101.2	98.0	89.0	.....	78.8	78.4	81.9	83.6	82.6	.....	.....
Black, glossy enamel on steel—acid-resistant type																		
H–1	12	e	1,500	66	27.0	71.9	66.8	73.3	73.0	80.0	84.3	99.1	99.0	97.3	97.6	99.3	AA	0.5
H–2	13	e	1,510	66	35.2	64.8	67.0	72.8	81.2	81.9	89.8	98.2	98.5	98.0	99.1	99.0	A	1.7
H–3	14	c	1,480	60	36.6	57.0	68.9	82.7	82.6	78.7	88.0	97.8	98.7	95.2	97.3	98.7	A	0.9
H–4	10	c	1,500	61	8.0	17.3	68.0	78.1	84.7	84.5	76.5	85.3	99.2	95.5	90.5	96.9	A	2.1
Average					26.7	52.8	67.7	76.7	80.4	81.3	84.7	95.1	98.8	96.5	96.1	98.5	.....	.....
Black, glossy enamel on steel—non-acid-resistant type																		
K–1	12	e	1,500	62	25.2	25.3	62.4	75.3	74.6	76.2	74.1	83.4	98.3	95.5	99.2	99.3	C	20.9
K–2	13	e	1,510	61	13.5	17.0	62.5	77.1	75.1	75.0	85.8	87.8	98.2	95.8	98.8	98.4	D	19.2
K–3	14	c	1,480	57	.....	22.3	66.8	76.1	72.4	77.8		69.3	83.8	81.7	77.5	86.8	D	43.8
K–4	10	c	1,500	53	9.1	10.6	33.0	56.2	67.0	69.1	71.6	69.5	69.2	72.0	56.8	75.0	D	63.9
Average					15.9	18.8	56.2	71.2	72.3	74.5	77.2	77.6	87.3	86.3	69.2	89.9	.....	.....
Titanium pastel yellow, glossy enamel on steel—non-acid-resistant type																		
L–1	6	b	1,525	62	34.4	47.7	61.8	86.5	84.4	86.9	96.4	96.8	97.6	98.7	98.0	98.2	A	1.9
L–2	7	b	1,525	60	30.2	30.0	62.0	85.6	87.5	86.9	95.3	94.1	97.6	96.9	98.6	98.8	A	2.2
L–3	11	c	1,470	67	18.4	15.0	57.8	85.1	84.9	88.1	92.5	93.0	94.6	97.8	93.7	91.5	A	3.2
L–4	12	c	1,480	62	38.4	52.2	63.2	88.6	87.0	86.4	97.0	96.0	97.7	99.0	96.7	98.4	AA	0.8
Average					30.3	36.2	61.2	86.5	86.0	87.1	95.3	95.0	96.9	98.1	96.8	96.7	.....	.....

See footnotes at end of table.

TABLE 1. *Initial data and summary of gloss and color retention data for enamels exposed for 15 years.*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial gloss[a]	Percentage gloss retention for enamels exposed at:[b]						Color retention for enamels exposed at:[c]						Citric acid spot test rating[d]	Acid solubility[e]
					Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas	Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas		
Blue, ground-coat, enamel on steel—acid-resistant type																		
M-1	18	a	1,580	57	50.6	69.8	75.1	80.6	79.9	82.3	94.2	95.0	97.3	96.5	95.9	97.1	A	2.7
M-2	8	a	1,580	57	13.6	40.3	73.5	79.2	80.0	82.1	85.8	89.4	92.7	96.4	89.6	92.9	A	2.6
M-3	7	d	1,540	57	68.3	50.9	70.9	81.9	84.7	80.0	97.4	96.9	98.4	96.4	98.2	96.8	A	1.9
M-4	16	d	1,540	58	69.4	50.2	71.9	75.6	85.5	83.5	93.8	95.8	97.9	95.1	97.0	97.5	A	2.5
Average					50.5	52.8	72.9	79.3	82.5	82.0	92.8	94.3	96.6	96.1	95.2	96.1		
Blue, ground-coat enamel on steel—non-acid-resistant type																		
N-1	4	c	1,540–60	55		48.0	65.3	74.1	68.4	74.2		75.8	85.9	91.3	86.5	88.1	C	21.1
N-2	9	c	1,540–60	52		48.6	60.9	72.8	61.9	73.0		81.8	70.3	77.4	81.0	88.0	D	34.3
N-3	1	d	1,540	55	35.7	15.9	68.4	71.9	72.0	80.4	81.3	81.7	76.5	91.5	98.2	97.1	C	36.1
N-4	18	d	1,540	55	52.3	26.1	67.1	75.0	77.6	79.2	75.2	79.0	75.6	93.0	98.0	95.8	C	41.5
Average					44.0	34.7	65.4	73.5	70.0	76.7	78.2	79.6	77.1	88.3	90.9	92.3		
Green mat enamel on steel—clear, acid-resistant frit matted with calcined aluminum oxide																		
P-1	2	a	1,510	52	40.1	65.4	72.9	77.1	73.0	74.2	95.1	95.9	96.9	97.9	97.5	96.5	A	2.2
P-2	6	a	1,520	43	45.1	66.8	71.3	82.9	73.4	83.2	95.3	97.0	97.1	98.6	96.3	95.1	B	3.7
P-4	7	d	1,480	35	9.2	4.5	19.9	87.0	75.1	91.1	92.8	91.6	91.5	98.0	96.1	94.0	C	30.1
Average					31.5	45.6	54.7	82.3	73.8	82.8	94.4	94.8	95.2	98.2	96.6	95.2		
Green mat enamel on steel—semiopaque, acid-resistant frit matted with calcined aluminum oxide																		
PA-1	7	a	1,480	30	14.6	11.1	49.0	29.4	71.3	62.8	91.6	90.3	89.5	92.6	96.6	96.9	D	42.4
PA-2	3	a	1,480	40	16.2	15.2	44.3	53.6	84.5	65.9	92.5	91.3	92.2	94.1	98.2	97.1	C	56.9
PA-3	2	d	1,480	17	42.9	39.1	71.8	99.6	81.1	86.6	94.2	90.8	94.8	97.7	97.6	97.2	C	30.5
PA-4	6	d	1,480	13	92.2	47.1	74.9	125.2	76.1	85.7	93.4	90.7	95.2	98.0	95.9	96.2	C	36.2
Average					41.5	28.1	60.0	77.0	78.3	75.3	92.9	90.8	92.9	95.6	97.1	96.9		
Green mat enamel on steel—clear, acid-resistant frit matted with barium metaphosphate																		
R-1	8	a	1,430	18	15.1	28.1	50.0	83.8	70.1	72.6	92.7	93.0	94.8	97.2	94.5	94.4	B	11.1
R-2	10	a	1,520	19	21.1	31.6	47.6	56.3	68.5	70.0	91.1	91.1	93.9	96.5	94.3	92.0	B	12.0
R-4	2	d	1,480	30	13.4	25.6	37.1	82.7	47.6	46.9	95.2	93.2	93.6	97.7	95.5	94.8	B	8.0
Average					16.5	28.4	44.9	74.3	62.1	63.2	93.0	92.4	94.1	97.1	94.8	93.7		
Green mat enamel on steel—semiopaque, acid-resistant frit matted with barium metaphosphate																		
RA-1	2	a	1,480	31	17.0	52.9	70.4	82.6	67.1	76.2	82.6	87.9	92.3	95.2	96.3	93.9	B	17.3
RA-2	18	a	1,480	32	31.2	38.7	53.9	65.3	61.4	72.2	92.0	91.6	93.9	96.3	97.3	94.7	B	17.0
RA-3	8	d	1,430	21	18.2	33.1	63.4	81.2	70.6	83.1	95.7	94.4	95.5	97.2	97.3	96.6	B	14.1
RA-4	6	d	1,480	7	37.6	28.6	50.2	94.3	61.8	53.8	95.6	94.1	95.0	89.1	90.8	98.4	B	7.4
Average					26.0	38.3	59.5	80.9	65.2	71.3	91.5	92.0	94.2	94.4	95.4	95.9		
Green mat enamel on steel—clear, acid-resistant frit matted by proprietary additive																		
S-1	3	e	1,500	38	30.4	33.0	42.5	64.0	84.9	73.9	91.7	90.0	89.7	95.7	88.8	94.5	C	24.8
S-2	14	e	1,480	44	9.0	10.9	23.4	43.4	67.0	66.9	90.5	89.7	89.8	93.8	94.3	94.2	C	30.1
Average					19.7	22.0	33.0	53.7	76.0	70.4	91.1	89.9	89.8	94.8	91.6	94.4		

See footnotes at end of table.

TABLE 1. *Initial data and summary of gloss and color retention data for enamels exposed for 15 years.*—Continued

Specimen identification	Producer of specimens	Frit supplier	Reported firing temperature °F	Average initial gloss[a]	Percentage gloss retention for enamels exposed at:[b]						Color retention for enamels exposed at:[c]						Citric acid spot test rating[d]	Acid solubility[e]
					Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas	Kure Beach 80	Kure Beach 800	Washington	Pittsburgh	Los Angeles	Dallas		
Green mat enamel on steel—semiopaque, acid-resistant frit matted with proprietary additive																		
SA–1	4	e	1,520	38	14.4	17.6	37.6	63.7	67.6	78.1	94.2	93.8	91.8	97.0	90.6	95.1	C	16.4
SA–2	9	e	1,540	43	7.9	10.5	30.4	60.1	59.2	61.9	93.8	94.2	92.7	97.3	96.2	94.9	C	14.6
Average					11.2	14.1	34.0	61.9	63.4	70.0	94.0	94.0	92.3	97.2	93.5	95.0		
Green, glossy 1,300 °F enamel on steel																		
T–1	11	f	1,330	57	22.2	41.5	73.4	71.4	80.6	85.7	94.5	95.2	97.7	97.4	96.2	96.4	B	4.0
T–2	19	f	1,300	58	53.0	56.5	76.8	71.2	87.3	87.7	95.3	94.9	98.2	96.6	94.5	94.5	AA	3.1
Average					37.6	49.0	75.1	71.3	84.0	86.7	94.9	95.1	98.0	97.0	95.4	95.5		
Red, glossy 1,300 °F enamel on steel																		
U–1	11	f	1,320	52	17.1	38.9	64.7	95.8	99.1	95.7	77.7	84.3	96.9	93.9	94.7	93.4	B	3.9
U–2	19	f	1,300	53	41.6	52.2	79.7	101.2	89.5	82.4	88.3	93.4	97.7	98.3	98.4	98.2	B	2.1
Average					29.4	45.5	72.2	98.5	94.3	89.1	83.0	88.9	97.3	96.1	96.6	95.8		
Yellow, glossy enamel on aluminum—acid-resistant type																		
V–1	20	e	1,000	65	7.5	23.1	57.2	75.4	79.3	82.4	91.5	89.5	95.2	89.4	90.4	90.4	AA	8.2
V–2	10	e	1,000	70	7.8	19.0	58.4	73.4	72.3	71.4	90.9	92.3	92.7	88.3	86.3	90.4	AA	12.0
V–3	20	g	1,000	83	4.1	5.4	44.2	73.5	78.4	50.3	59.2	60.3	86.9	90.8	93.0	93.0	B	11.4
V–4	10	g	1,000	85	4.3	4.3	43.8	71.6	79.1	62.5	64.2	64.5	88.5	86.6	95.0	96.5	A	10.1
Average					5.9	13.0	50.9	73.5	77.3	66.7	76.4	76.7	90.8	88.8	91.2	92.6		
White, glossy enamel on aluminum																		
VA–1	20	a	980	81	4.7	6.1	47.7	71.0	83.4	68.4	95.8	95.5	95.2	95.6	96.0	95.2	AA	8.2
VA–2	10	a	1,000	81	8.6	4.5	44.4	83.2	78.9	68.8	92.4	96.1	97.2	96.3	95.6	96.8	AA	6.1
Average					6.7	5.3	46.1	77.1	81.2	68.6	94.1	95.8	96.2	96.0	95.8	96.0		
Green, glossy enamel on aluminum—acid resistant type																		
W–1	20	e	980	69	5.7	7.7	47.7	75.8	71.3	78.1	88.8	86.9	92.1	92.9	94.5	94.5	A	6.2
W–2	10	e	1,000	77	10.6	25.1	54.3	57.9	73.3	72.5	90.8	94.7	95.3	93.3	93.7	95.7	AA	6.9
W–3	20	g	1,000	82	1.5	1.8	60.2	79.8	76.8	60.7	73.6	74.8	90.7	97.6	94.7	93.1	A	21.1
W–4	10	g	1,000	81	1.8	1.7	62.6	79.9	76.0	54.3	72.4	74.9	93.0	97.5	95.1	93.7	A	19.9
Average					4.9	9.1	56.2	73.4	74.4	66.4	81.4	82.8	92.8	95.3	94.5	94.3		
Green, mat enamel on aluminum																		
X–1	20	e	990	13	25.3	54.9	62.5	75.9	66.4	74.6	82.6	90.4	94.7	95.3	92.8	94.4	AA	6.5
X–2	10	e	1,000	56	5.1	33.2	64.7	83.8	70.2	70.9	86.9	89.5	96.5	98.3	95.7	96.6	AA	6.3
X–3	20	g	1,000	4	39.4	51.4	121.2	130.0	66.8	82.1	88.8	89.4	91.9	95.3	95.7	95.6	A	20.7
X–4	10	g	1,000	20	9.7	14.9	139.7	106.7	71.1	77.8	88.9	89.8	96.9	96.3	95.0	94.6	A	8.1
Average					20.0	38.6	97.0	99.1	68.6	76.4	86.8	89.8	95.0	96.3	94.8	95.3		
Green, glossy 1,000 °F enamel on steel																		
Y–1	21	e	1,020	70		32.4	68.5	84.2	79.6	80.3		92.2	89.1	91.0	91.0	98.9	AA	2.8
Average						32.4	68.5	84.2	79.6	80.3		92.2	89.1	91.0	91.0	98.9		
Red, glossy 1,000 °F enamel on steel																		
Z–1	21	e	1,000	47		23.4	63.7	111.7	80.5	92.7		47.0	70.4	94.2	90.4	88.7	B	
Average						23.4	63.7	111.7	80.5	92.7		47.0	70.4	94.2	90.4	88.7		

[a] 45° specular gloss was measured in accordance with ASTM Designation C346.
[b] Computed from three specimens at each site.
[c] The color retention is 100 minus the color change in NBS units computed from three specimens at each site.
[d] Ratings were made in accordance with ASTM Designation C282.
[e] Acid solubilities determined in accordance with ASTM Designation C283.

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 these 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 six exposure-test locations and the general exposure conditions for each site are given in table 2. The sites were selected to represent a range of exposure conditions found in the United States. The racks at four sites were located on rooftops in industrial city areas of Los Angeles, California; Dallas, Texas; Washington, D.C.; and Pittsburgh, Pennsylvania. The remaining two sites were ground sites at the International Nickel Company's Corrosion Laboratory at Kure Beach, North Carolina—one at 80 feet from the ocean and the other at 800 feet. Table 3 summarizes the average weather and air quality data for each of the six sites as obtained from the National Oceanic and Atmospheric Administration and the National Air Sampling Network. There are no data in this report on the specimens exposed at New Orleans because they were removed from the roof of the Post Office Building prior to a hurricane after 8 years' exposure and were not reinstalled.

TABLE 2. *Exposure test locations*

City	Exposure site	Exposed 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 Building, National Bureau of Standards.	Temperate, commercial.
Pittsburgh, Pa.....	Roof, U.S. Post Office.	Temperate, commercial.
Dallas, Texas	Roof, U.S. Post Office.	Texas, commercial.
Los Angeles, Calif ...	Roof, U.S. Post Office.	Southern California, commercial.

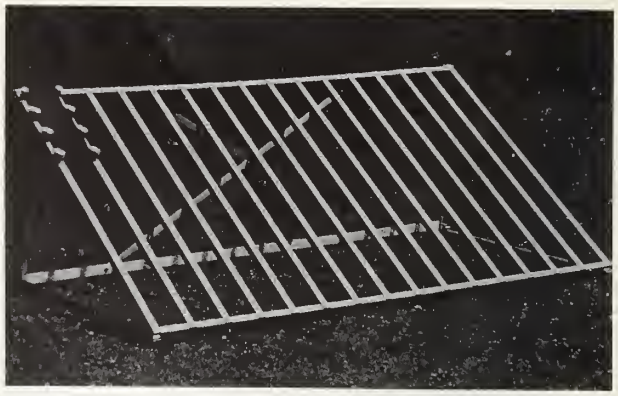

FIGURE 1. *Exposure rack showing the supporting struts, and ceramic insulators used to position 3 of the 150 specimens the rack will hold when it is filled.*

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, enameled face up, and faced south except at the Kure Beach–80 ft station where they faced the ocean at east-south-east. Figure 1 shows an exposure rack with 3 of the 150 specimens in place.

TABLE 3. *Average weather and air quality data for the various exposure sites*

Exposure site	pH [a, b]	Average annual [c] relative humidity	Average annual [c] temperature	Total annual [c] sunshine	Total annual [c] precipitation	Suspended [a] particulate matter
		(*percent*)	(*deg F*)	(*hours*)	(*inches*)	(mg/m^3)
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
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] The suspended particulate matter was collected on an 8 × 10-inch (20.3 × 25.4-cm) high volume (40 to 50 cubic feet (1.1 to 1.4 cubic meters) per minute) air filter. The filters were collected at approximately two week intervals. The pH values in table 3 are the pH of the solutions formed by refluxing an 8 percent aliquot of the filter with 50 ml of distilled water and diluting to 80 ml.
[c] Averages for National Oceanographic and Atmospheric Administration.
[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 remaining in the test were returned to the laboratory for inspection after they had been exposed for 15 years. Upon arrival, each specimen was scoured for 30 strokes with a soft cellulose sponge that had been moistened with a one percent, by weight, solution of trisodium phosphate and sprinkled with calcium carbonate. The specimens were then rinsed successively with tap water, distilled water and ethyl alcohol. This cleaning treatment was sufficient to clean the specimens exposed at all sites except Pittsburgh. The specimens from Pittsburgh were vigorously scoured with calcium carbonate until the surfaces appeared clean. They were then rinsed with tap water, distilled water and ethyl alcohol.

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 exposed at Pittsburgh or Dallas showed any signs of corrosion of the base metal. One enamel exposed at Washington, one at Los Angeles, 34 at Kure Beach–800, and 39 at Kure Beach–80 showed some rusting of the base metal. The one enamel that permitted rusting at these four sites was a 1000° F enamel on steel (Y–1). Since there were only two enamels of this type included in this test, more exposure testing is needed before they should be recommended for outdoor exposure applications.

The other enamels that permitted rusting at the Kure Beach sites were not confined to any one enamel type but generally appeared to be specimens which had pinhole-type defects or blisters present prior to exposure. Since none of these specimens showed any signs of rust until the seven-year inspection, it seems probable that a thin layer of a high iron content glass existed at the bottom of the defect which gradually corroded away during exposure to the weather.

The two exceptions to this pinhole-type rusting were enamels B–1, and B–2 exposed at Kure Beach–80. The cover coats of these enamels were completely eroded after 15 years' exposure, and the remaining ground coat was not corrosion resistant enough to protect the metal from rusting. Thus, for severe environments, such as Kure Beach–80, only the enamels with good acid and alkali resistance should be used.

It is interesting to note that 25 of the 39 enamels which had permitted rusting during 15 years' exposure at Kure Beach–80, had also shown rust on the enamel surface after 7 years' exposure. However, only one of these enamels, M–4, had permitted the base metal to corrode through with the additional 8 years' exposure.

4.3. Measurements of Gloss and Color After 15 Years

The degree of weathering was evaluated by changes in color and 45 degree specular gloss. The gloss [8] is reported as the percentage of initial gloss retained after exposure, and the color is reported as color retention, which is 100 minus the color change in NBS units [4] [9].

The individual gloss and color retention values for each enamel after 15 years' exposure are presented 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. The screening paste enamels were also excluded from the averages because of their abnormally large color changes. Also, the gloss and color values for enamels K–3, N–1, N–2, Y–1 and Z–1 were excluded from the averages for enamels exposed at Kure Beach, because these specimens were not reexposed after the seven year inspection because of severe surface degradation.

4.4. Effect of Exposure Time on Changes in Gloss and Color

The effect of exposure time on gloss and color retention is illustrated in figures 2 and 3. The gloss data in figure 2 indicate that the greatest gloss loss occurs during the first 2 to 4 years' exposure after which, for most locations, it tends to reach a constant rate. The data between three and fifteen years were extrapolated (as shown by the dashed lines in figure 2) to give predicted gloss retention values after 30 years' exposure. (The next inspection of these enamels is tentatively scheduled after 30 years' exposure.) These extrapolated data indicate that the enamels at the four milder sites, Pittsburgh, Los Angeles, Dallas and Washington, would be expected to have good gloss retention after 30 years' exposure, while the enamels exposed at the two sites at Kure Beach would be expected to have their original fire-polished surface completely removed after 30 years' exposure. The slight increase in gloss is probably a result of the polishing action required to clean the specimens exposed at Pittsburgh.

The color data shown in figure 3 indicate that the greatest color changes occur during the first one to two years' exposure. After this, the color changes at

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[4] The tristimulus color difference parameters, L (lightness–darkness), a (red–green), and b (yellow–blue) were measured with a color difference meter. The color change, in NBS Units, was calculated by the following formula:

$$\text{Color Change } (\Delta E) = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

where L is $10\sqrt{Rd}$,
and Rd is the 45°, 0° luminous daylight reflectance.

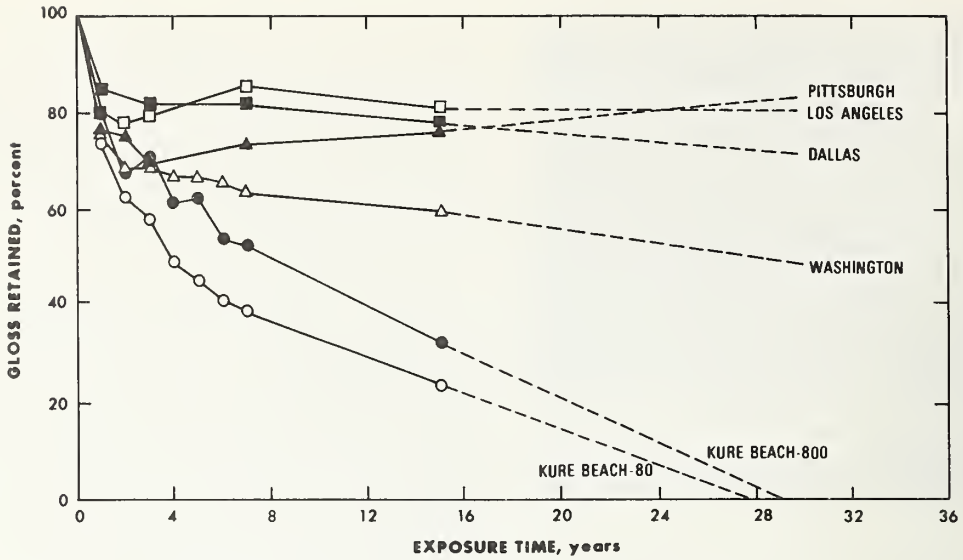

FIGURE 2. *Effect of exposure time on percentage gloss retained.*
(Points are averages for all enamels except screening pastes and K–3, W–3, N–1, Y–1 and Z–1 at Kure Beach.)

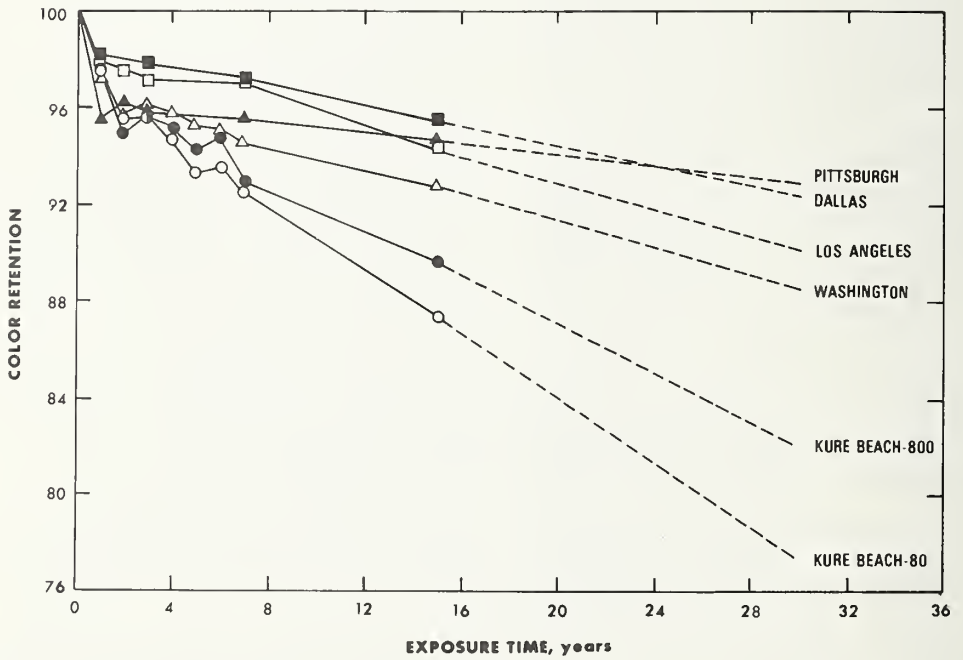

FIGURE 3. *Effect of exposure time on the color retention.*
(Points are averages for all nonwhite enamels except screening pastes and K–3, W–3, N–1, Y–1 and Z–1 at Kure Beach.)

a nearly constant rate which depends on the site. The color data between three and fifteen years were extrapolated to 30 years. These extrapolations showed the same trend as the gloss did. The enamel at the four milder sites changed only about 4 NBS units in the additional 15 years' exposure, while the enamels exposed at the Kure Beach sites changed about twice that much. The dirt on the enamels exposed at Pittsburgh may have protected the surface from color changes.

4.5. Compairson 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 except the screening pastes, 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. This analysis showed that no differences (significant at the 5% level) existed between Pittsburgh, Los Angeles and Dallas. However, the remaining three sites, Kure Beach–80, Kure Beach–800 and Washington, were significantly different from these three sites and from each other. This ranking again suggests the effectiveness of the dirt film in protecting the enamel surface on the specimens exposed at Pittsburgh from change since the ranking of this site has changed from moderate to mild between the 3 and 15 year inspections.

The differences in the durability of the enamels exposed at the various sites are undoubtedly caused by differences in the atmospheres at the exposure sites. After seven years' exposure [7], it was found that the differences in gloss and color retention for the enamels exposed at the various sites correlated fairly well with the average pH of a solution formed by dissolving an 8 percent aliquot of the collected suspended particulate matter in 80 cc of distilled water, and the average relative humidity at the exposure site. This finding still appears to be valid after 15 years' exposure as illustrated in figures 4 through 7. It seems likely that the atmospheric moisture condenses on the surface of the porcelain enamel, dissolving some of the particulate matter which had settled there. The solution thus formed, having varying pH values as indicated in table 3 would then attack the enamel surface.

TABLE 4. *Average color retention and percentage gloss retained after 15 years' exposure*

Exposure site	Color retention [a]	Gloss retained [b]
		(percent)
Kure Beach-80	87.3	24.4
Kure Beach-800	89.7	33.3
Washington	92.9	59.8
Pittsburgh	94.7	76.4
Los Angeles	94.3	81.3
Dallas	95.5	77.4

[a] Color retention is given for all nonwhite enamels except screening pastes.

[b] Percentage gloss retained is given for all enamels except screening pastes.

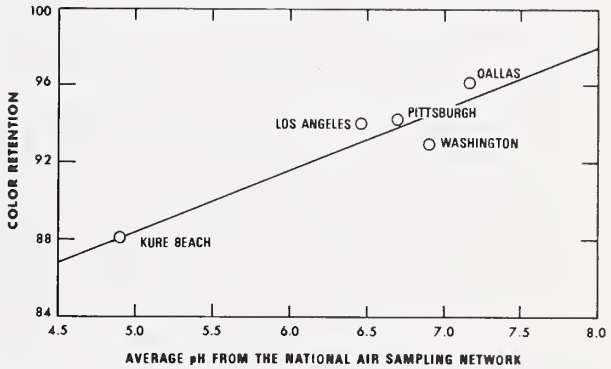

FIGURE 5. *Effect of pH of the particulate matter on the average color retention of the nonwhite glossy enamels on steel.*

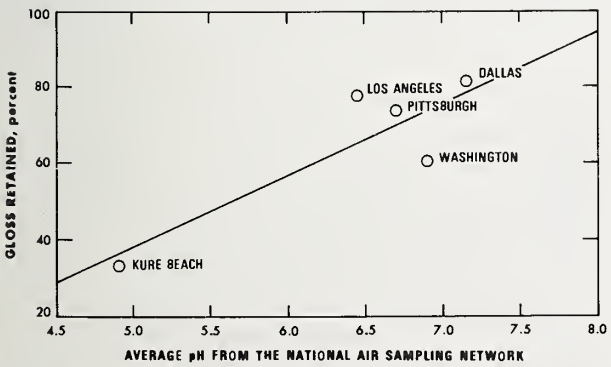

FIGURE 4. *Effect of pH of particulate matter on the average gloss retention of the glossy enamels on steel.*

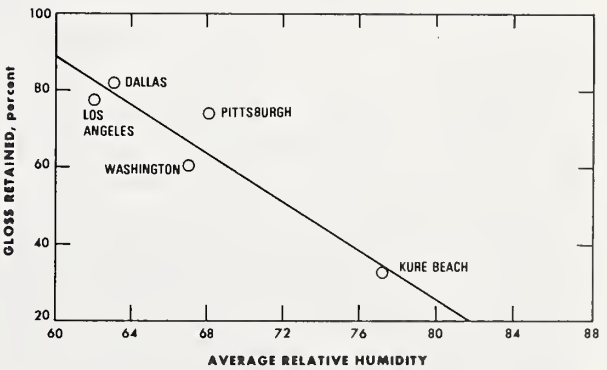

FIGURE 6. *Effect of average site humidity on the average gloss retention values for the glossy enamels on steel.*

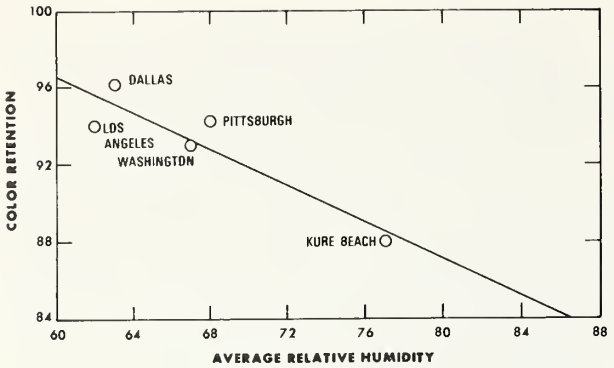

FIGURE 7. *Effect of average site humidity on the average color retention for nonwhite glossy enamels on steel.*

4.6. Comparison of Enamel Types

The average color and gloss retention at all sites for each enamel type is given in table 5. The enamel types are ranked according to average color retention. These data indicate that the glossy, acid-resistant enamels on steel had the best color retentions, while the glossy enamels on aluminum had the worst color retentions. However, the rankings of the last four enamel types may be in error since many of the enamels exposed at Kure Beach–80, the most severe site, were not included in these averages because they were not re-exposed after the 7-year inspection.

The average gloss and color retention values for the porcelain enamels on aluminum were much lower than had been anticipated. However, these enamels were among the first commercially available porcelain enamels for aluminum. There have been many improvements in the enamel formulations since this test was started in 1956. A test of these newer improved porcelain enamels on aluminum initiated in 1964 showed marked improvements in gloss and color retention [10, 11].

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

Enamel type	Color retention	Percentage gloss retained
Regular glossy on steel, AR [a]	95.6	67.8
1300 °F on steel	94.4	69.4
Matte on steel	94.2	57.5
Matte on aluminum	93.0	66.6
Regular glossy on steel, Non-AR [b]	90.0	50.3
1000 °F on steel [c]	85.3	71.8
Screening paste enamels [c]	83.9	70.0
Glossy on aluminum	83.0	47.6

[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 (non-acid-resistant).

[b] These averages exclude the values for three enamels (K–3, N–1, and W–2) exposed at Kure Beach-80 which were removed from further testing after 7 years exposure.

[c] These averages exclude the values for enamels exposed at Kure Beach-80 since these enamels were removed from further testing after 7 years exposure.

4.7. Correlation of Weather Resistance With Acid Resistance

The primary accelerated test used to predict the weather resistance of porcelain enamels is the citric acid spot test [12]. This test divides the enamels into five categories having the alphabetical designations AA, A, B, C or D. The enamels recommended for exterior architectural applications are those designated AA or A.

The 15-year color and gloss data for glossy enamels on steel indicate that the AA and A enamels have, on the average, the best gloss and color retentions. This is illustrated for the enamels exposed at Washington (figures 8 and 9). These data also indicate that there is considerable scatter in the enamels designated C or D and that several of these enamels had gloss and color retentions as high as those designated A or AA. In addition, the citric acid spot test is difficult to evaluate on matte enamels. Therefore, the color data were plotted as a function of the enamels' boiling acid solubility [13]. These data are illustrated for both the glossy and matte enamels on steel exposed at Washington in figure 10.

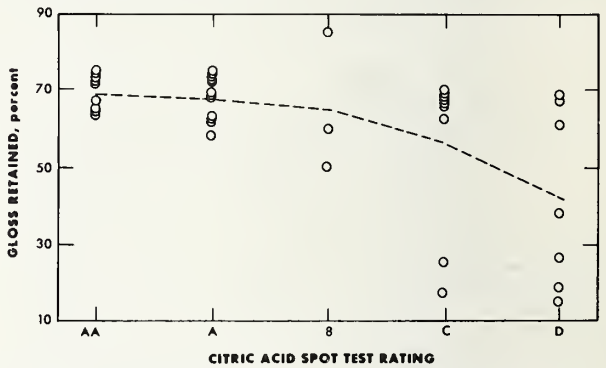

FIGURE 8. *Correlation between citric acid spot test ratings and weather resistance as measured by gloss retention for the glossy enamels on steel exposed at Washington.*

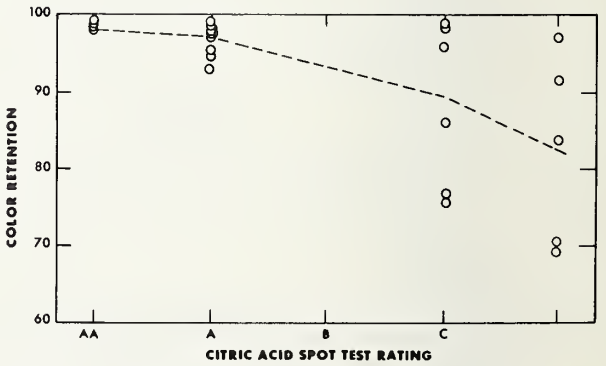

FIGURE 9. *Correlation between citric acid spot test ratings and weather resistance as measured by color retention for the glossy enamels on steel exposed at Washington.*

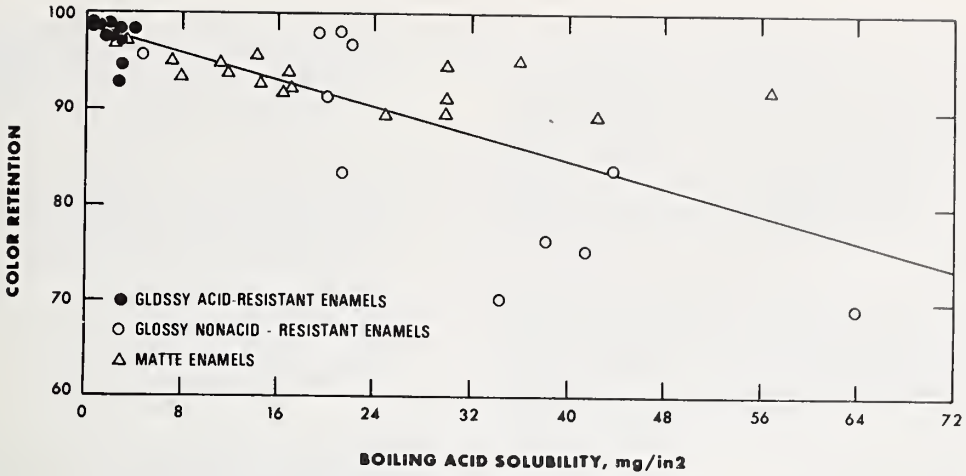

FIGURE 10. *Correlation between the boiling acid solubility and weather resistance as measured by color retention for the glossy and matte enamels on steel exposed at Washington.*

More scatter was observed in these data than was observed at 7-years' exposure [7]. However, the enamels considered acid-resistant by this test (under 12 mg/in² acid solubility) all had good color retentions.

While the data illustrated are only for the enamels exposed at Washington, the enamels exposed at the other sites followed the same general pattern.

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

The cupric sulfate test to determine the color retention of acid resistant red and yellow cadmium-selenium-sulfide pigmented enamels [14] was developed after the first year inspection. This test has been successful, giving results which correlate with color retention at all sites, for the acid-resistant red and yellow screening paste enamels. The average color retentions for the acid-resistant red and yellow glossy enamels on steel which passed this test are good. It therefore appears that this test is a useful tool to evaluate the color retention of these enamel colors.

4.9 Effect of Exposure Angle

It was felt that changing the exposure angle from 90° (vertical), as would be used in siding applications, to 45°, as might be found in roofing installations, would greatly accelerate the weathering of the enamels. Therefore, duplicate specimens of 44 enamels were exposed at 90° as well as 45° at Washington. The average color and gloss retentions for these enamels are given in table 6. These data indicate that changing the exposure angle from 90° to 45° does not significantly change the rate of weathering of porcelain enamels at Washington.

4.10 Comparison with late 1930's enamels

Table 7 compares the average gloss and color retentions for the regular enamels on steel exposed for 15 years at Washington in this test and in the test initiated in 1939. These data indicate that the average color retention of the acid-resistant enamels after 15 years' exposure varies by only 0.1 NBS unit while the gloss retention differs by 6.1 percent which is a barely discernable change. Thus, it may be said that the new enamels for steel produced in the early 1950's are equally resistant to weathering, as measured by changes in gloss and color, as those produced in the late 1930's.

TABLE 6. *Comparison of the average gloss and color retentions for the enamels exposed at angles of 45° and 90° at Washington, D.C.*

Exposure angle	Gloss retained	Color retention
	(percent)	
45°	57.7	92.4
90° (vertical)	61.7	93.9

TABLE 7. *Comparison of 15-year results for enamels on steel from the 1939 and 1956 exposure tests*

Exposure test	Enamel type	Color retention	Percentage gloss retained
1956	AR[a]	97.7	68.4
1956	Non-AR[b]	90.7	51.2
1939	AR[a]	97.6	74.5
1939	Non-AR[b]	92.1	48.5

[a] Same as table 5.
[b] Same as table 5.

5. Summary

After 15 years' exposure at Los Angeles, California; Dallas, Texas; Pittsburgh, Pennsylvania; Washington, D.C.; and two sites at Kure Beach, North Carolina, triplicate specimens of 91 porcelain enamels were examined visually for corrosion of the base metal and were measured for changes in gloss and color. A summary of the more important findings follows:

1. Comparison with enamel specimens exposed for 15 years in an earlier test showed that procelain enamels produced in the early 1950's were equally resistant to changes in gloss and color as those produced in the late 1930's.

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

3. A correlation was found between an enamel's acid resistance as measured by either the citric acid spot test or the boiling acid solubility test, and weather resistance as measured by changes in gloss and color.

4. No significant difference was found in the weathering of enamels exposed at 90° and 45° to the horizontal, respectively, at Washington.

5. A correlation was found between both the pH of the suspended particulate matter and the average relative humidity at an exposure site, and the changes in both gloss and color of porcelain enamels exposed at that site.

6. The severity of the exposure conditions on the enamel specimens was found to differ for different sites, except those at Pittsburgh, Los Angeles, and Dallas were similar. The sites in order from most severe to mildest were: Kure Beach–80, Kure Beach–800, Washington, and (Pittsburgh, Los Angeles and Dallas).

7. No corrosion of the base metal was noted on any of the enamels exposed at Dallas or Pittsburgh. One enamel exposed at Washington and one at Los Angeles showed rusting of the base metal, while 34 enamels at Kure Beach–800, and 39 enamels at Kure Beach–80 permitted the base metal to rust.

8. All specimens could be cleaned easily except those exposed at Pittsburgh. The adherent dirt film on the enamels exposed at Pittsburgh appears to have protected the enamel from weathering action.

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

In 1956, an exposure test of porcelain enamels at 4 urban and 2 ocean shore sites in the continental United States was initiated by the National Bureau of Standards and the Porcelain Enamel Institute. After fifteen years, all exposed specimens were returned to the Bureau and the changes in gloss and color determined. The gloss changes were found to be significantly different at all exposure sites except Pittsburgh, Los Angeles and Dallas. The most severe changes occurred at the Kure Beach, North Carolina, site nearest the ocean, while the least changes occurred at Pittsburgh, Los Angeles and Dallas. The differences in behavior of the specimens correlated with both the average relative humidity and the pH of the suspended particulate matter at the different sites.

A correlation appeared to exist between the acid resistance of the enamels and changes in gloss and color. The regular, glossy, acid-resistant enamels on steel showed the best weather resistance of the various types tested.

Comparison with enamel specimens exposed for fifteen years in an earlier test showed that porcelain enamels produced in the early 1950's were equally resistant to changes in gloss and color as those produced in the late 1930's.

17. KEY WORDS (*six to twelve entries; alphabetical order, capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Acid resistance; color; gloss; pH; porcelain enamel; relative humidity; weather resistance.

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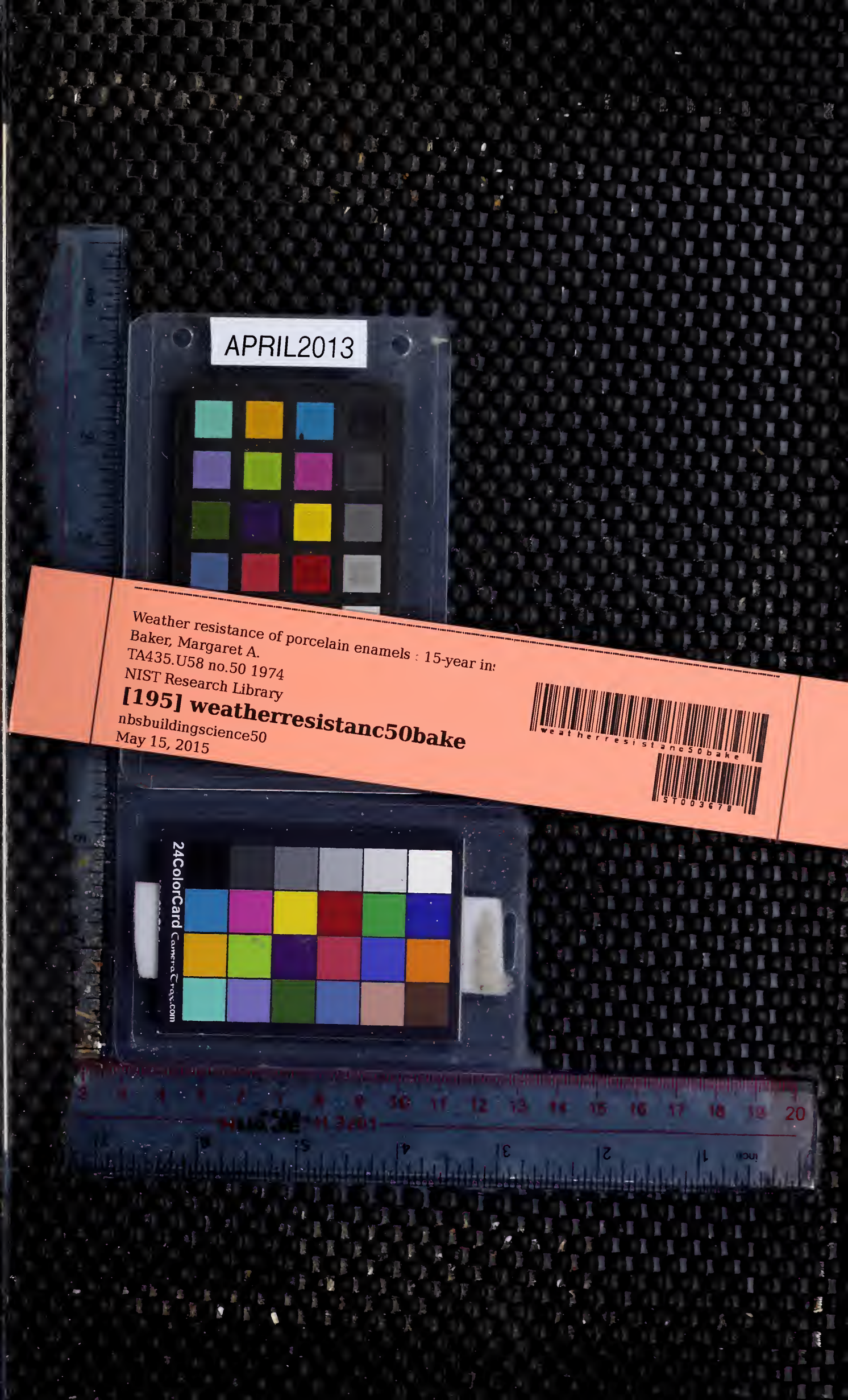
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