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Effect of Exposure Site on Weather Resistance of Porcelain Enamels Exposed for Three Years

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Effect of Exposure Site on Weather Resistance of Porcelain Enamels Exposed for Three Years

Dwight G. Moore and Alan Potter

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Effect of Exposure Site on Weather Resistance of Porcelain Enamels Exposed for Three Years

Dwight G. Moore and Alan Potter *

An exposure test of porcelain-enameled steel and aluminum specimens is being conducted jointly by the Porcelain Enamel Institute and the National Bureau of Standards. The exposure sites are Dallas, Tex.; Los Angeles, Calif.; New Orleans, La.; Pittsburgh, Pa.; Washington, D.C.; and two sites at Kure Beach, N.C.

The present report gives the results of the third-year inspection. Changes in gloss and color were taken as criteria of weathering. Based on averages for all enamels, the 80-ft site at Kure Beach caused the greatest change in gloss and color, while the conditions at Dallas, Los Angeles, and New Orleans caused the least change. The conditions at Washington, Pittsburgh, and the second Kure Beach site (800 ft from the ocean) were of intermediate severity. Comparison of the gloss and color changes with data obtained by the National Air Sampling Network indicated that air pollution by acidic contaminants was a factor in site severity.

A direct relation existed between acid resistance and weather resistance. This relation was apparent, however, only when averages were considered. There were individual exceptions within groups of enamels of the same general type. In addition, enamels of different types, such as aluminum and steel enamels, having the same acid resistance (citric acid spot test) did not necessarily show the same weather resistance. Further, some red and yellow enamels with good acid resistance showed poor color stability. It was found, however, that this poor stability could be predicted by a specially developed cupric sulfate test.

As a group, the regular glossy enamels for steel showed the best weather resistance among the various types tested.

1. Introduction

The use of porcelain enamel as an exterior finish for many types of building structures has been expanding rapidly during the past decade [1].[1] The factors responsible for this increase include: (a) the trend in the building industry towards curtain wall construction, (b) the emphasis on color in modern architecture, (c) the ease with which most porcelain enamel finishes can be cleaned, and (d) the excellent weather resistance of many porcelain enamels.

An earlier investigation conducted by the National Bureau of Standards [2] provided information on weather resistance for porcelain enamels that were in common use when the exposure tests were started (1940). After World War II, several new types of enamel were introduced. These included (a) enamels for aluminum, (b) "low-temperature" enamels for steel, and (c) steel enamels opacified with titanium dioxide.

The present investigation, initiated in 1956, is a joint effort of the Enameled Metals Laboratory at the National Bureau of Standards and the Porcelain Enamel Institute, working through its Research Associateship at the Bureau. The goals are twofold: (1) to evaluate the weather resistance of new types of porcelain enamel that have been introduced during the past 15 yr, and (2) to develop reliable tests for predicting weather resistance.

The first report of the current investigation was published in 1957 [3]. This was not a complete report, but was concerned almost entirely with observations on the red and yellow screening-paste enamels after the first year of exposure. The present report describes the condition of all of the porcelain enamels after exposure for 3 yr.

2. Types and Sources of Enamels

The 28 types of enamel used in the test were furnished to 21 fabricators of architectural enamel parts by seven companies who manufacture enamel frits.[2] The fabricators then applied the enamels to the test specimens. A later table (table 3) includes coded identification of the frit suppliers and fabricators. Minor variations in composition probably occurred in the same enamel type as furnished by different frit companies. Likewise, in many cases, different fabricators applying the same enamel may not have achieved an identical finish because of minor variations in milling and firing. If these variations in history of the specimens 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.

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[1] Figures in brackets indicate the literature references at the end of this Monograph.

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

3. Description of Specimens and Method of Mounting

The type of specimen being used in the tests is shown in figure 1. A large supply of 18-gage metal blanks with this configuration were obtained and forwarded to the fabricators. The fabricators, in turn, applied each porcelain enamel, as specified, to about 60 specimens. Twenty-one of these were used for exposure testing (three at each site), while the remainder were kept in dry storage for later use in development of accelerated tests.

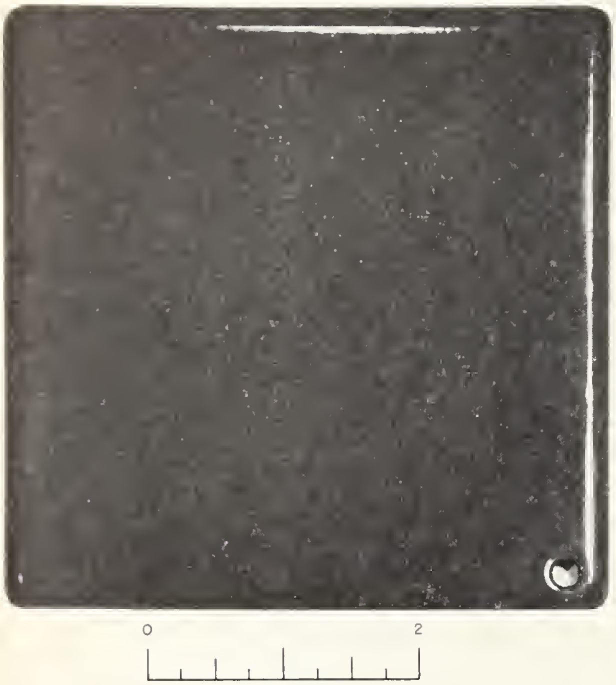

FIGURE 1. *Exposure test specimen.*

The specimens are mounted loosely in ceramic insulators which are fastened to the metal stretchers of the supporting racks. The racks are constructed of aluminum alloy except for two seashore locations, where Monel metal is used. The racks face south except at the Kure Beach–80 ft station, where they face the ocean (east-southeast). Figure 2 shows a typical installation.

The normal exposure angle for the specimens is 45°. However, at Washington an additional rack is installed in which a representative group of specimens is exposed vertically.

4. Exposure Sites

The seven exposure-test locations and the general exposure conditions that each site represents are given in table 1. The sites were selected as being representative of the various exposure conditions in different parts of the United States. The racks at five sites are located in the commercial area of the city; the remaining two are in a rural sea coast location.

TABLE 1. *Exposure Test Locations*

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

The weather data for the actual period of exposure are given in table 2.

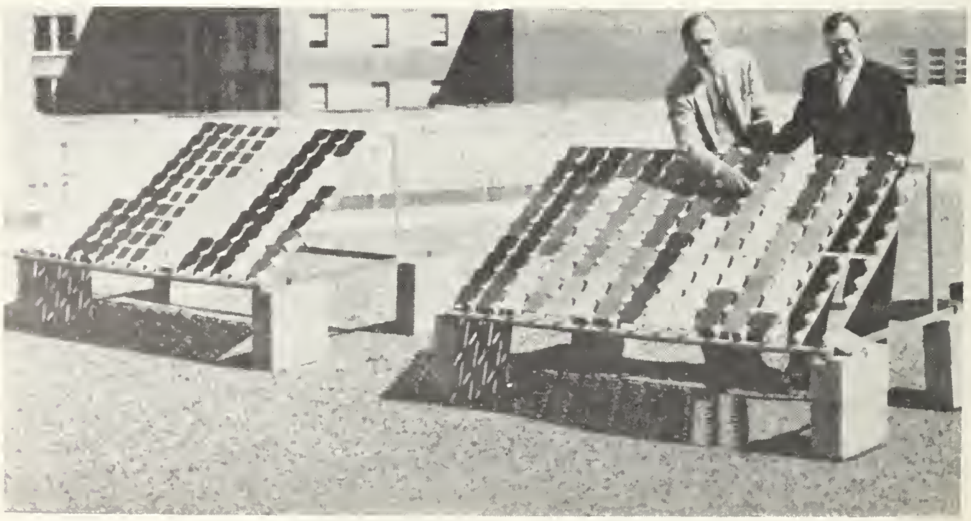

FIGURE 2. *Exposure test site on roof of U.S. Post Office Building in Dallas, Texas.*

TABLE 2. *Weather data for the 3-yr exposure period*

From U.S. Weather Bureau Records.

City	Exposure period	Average annual rainfall	Average annual sunshine	Average temperature
		In.	*Hr.*	*°F.*
Dallas, Tex	June 1956–June 1959	35.3	2,821	66.0
Kure Beach, N.C	May 1956–May 1959	54.4	2,873	63.0
Los Angeles, Calif	June 1956–June 1959	12.1	3,367	66.4
New Orleans, La	June 1956–June 1959	66.7	2,446	69.8
Pittsburgh, Pa	July 1956–July 1959	33.8	1,807	53.2
Washington, D.C	Aug. 1956–July 1959	38.8	2,539	57.0

5. Results

After exposure for 3 yr, all specimens were removed and returned to Washington, where they were evaluated for ease of cleaning, corrosion of base metal, changes in gloss, and changes in color. The specimens were then returned to the racks for further exposure.

5.1. Ease of Cleaning

The ease with which specimens could be cleaned after exposure for 3 yr varied with the exposure location. The specimens from Dallas, Washington, and the two Kure Beach sites could be cleaned easily by washing with a one percent by weight solution of trisodium phosphate. The same treatment removed almost all of the adhering dirt film from the specimens exposed at Los Angeles and New Orleans and, because the small amount that remained did not detract from the overall appearance of the enamels, these specimens were given no further cleaning treatment.

Most of the Pittsburgh specimens, on the other hand, could not be cleaned satisfactorily by the washing treatment. They were covered by a thin, but tightly adherent, deposit which appeared to consist mostly of fly ash and soot. The ease with which the deposit could be removed varied with the type of specimen surface. Cleanability ratings were assigned to the various enamels from the Pittsburgh site and these ratings were then compared to both the initial 45° specular gloss and the 45° gloss after 3 yr of exposure. The following summarizes the results:

Cleanability rating [a]	No. of specimens averaged	Average and initial 45° gloss	Average 3-yr 45° gloss
1	26	58.8	41.8
2	64	49.0	34.4
3	4	67.1	28.8

[a] No. 1—cleanable by washing with a trisodium phosphate solution; No. 2—cleanable by scouring with a commercial scouring powder; No. 3—not completely cleanable by scouring.

As might be expected, the ease of cleaning of the Pittsburgh specimens was not related to the initial gloss but rather to the gloss of the surface after 3 yr of exposure. However, the correlation was good after 3 yr only when averages were considered and many individual exceptions to the correlation were observed.

5.2. Corrosion Protection

No serious corrosion of the base metal was noted on any of the specimens after exposure. However, a mild rusting at edges and at areas of poor coverage on the backs was observed on some of the enameled steel specimens that had been exposed to the sea air conditions at Kure Beach. The only undamaged specimens [3] that showed evidence of corrosion on the face side at any of the sites were those to which the 1,000 °F steel enamels had been applied (Y–1 and Z–1 in table 3). A few scattered pinholes were present in these enamels. At both Kure Beach sites rust stains appeared on small areas of the enamel surface adjacent to the pinholes and these stains could not be removed completely even by vigorous scouring.

5.3. Changes in Gloss

Specular gloss measurements were made with a Gardner 45° Glossmeter [4] which was calibrated and operated in accordance with the ASTM Tentative Method of Test for 45-Deg Specular Gloss of Ceramic Materials [5]. Measurements were made at four fixed locations at the center of each specimen and compared with similar measurements made at the start of the investigation. The data were expressed as the percentage of initial specular gloss retained.

The specimens were cleaned prior to measurement with a 1-percent-by-weight aqueous solution of tri-sodium phosphate. While this treatment was not always effective in removing the last remnants of adhering dirt particles (see 5.1), the surfaces were nevertheless believed to be of comparable cleanliness to a "cleaned" architectural installation. Except for the Pittsburgh specimens (see 5.1), scouring was not used as a cleaning treatment because the protective surface films [2] would have been removed, and the subsequent weathering behavior of the enamel might have been changed significantly.

The results of the gloss measurements are given in table 3.

5.4. Changes in Color

A Hunter Color-Difference Meter [6] was used to measure the change in color. Measurements were made on each specimen at the beinning of the investigation and again after exposure. The color difference in NBS units [7] was computed from these measurements and expressed in terms

[3] A few specimens were damaged at the Pittsburgh site when one of racks overturned during a strong windstorm.

TABLE 3. *Optical data and acid resistance spot test ratings of enamels*

Specimen identification	Fabricator of specimens	Frit supplier	Reported firing temperature	Average initial specular gloss [a]	Percentage of initial gloss retained (G_R) and color retention (C_R) after exposure for 3 yrs at —[b]—																Citric acid spot-test rating [d]
					Kure Beach—80 ft		Kure Beach—800 ft		New Orleans		Dallas		Los Angeles		Pittsburgh [c]		Washington		Average		
					G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	
TITANIUM WHITE, GLOSSY ENAMEL ON STEEL—RESISTANT TO ACIDS AND ALKALIES																					
			°F																		
A-1	1	a	1,540	64	78.2	97.8	77.7	99.1	88.1	98.4	90.0	98.2	93.8	98.8	81.3	98.0	85.3	98.4	94.9	98.4	AA
A-2	2	a	1,520	60	84.5	99.1	80.0	99.4	90.0	99.2	94.0	99.0	95.9	98.8	81.2	97.4	88.2	99.1	87.7	98.9	AA
A-3	3	b	1,525	71	75.4	98.7	98.7	99.4	90.2	99.7	91.8	99.5	98.8	98.6	71.9	98.5	94.8	98.9	88.8	99.0	AA
A 4	4	b	1,430	62	84.3	98.4	85.5	98.1	87.8	98.1	82.1	98.2	83.6	98.2	73.3	98.3	82.0	98.0	84.9	99.2	AA
Average					80.6	98.5	85.5	99.0	89.0	98.8	89.5	98.7	93.0	98.6	76.9	98.0	87.6	98.6			
TITANIUM WHITE, GLOSSY ENAMEL ON STEEL—RESISTANT TO ACIDS BUT NOT TO ALKALIES																					
B-1	5	a	1,450	60	74.9	97.7	80.4	98.8	86.9	98.1	87.7	98.5	88.8	98.4	79.6	96.7	75.1	98.7	81.9	98.1	B
B-2	6	a	1,425	63	72.7	97.3	83.7	98.6	86.1	97.5	87.6	98.4	91.1	98.5	78.0	96.8	70.5	97.6	81.4	97.8	B
B-3	7	b	1,450	60	69.5	97.4	76.4	99.3	88.5	97.8	90.0	98.6	90.2	99.0	77.3	97.0	80.9	98.0	81.8	98.2	A
B-4	8	b	1,430	60	66.2	97.9	73.1	99.0	86.5	98.7	84.6	98.7	92.3	98.4	74.3	97.0	79.8	98.7	79.6	98.3	B
Average					70.8	97.6	78.4	98.9	87.0	98.0	87.5	98.6	90.6	98.6	77.3	96.9	76.6	98.2			
ZIRCONIUM WHITE, GLOSSY ENAMEL ON STEEL—RESISTANT TO ALKALIES BUT NOT TO ACIDS																					
C-1	9	a	1,430	65	42.5	97.7	57.1	98.8	73.6	97.9	75.1	99.0	74.4	97.9	40.8	93.9	31.6	98.0	56.4	97.6	C
C-2	8	a	1,540	70	34.4	97.5	55.6	98.7	74.4	98.2	74.2	99.2	75.1	98.0	50.2	94.2	37.4	98.2	57.3	97.7	C
C-3	1	b	1,520	64	18.8	98.0	33.4	98.7	68.0	98.2	69.0	99.0	75.4	97.5	41.2	92.0	36.7	98.4	48.9	97.4	D
C-4	2	b	1,500	65	19.5	97.7	31.1	98.4	66.1	98.4	69.0	99.7	70.2	97.5	39.3	92.1	31.2	97.6	46.6	97.4	D
Average					28.8	97.7	44.3	98.6	70.5	98.2	71.8	99.2	73.8	97.7	42.9	93.0	34.2	98.0			
RED, GLOSSY ENAMEL ON STEEL—ACID-RESISTANT TYPE																					
D-1	10	c	1,500	40	66.3	93.8	78.1	96.7	87.4	95.8	90.8	95.8	97.1	96.8	81.0	96.6	75.2	95.9	82.3	95.9	C
D-2	11	c	1,520	56	70.1	97.6	80.7	98.1	86.3	98.7	78.4	98.6	83.8	95.0	73.5	96.8	78.1	99.1	78.7	97.7	A
D-3	12	d	1,480	62	97.2	96.2	72.7	98.9	87.0	99.4	86.6	99.5	87.3	99.1	74.1	96.8	76.2	98.9	83.0	98.4	AA
D-4	13	d	1,490	62	89.0	97.5	68.5	98.9	87.8	99.2	88.1	99.0	92.2	98.1	75.8	96.7	72.1	98.8	81.9	98.3	AA
Average					80.6	96.3	75.0	98.2	87.1	98.3	86.0	98.2	90.1	97.2	76.1	96.7	75.4	98.2			
RED, LOSSY GENAMEL ON STEEL—NON-ACID-RESISTANT TYPE																					
E-1	12	c	1,510	53	55.1	98.0	67.2	99.1	80.8	98.8	79.8	99.0	86.2	99.0	69.8	97.4	71.7	99.5	73.0	98.7	C
E-2	13	c	1,510	54	55.1	98.1	67.8	98.8	82.8	99.1	80.8	99.4	86.7	98.6	70.5	96.0	70.8	97.6	73.5	98.2	C
E-3	10	d	1,520	56	59.0	97.3	67.0	98.1	77.6	98.9	78.4	98.4	85.0	97.8	59.5	93.1	44.9	90.8	67.3	96.3	D
E-4	14	d	1,480	55	54.2	98.4	64.0	98.8	75.4	99.4	79.8	99.5	88.3	99.4	68.7	94.7	74.2	99.1	72.1	98.5	D
Average					55.8	98.0	66.5	98.7	79.2	99.0	79.7	99.1	86.6	98.7	67.1	95.3	65.4	96.8			
RED, GLOSSY SCREENING PASTE ENAMEL ON STEEL—ACID-RESISTANT TYPE (Predicted by manufacturers as being likely to have good weather resistance)																					
F-1	5	a	1,500	63	23.1	68.6	46.7	76.1	73.6	82.2	70.6	90.7	78.1	81.8	70.3	83.4	44.1	81.5	58.1	80.6	C
F-2	15	a	1,500	61	50.5	68.9	63.2	79.0	79.2	87.2	76.2	94.6	83.9	86.1	70.2	86.1	59.2	87.4	68.9	84.2	A
F-3	16	a	1,500	61	43.4	70.3	63.5	79.1	79.5	85.8	74.7	92.6	82.2	84.1	74.3	85.8	44.2	85.6	66.0	83.3	B
F-4	17	a	1,500	62	22.9	71.6	52.0	77.7	77.3	80.6	73.7	91.2	82.4	80.4	70.4	83.3	45.6	82.2	60.6	81.0	C
Average					35.0	69.8	56.4	78.0	77.4	84.0	73.8	92.3	81.6	83.1	71.3	84.6	48.3	84.2			
RED, GLOSSY SCREENING PASTE ENAMEL ON STEEL—ACID-RESISTANT TYPE (Predicted as being likely to have poor weather resistance)																					
			°F																		
FA-1	5	a	1,500	52	36.0	53.3	70.6	50.7	73.2	50.4	71.3	77.5	82.6	63.8	71.8	45.8	55.3	45.4	65.8	55.3	C
FA-2	15	a	1,500	50	51.8	48.3	78.6	54.4	77.1	54.9	75.8	83.2	93.8	72.0	75.4	49.9	76.4	50.3	75.6	59.0	B
FA-3	16	a	1,500	52	51.2	49.3	81.8	51.4	82.1	52.2	75.7	82.5	87.6	67.0	76.4	52.5	65.9	48.9	74.4	57.7	B
FA-4	17	a	1,500	53	21.2	53.9	57.1	50.1	75.5	50.4	74.7	75.2	82.6	62.3	67.7	48.8	56.2	49.0	62.2	55.7	C
Average					40.0	51.2	72.0	51.6	77.0	52.0	74.4	79.6	86.6	66.3	72.8	49.2	63.4	48.4			
YELLOW, GLOSSY SCREENING PASTE ENAMEL ON STEEL—ACID-RESISTANT TYPE (Predieted as being likely to have good weather resistance)																					
G-1	5	b	1,500	39	78.4	91.5	71.9	92.3	79.6	93.2	79.5	96.0	89.0	90.6	79.8	91.2	71.5	94.4	78.5	92.8	A
G-2	15	b	1,500	46	52.5	84.9	66.2	85.0	72.7	88.6	84.7	95.1	80.0	87.5	77.3	90.7	69.9	89.9	71.5	88.8	AA
G-3	17	b	1,500	40	60.7	90.0	71.2	92.7	82.2	93.2	78.3	95.9	91.0	90.8	79.2	93.4	67.8	94.2	75.8	92.9	A
G-4	16	b	1,500	45	61.7	89.4	72.3	89.7	80.3	92.4	78.4	96.0	77.5	91.7	64.6	94.1	68.6	93.8	71.9	92.5	A
Average					63.3	89.0	70.4	89.9	78.7	91.8	79.5	95.8	84.4	90.2	75.2	92.4	69.4	93.1			

See footnotes at end of table.

TABLE 3. *Optical data and acid resistance spot test ratings of enamels*—Continued

Specimen identification	Fabricator of specimens	Frit supplier	Reported firing temperature	Average initial specular gloss [a]	Percentage of initial gloss retained (G_R) and color retention (C_R) after exposure for 3 yrs at —b— Kure Beach—80 ft		Kure Beach—800 ft		New Orleans		Dallas		Los Angeles		Pittsburgh [c]		Washington		Average		Citric acid spot-test rating [d]
					G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	
YELLOW, GLOSSY SCREENING PASTE ENAMEL ON STEEL—ACID-RESISTANT TYPE (Predicted as being likely to have poor weather resistance)																					
GA-1	5	b	1,500	34	67.0	81.2	76.2	78.3	78.6	80.9	79.7	90.0	90.0	85.2	69.6	83.1	74.8	79.9	76.6	82.6	A
GA-2	15	b	1,500	45	56.8	78.9	64.3	75.3	72.6	80.3	77.2	90.9	73.3	84.7	68.3	82.7	76.4	80.4	69.8	81.9	A
GA-3	16	b	1,500	37	64.2	79.9	70.6	77.8	76.4	82.6	88.7	91.0	92.7	86.2	73.7	85.0	74.1	81.2	77.2	83.4	A
GA-4	17	b	1,500	32	67.9	80.4	75.1	77.9	81.2	82.2	91.6	89.8	103.2	84.8	78.6	83.3	75.6	81.2	81.9	82.8	A
Average					64.0	80.1	71.6	77.3	77.2	81.5	84.3	90.4	89.8	85.2	72.6	83.5	75.2	80.7			
BLACK, GLOSSY ENAMEL ON STEEL—ACID-RESISTANT TYPE																					
H-1	12	e	1,500	66	74.1	98.4	84.7	98.3	81.5	99.1	73.9	99.2	79.3	99.1	59.8	97.6	70.9	98.0	74.9	98.5	AA
H-2	13	e	1,510	66	77.2	98.4	76.9	98.1	82.5	98.9	75.5	99.1	80.0	99.2	60.3	97.7	70.5	98.2	74.7	98.5	A
H-3	14	c	1,480	60	87.1	97.8	83.7	99.2	84.2	98.6	86.4	98.7	90.7	99.3	71.5	95.9	80.4	99.5	83.4	98.4	A
H-4	10	c	1,500	61	65.7	95.9	69.3	98.4	84.8	98.3	88.0	98.1	94.6	98.9	73.1	95.5	84.0	98.2	79.9	97.6	A
Average					76.0	97.6	78.6	98.5	83.2	98.7	81.0	98.8	86.2	99.1	66.2	96.7	76.4	98.5			
BLACK, GLOSSY ENAMEL ON STEEL—NON-ACID-RESISTANT TYPE																					
K-1	12	e	1,500	62	59.3	98.5	49.2	99.0	77.0	99.2	74.1	99.2	79.6	99.2	66.2	95.9	72.7	98.6	68.3	98.5	C
K-2	13	e	1,510	61	48.4	97.4	45.8	99.0	76.8	98.7	75.0	98.8	80.8	98.9	69.0	96.0	72.5	98.4	66.9	98.2	D
K-3	14	c	1,480	57	48.4	92.7	54.0	96.6	78.5	97.0	77.0	98.8	85.4	97.2	71.5	97.7	73.8	95.8	69.8	96.5	D
K-4	10	c	1,500	53	62.1	91.6	71.2	95.1	77.3	91.0	76.1	95.6	79.8	90.6	70.6	93.0	65.1	81.9	71.8	91.2	D
Average					54.6	95.0	55.0	97.4	77.4	96.5	75.6	98.1	81.4	96.5	69.3	95.6	71.0	93.7			
TITANIUM PASTEL YELLOW, GLOSSY ENAMEL ON STEEL—ACID-RESISTANT TYPE																					
L-1	6	b	1,525	62	72.0	98.4	78.1	97.9	85.7	98.4	86.4	98.2	86.1	98.3	75.3	97.6	79.3	98.3	80.4	98.2	A
L-2	7	b	1,525	60	72.8	98.5	74.0	98.0	86.2	98.8	87.3	98.6	89.2	98.7	74.9	97.3	79.2	98.7	80.5	98.4	A
L-3	11	c	1,470	67	52.8	98.8	69.8	95.5	84.4	99.3	84.4	98.9	84.7	99.2	74.9	97.9	79.5	98.8	75.8	98.3	A
L-4	12	c	1,480	62	84.3	98.4	85.5	98.1	87.8	98.1	82.1	98.2	83.6	98.2	73.3	98.3	82.0	98.0	82.7	98.2	AA
Average					70.5	98.5	76.8	97.4	86.0	98.6	85.0	98.5	85.9	98.6	74.6	97.8	80.0	98.4			
BLUE, GROUND-COAT ENAMEL ON STEEL—ACID-RESISTANT TYPE																					
			°F																		
M-1	18	a	1,580	57	72.6	99.0	76.5	99.0	83.4	99.4	78.8	99.2	84.3	98.9	69.1	98.3	79.3	98.8	77.7	99.0	A
M-2	8	a	1,580	57	65.5	97.8	76.1	98.8	83.8	99.0	78.5	99.1	81.1	98.5	73.7	95.0	82.1	99.0	77.2	98.2	A
M-3	7	d	1,540	57	78.0	99.1	73.4	96.5	88.9	99.0	89.5	99.0	93.4	98.8	75.8	95.1	88.9	98.7	84.0	98.0	A
M-4	16	d	1,540	58	77.2	97.9	72.2	97.5	85.6	97.9	88.5	97.4	92.3	97.2	69.4	93.8	89.8	97.0	82.1	97.0	A
Average					73.3	98.4	74.6	98.0	85.4	98.8	83.8	98.7	87.8	98.4	72.0	95.6	85.0	98.4			
BLUE, GROUND-COAT ENAMEL ON STEEL—NON-ACID-RESISTANT TYPE																					
N-1	4	c	1,540-60	55	55.4	92.9	73.2	95.6	76.3	95.1	74.8	97.5	77.0	94.4	70.6	95.6	69.9	94.9	71.0	95.2	C
N-2	9	c	1,540-60	52	68.5	89.8	83.4	92.2	77.8	92.1	83.4	94.8	78.4	92.2	68.2	90.7	70.0	86.0	75.7	91.1	D
N-3	1	d	1,540	55	66.0	97.8	67.7	98.4	81.9	98.8	80.7	99.1	85.3	99.2	67.6	96.2	75.3	94.9	75.0	97.8	C
N-4	18	d	1,540	55	66.6	96.8	72.4	98.4	82.0	99.0	82.1	98.9	85.3	99.0	69.5	96.2	76.4	94.8	76.3	97.6	C
Average					64.1	94.3	74.2	96.2	79.5	96.2	80.2	97.6	81.5	96.2	69.0	94.7	72.9	92.6			
GREEN MAT ENAMEL ON STEEL—CLEAR, ACID-RESISTANT FRIT MATTED WITH CALCINED ALUMINUM OXIDE																					
P-1	2	a	1,510	52	72.3	98.8	82.9	99.6	80.4	99.4	71.1	99.5	76.8	99.5	65.2	98.1	73.6	99.5	74.6	99.2	A
P-2	6	a	1,520	43	76.9	94.6	85.5	99.1	82.2	99.1	71.6	99.1	72.2	99.0	70.4	95.0	73.9	99.0	76.1	97.8	B
P-4	7	d	1,480	35	90.9	92.9	96.0	98.1	96.5	99.6	89.9	99.2	86.1	98.8	82.5	97.9	53.8	95.7	85.1	97.5	C
Average					80.0	95.4	88.1	98.9	86.4	99.4	77.5	99.3	78.4	99.1	72.7	97.0	67.1	98.1			
GREEN MAT ENAMEL ON STEEL—SEMI-OPAQUE, ACID-RESISTANT FRIT MATTED WITH CALCINED ALUMINUM OXIDE																					
PA-1	7	a	1,480	30	40.3	96.3	62.2	96.6	85.2	98.8	85.4	99.1	74.1	98.2	34.6	95.9	61.0	89.0	63.3	96.3	D
PA-2	3	a	1,480	40	47.1	96.5	69.7	97.3	82.6	98.3	96.1	99.1	81.4	98.2	64.2	97.9	58.2	95.1	71.3	97.5	C
PA-3	2	d	1,480	17	91.6	99.4	92.3	99.1	95.0	98.6	90.8	98.4	87.8	98.4	92.0	98.8	89.2	98.2	91.2	98.7	C
PA-4	6	d	1,480	13	88.7	98.4	90.1	98.1	92.6	97.9	87.6	98.0	82.2	98.0	95.8	97.9	91.8	98.1	89.8	98.1	C
Average					66.9	97.6	78.6	97.8	88.8	98.4	90.0	98.6	81.4	98.2	71.6	97.6	75.0	95.1			

See footnotes at end of table.

TABLE 3. *Optical data and acid resistance spot test ratings of enamels*—Continued

Specimen identification	Fabricator of specimens	Frit supplier	Reported firing temperature	Average initial specular gloss [a]	Percentage of initial gloss retained (G_R) and color retention (C_R) after exposure for 3 yrs at —[b]— Kure Beach—80 ft		Kure Beach—800 ft		New Orleans		Dallas		Los Angeles		Pittsburgh [c]		Washington		Average		Citric acid spot-test rating [d]
					G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	
GREEN MAT ENAMEL ON STEEL—CLEAR, ACID-RESISTANT FRIT MATTED WITH BARIUM METAPHOSPHATE																					
R-1	8	a	1,430	18	52.3	97.0	68.8	96.4	74.2	96.4	72.0	95.8	64.3	97.0	76.0	97.9	59.2	97.4	66.7	96.8	B
R-2	10	a	1,520	19	53.3	97.3	62.4	95.8	66.5	95.9	69.3	95.3	66.2	97.2	56.0	96.4	58.3	96.9	61.7	96.4	B
R-4	2	d	1,480	30	36.2	96.0	42.5	95.4	47.2	94.2	45.9	94.7	46.2	94.4	97.6	96.5	47.4	95.1	51.9	95.2	B
Average					47.3	96.8	57.9	95.9	62.6	95.5	62.4	95.3	58.9	96.2	76.5	96.9	55.0	96.5			
GREEN MAT ENAMEL ON STEEL—SEMI-OPAQUE, ACID-RESISTANT FRIT MATTED WITH BARIUM METAPHOSPHATE																					
RA-1	2	a	1,480	31	61.2	93.8	74.3	94.0	82.2	95.9	78.9	95.4	42.1	95.5	92.0	97.3	84.0	95.1	73.5	95.3	B
RA-2	18	a	1,480	32	64.4	94.6	54.6	94.3	74.0	96.1	74.5	95.0	40.8	96.5	69.5	96.7	70.5	94.2	64.0	95.3	B
RA-3	8	d	1,430	21	64.1	97.4	76.6	96.3	85.4	97.1	87.3	95.9	69.6	97.4	80.8	96.0	86.7	96.2	78.6	96.6	B
RA-4	6	d	1,480	7	62.1	95.8	53.4	95.4	63.2	94.7	62.7	95.8	67.5	95.9	60.1	89.5	62.6	95.0	61.6	94.6	B
Average					63.0	95.4	64.7	95.0	76.2	96.0	75.8	95.5	55.0	96.3	75.6	94.9	76.0	95.1			
GREEN MAT ENAMEL ON STEEL—CLEAR, ACID-RESISTANT FRIT MATTED BY PROPRIETARY ADDITIVE																					
S-1	3	e	1,500	38	51.0	96.2	52.5	94.3	67.9	95.9	73.6	96.2	77.8	96.7	57.1	95.8	59.1	93.6	62.7	95.5	C
S-2	14	e	1,480	44	36.1	95.8	45.7	94.0	49.5	95.2	68.9	98.0	44.0	96.5	44.9	95.6	44.5	94.2	47.6	95.6	C
Average					43.6	96.0	49.1	94.2	58.7	95.6	71.2	97.1	60.9	96.6	51.0	95.7	51.8	93.9			
GREEN MAT ENAMEL ON STEEL—SEMI-OPAQUE, ACID-RESISTANT FRIT MATTED WITH PROPRIETARY ADDITIVE																					
			°F																		
SA-1	4	e	1,520	38	55.4	95.2	68.0	92.9	71.9	95.4	79.8	95.8	69.8	96.1	63.0	96.4	58.0	91.6	66.6	94.8	C
SA-2	9	e	1,540	43	42.6	96.4	47.9	95.4	55.9	97.1	64.2	97.9	67.4	98.1	48.0	96.8	39.3	94.7	52.2	96.6	C
Average					49.0	95.8	58.9	94.2	63.9	96.2	72.0	96.8	68.6	97.1	55.5	96.6	48.6	93.2			
GREEN, GLOSSY 1,300° F ENAMEL ON STEEL																					
T-1	11	f	1,330	57	73.7	98.6	80.2	99.3	87.1	98.7	83.2	97.8	86.3	98.6	73.6	98.3	83.6	98.7	81.1	98.6	B
T-2	19	f	1,300	58	85.2	99.2	93.8	99.4	91.3	99.6	89.5	99.7	91.7	97.7	74.6	97.4	92.7	98.8	88.4	98.8	AA
Average					79.4	98.9	87.0	99.1	89.2	99.2	86.4	98.8	89.0	98.2	74.1	97.8	88.2	98.8			
RED, GLOSSY 1,300° F ENAMEL ON STEEL																					
U-1	11	f	1,320	52	62.4	89.5	86.8	92.8	93.6	94.7	89.0	94.9	95.6	90.8	81.2	93.2	79.4	95.0	84.0	93.0	B
U-2	19	f	1,300	53	78.7	93.5	84.8	95.5	89.8	95.9	87.8	95.8	96.1	93.8	92.5	95.9	85.1	95.9	87.8	95.2	B
Average					70.6	91.5	85.8	94.2	91.7	95.3	88.4	95.4	95.8	92.3	86.8	94.6	82.2	95.4			
YELLOW, GLOSSY ENAMEL ON ALUMINUM—ACID-RESISTANT TYPE																					
V-1	20	e	1,000	65	40.5	96.5	49.4	95.6	67.9	95.1	79.6	96.8	77.1	97.2	66.6	94.0	60.0	98.0	63.0	96.2	AA
V-2	10	e	1,000	70	29.6	97.0	47.2	96.7	69.3	96.2	78.3	96.7	77.6	96.8	55.9	92.0	62.8	98.5	60.1	96.3	AA
V-3	20	g	1,000	83	25.8	81.7	71.2	85.8	79.2	95.5	78.8	96.5	81.1	94.6	65.8	92.5	59.5	94.0	65.9	91.5	B
V-4	10	g	1,000	85	18.9	85.8	69.7	89.7	78.4	96.4	81.4	97.9	81.8	96.1	66.0	88.3	53.6	96.0	64.3	92.9	A
Average					28.7	90.2	59.4	92.0	73.7	95.8	79.5	97.0	79.4	96.2	63.6	91.7	59.0	96.6			
GREEN, GLOSSY ENAMEL ON ALUMINUM—ACID-RESISTANT TYPE																					
W-1	20	e	980	69	35.8	95.8	41.4	95.5	78.5	97.2	82.3	97.8	77.5	97.1	65.9	96.4	55.5	95.5	62.4	96.5	A
W-2	10	e	1,000	77	39.8	98.6	68.1	93.7	65.3	98.0	77.1	98.6	70.5	97.6	63.9	96.5	59.8	99.0	63.5	97.4	AA
W-3	20	g	1,000	82	11.6	85.0	33.9	90.1	76.9	96.9	80.2	99.0	73.9	98.7	70.0	98.5	67.9	95.6	59.2	94.8	A
W-4	10	g	1,000	81	21.5	87.7	41.1	88.9	70.3	96.4	78.6	99.5	69.9	98.6	69.7	98.4	55.3	96.7	58.1	95.2	A
Average					27.2	91.8	46.1	92.0	72.8	97.1	79.6	98.7	73.0	98.0	67.4	97.4	59.6	96.7			
GREEN, MAT ENAMEL ON ALUMINUM																					
X-1	20	e	990	13	93.6	98.6	86.1	98.1	81.7	97.0	80.8	97.7	68.2	97.6	67.5	96.3	68.8	96.8	78.1	97.5	AA
X-2	10	e	1,000	56	67.9	97.2	89.7	98.8	77.8	98.9	78.1	99.1	72.4	99.1	72.0	99.0	61.5	99.1	74.2	98.8	AA
X-3	20	g	1,000	4	96.9	95.6	90.6	95.8	100.0	97.5	83.7	97.7	62.3	96.0	85.1	97.3	70.8	96.6	84.2	96.6	A
X-4	10	g	1,000	20	64.6	95.2	58.4	95.5	83.6	97.9	81.1	98.0	65.3	98.2	67.7	97.7	52.4	97.9	67.6	97.2	A
Average					80.8	96.6	81.2	97.0	85.8	97.8	80.9	98.1	67.0	97.7	73.1	97.6	63.4	97.6			

See footnotes at end of table.

Table 3. *Optical data and acid resistance spot test ratings of enamels*—Continued

Specimen identification	Fabricator of specimens	Frit supplier	Reported firing temperature	Average initial specular gloss [a]	Percentage of initial gloss retained (G_R) and color retention (C_R) after exposure for 3 yrs at —[b]— Kure Beach—80 ft		Kure Beach—800 ft		New Orleans		Dallas		Los Angeles		Pittsburgh [c]		Washington		Average		Citric acid spot-test rating [d]
					G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	G_R	C_R	
WHITE, GLOSSY ENAMEL ON ALUMINUM																					
VA-1	20	a	980	81	14.7	96.5	89.7	95.9	82.1	95.2	77.6	97.5	77.4	95.9	64.3	95.1	66.1	98.3	67.4	96.3	AA
VA-2	10	a	1,000	81	67.2	95.6	103.8	95.7	76.9	96.7	78.9	98.5	77.8	96.5	59.0	96.2	53.8	97.6	73.9	96.7	AA
Average					41.0	96.0	96.8	95.8	79.5	96.0	78.2	98.0	77.6	96.2	61.6	95.6	60.0	98.0			
GREEN, GLOSSY 1,000° F ENAMEL ON STEEL																					
Y-1	21	e	1,020	70	73.6	93.9	85.0	95.9	82.9	96.9	82.1	88.2	77.5	90.8	71.4	90.1	68.3	89.9	77.2	92.2	AA
RED, GLOSSY 1,000° F ENAMEL ON STEEL																					
Z-1	21	e	1,000	47	36.7	55.4	68.3	63.4	89.7	91.2	92.2	92.0	79.6	90.5	77.3	91.1	74.9	85.3	74.1	81.3	B

[a] 45° gloss measured in accordance with ASTM Designation: C346–55T (ref. 5).
[b] Computed from averages of three specimens at each site.
[c] Dirt films were present on some specimens after cleaning treatment.
[d] Ratings were made in accordance with Test for Acid Resistance of Enamels, Part I. Flatware (ref. [9]) except that grading of class A and class B enamels was modified to conform with Specification for Architectural Porcelain Enamel on Steel for Exterior use (ref. [10]).

of the 3-yr color retention, C_R, which was arbitrarily defined as:

$$C_R = 100 - \Delta E.$$

The color difference, ΔE, was computed from the measured values by use of a high-speed digital computer [8]. The computer program was arranged to give averages and standard deviations as well as individual values for C_R.

The average 3-yr color retention for each enamel at each site is listed in table 3.

6. Comparison of Exposure Sites

Table 4 gives the average values for percentage gloss retained and color retention at each exposure site. The averages are for all porcelain enamels tested.

The data listed in table 4 were treated statistically to determine the significance of the differences (95 percent confidence level) between sites.

Table 4. *Average gloss and color retentions for all enamels tested*

Exposure site	Site severity	G_R [a]	C_R [b]
Dallas	Mild	80.2	96.3
Los Angeles	do	80.6	94.6
New Orleans	do	79.9	94.0
Pittsburgh	Moderate	70.1	92.8
Kure Beach, 800 ft	do	70.1	92.6
Washington	do	68.4	93.1
Kure Beach, 80 ft	Severe	59.1	91.7

[a] Percentage of initial gloss retained.
[b] Color retention, $C_R = 100 - \Delta E$ where ΔE is color change in NBS units.

This analysis showed that the sites could be placed into three groups: (1) mild—Dallas, Los Angeles, and New Orleans; (2) moderate—Pittsburgh, Kure Beach–800 ft, and Washington; (3) severe—Kure Beach–80 ft. The differences between groups are highly significant.

The effect of exposure site on the different enamel types is given in tables 5 and 6. In these two tables the enamels of each type have been further subdivided according to their citric acid spot-test ratings. These ratings were assigned on the basis of the Porcelain Enamel Institute Test for the Acid Resistance of Porcelain Enamels [9], except that the rating of class A and class B enamels was modified to conform to a recent specification for architectural porcelain enamels on steel [10].

A close inspection of tables 5 and 6 shows that for almost every enamel type, the exposure conditions are less severe at Dallas, Los Angeles, and New Orleans than at the other four sites. These differences in severity are especially noticeable in the case of the regular glossy steel enamels. For these regular glossy steels, some of the nonacid-resistant types had equally as high percentage gloss retained and color retention at the mild sites as the acid resistant types did at the other sites. A statistical analysis showed, for example, that there was no significant difference (95 percent confidence level) in either percentage gloss retained or color retention between the average for class C enamels exposed at Dallas, Los Angeles, and New Orleans and the average for class AA enamels exposed at Kure Beach–800 ft, Washington, and Pittsburgh.

Table 5. *Effect of mild, moderate, and severe sites on the percentage gloss retained of glossy enamels with different acid spot-test ratings*

Enamel type	Exposure sites averaged	Exposure represented	Average percentage gloss retained (G_R) for enamels with acid spot-test rating of— [a]				
			AA	A	B	C	D
Reg. steel (fired 1,430–1,580 °F).	N.O., Dallas, L.A	Mild	88.2	85.7	87.7	81.0	76.1
	KB-800, Wash., Pitts.	Moderate	79.0	76.3	77.2	65.3	54.2
	KB-80	Severe	83.4	71.7	71.3	55.2	44.0
1,300 °F steel	N.O., Dallas, L.A	Mild	90.8	----	89.9	----	----
	KB-800, Wash., Pitts.	Moderate	87.8	----	83.0	----	----
	KB-80	Severe	85.2	----	71.6	----	----
1,000 °F steel	N.O., Dallas, L.A	Mild	80.8	----	86.4	----	----
	KB-800, Wash., Pitts.	Moderate	74.6	----	73.5	----	----
	KB-80	Severe	73.6	----	36.7	----	----
Screening-paste steel.	N.O., Dallas, L.A	Mild	78.1	81.6	81.0	76.4	----
	KB-800, Wash., Pitts.	Moderate	71.1	71.5	70.7	59.0	----
	KB-80	Severe	52.5	63.4	48.8	25.8	----
Aluminum	N.O., Dallas, L.A	Mild	75.5	77.5	79.7	----	----
	KB-800, Wash., Pitts.	Moderate	62.1	57.5	65.5	----	----
	KB-80	Severe	38.4	21.9	25.8	----	----

[a] Citric acid spot-test ratings were made in accordance with Test for Acid Resistance of Enamels, part 1, Flatware (Ref. g) except that the grading of class A and class B enamels was modified to conform with Specification for Architectural Porcelain Enamel on Steel for Exterior Use (Ref. 10).

Table 6. *Effect of mild, moderate, and severe sites on the color retention of colored enamels with different acid spot-test ratings*

Enamel type	Exposure sites averaged	Exposure represented	Average color retention (C^R) for enamels with acid spot-test rating of—[a]				
			AA	A	B	C	D
Reg.steel(glossy) (fired 1,430–1,580 °F.)	N.O., Dallas, L.A.	Mild	98.9	98.6	----	98.0	96.9
	KB-800, Wash., Pitts.	Moderate	98.1	97.6	----	96.8	93.7
	KB-80	Severe	97.6	98.1	----	96.2	95.2
Reg. steel (mat) (fired 1,430–1,540 °F.)	N.O., Dallas, L.A.	Mild	----	99.5	96.3	97.7	98.7
	KB-800, Wash., Pitts.	Moderate	----	99.1	95.9	96.4	93.8
	KB-80	Severe	----	98.8	95.8	96.4	96.3
1,300 °F steel (glossy).	N.O., Dallas. L.A.	Mild	99.0	----	95.7	----	----
	KB-800, Wash., Pitts.	Moderate	98.5	----	96.1	----	----
	KB-80	Severe	99.2	----	93.9	----	----
1,000 °F steel (glossy).	N.O., Dallas, L.A.	Mild	92.0	----	90.9	----	----
	KB-800, Wash., Pitts.	Moderate	92.0	----	80.0	----	----
	KB-80	Severe	93.9	---	55.4	----	----
Screening-paste steel (glossy).	N.O. Dallas, L.A.	Mild	90.4	88.3	74.9	73.9	----
	KB-800, Wash., Pitts.	Moderate	88.5	85.6	61.9	71.2	----
	KB-80	Severe	84.9	82.5	55.9	60.6	----
Aluminum (glossy).	N.O., Dallas, L.A.	Mild	97.0	97.6	95.5	----	----
	KB-800, Wash., Pitts.	Moderate	96.0	94.1	90.8	----	----
	KB-80	Severe	97.4	88.6	81.7	----	----
Aluminum (mat)	N.O., Dallas, L.A.	Mild	98.0	97.6	----	----	----
	KB-800, Wash., Pitts.	Moderate	98.3	96.8	---	---	----
	KB-80	Severe	97.9	95.4	----	----	----

[a] Citric acid spot test ratings were made in accordance with Test for Acid Resistance of Enamels, part 1, Flatware, (ref. [9]) except that the grading of class A and class B enamels was modified to conform with Specification for Architectural Porcelain Enamel on Steel for Exterior Use (ref. [10]).

The differences in severity of the sites cannot be explained by the differences in weather conditions (see table 2). New Orleans, for example, has the highest annual rainfall and the highest average temperature of any of the seven sites, yet the New Orleans exposure is one of the three mildest. This suggests that some other factor is affecting site severity.

Table 7 was prepared from unpublished data of the National Air Sampling Network of the U.S. Department of Health, Education, and Welfare. The methods used for collecting and analysing the samples is given in a report issued in 1958 [11]. No information was available as to the content of acid gases in the respective atmospheres. However, because these gases tend to react with other substances in the air to give acid salts, the composition of the particulate matter (columns 4 and 5 in table 7) is believed to give a good indication of the acid contents of the various atmospheres [11].

Table 7 shows that the New Orleans site has a relatively low level of air pollution. It has the lowest particulate and NO_3 contents, next to the lowest SO_4 content, and next to the highest pH. At the same time, Los Angeles, which is one of the mildest sites, has high air pollution (see table 7). However, the average annual rainfall in Los Angeles is only 12.1 in. It seems reasonable to assume that it is lack of moisture that accounts for the mild conditions at Los Angeles.

Table 7. *Averages of air pollution measurements made during 1958 by the National Air Sampling Network of the U.S. Department of Health, Education, and Welfare*

City	Total suspended particulates [a]	Composition of particulates [a]				pH [b]
		Organic matter	SO_4	NO_3	Other	
Los Angeles	214	30.4	16.1	9.5	158.0	6.0
Pittsburgh	167	13.0	15.2	2.7	136.1	6.4
Washington, D.C.	111	12.9	12.4	3.1	82.6	6.7
New Orleans	92	11.4	9.5	2.2	68.9	7.0
Dallas	113	10.2	7.1	2.3	93.4	7.1

[a] Micrograms per cubic meter of air. Values are averages of measurements taken at approximately biweekly intervals.
[b] Measured for solutions prepared by refluxing an 8 percent aliquot of particulates with 50 ml of distilled water and diluting to 80 ml. Values are averages of measurements made at approximately biweekly intervals.

Figure 3 shows two curves in which the pH of the atmospheric particulates has been plotted against the average 3-yr color retention for those sites which have rainfalls of 34 in. or greater and for which pH data were available (Pittsburgh, Washington, New Orleans, and Dallas).[4] The lower curve is for all enamels included in the test while the upper curve is for the class A and class AA regular glossy steel enamels. Both curves suggest that acidic substances in the atmosphere are affecting the site severity of these particular urban sites. The curve for the regular glossy steel architectural enamels (class A and class AA—see reference [10]) is of special interest in that [it

[4] The same general type of curves are obtained if the combined NO_3 and SO_4 contents in table 7 are plotted against color retention.

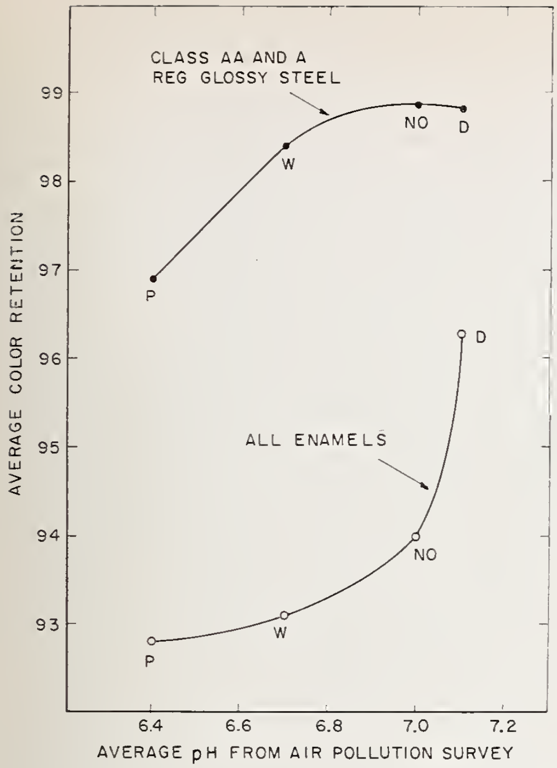

FIGURE 3. *Change in 3-yr color retention of enamels with pH for the urban exposure sites with annual rainfalls of 34 in. or greater.*

Measurements of *p*H were made during 1958 by the National Air Sampling Network. Letters adjacent to points indicate exposure city; P—Pittsburgh, W—Washington, NO—New Orleans, and D—Dallas.

shows that appreciable color change for enamels of this type occurs only when the *p*H of atmospheric particulates falls below 7.0. The lower curve (all enamel types) reflects the presence of enamels of class B, C, and D acid resistance in the averages. Some enamels with these ratings showed appreciable changes in gloss and color even at the mild sites. Also, the magnitude of the changes for enamels of poor resistance appeared to be less dependent on the *p*H of the air contaminants than on the average annual rainfall. This is evident by a comparison of the data in table 3 for Dallas and New Orleans with the acidities of air contaminants in table 7 and rainfalls in table 2.

Although the *p*H of sea water is approximately 8, the Kure Beach–80 ft site is, on the average, the most severe of the seven (see table 4). The nearest population center is some 20 miles distant from Kure Beach and almost no air pollution from fuel combustion would be expected. Salts from the ocean are present in abundance, however, and it is probably these salts combined with the almost continuous presence of moisture that creates the severe environment. The conditions 800 ft from the beach are less severe than those at 80 ft.

Tables 5 and 6 show that the sea spray conditions at the Kure Beach–80 ft site are especially severe on the aluminum enamels, the screening-paste steel enamels, and the class B 1,000 °F steel enamels and it is mostly because of this severity that the averages given in table 4 for the Kure Beach–80 ft specimens are so low. Aluminum enamels and the 1,000 °F steel enamels contain high proportions of lead oxide and the screening-paste steel enamels may contain some lead. It is possible that the chloride in the sea spray reacts with the lead in the enamel surface to form soluble lead chloride. Thus, it would seem from the 3-yr results that a porcelain enamel high in lead oxide should not be used in a sea-spray environment unless exposure data should first indicate its suitability. That some high-lead enamels do have fairly good resistance at the Kure Beach–80 ft site is evident from the mat enamels X–1 and X–2 in table 3.

7. Comparison of Enamel Types

Table 8 gives the average color retention and percentage gloss retained at all sites for each enamel type. The type with the best color stability is listed at the top; the type with the poorest, at the bottom. The percentage gloss retained for the mat enamels is not included inasmuch as this measurement has little meaning because of the low initial gloss values of the mat finishes.

TABLE 8. *Average color retention (C_R) and percentage gloss retained (G_R) for the eight types of enamels*

Enamel type [a]	Averages for all sites			
	Avg. for all enamels		Best enamel of type	
	C_R	G_R	C_R	G_R
A. Reg. glossy steel—AR	98.2	81.2	99.0	88.8
B. Mat aluminum—AR	97.5	--------	98.8	--------
C. 1,300 °F steel—AR	96.4	85.3	98.8	88.4
D. Mat steel—AR	96.4	--------	99.2	--------
E. Reg. glossy steel—Non-AR	96.5	67.8	98.7	76.3
F. Glossy aluminum—AR	95.1	63.8	97.4	65.9
G. 1,000 °F steel—AR	86.8	75.6	93.7	77.2
H. Red and yellow screening steel—AR	81.8	74.0	92.9	81.9

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

The averages given in the first two columns in table 8 are for all enamels of each type that were included in the test.[5] The last two columns list the C_R and G_R values for the particular enamel with the best weather resistance of each type tested. Even on this "best-of-class" basis, the regular glossy acid-resistant steel enamels appear to have the best resistance of the eight types while the glossy aluminum, 1,000 °F steel, and screening-steel enamels have the poorest. An analysis of the enamels opacified with titanium dioxide shows that this type is equally as resistant as the other types of regular steel enamels.

[5] Application of Fisher's "*t*" test to the data given in the first two columns of table 8 showed that there is a significant difference (95 percent confidence level) between all listed averages with the exception of C–D, C–E, and D–E for gloss and H–G for color.

While the mat steel enamels, as a group, are not especially resistant to color change (first column, table 8), the compositions with class AA spot-test ratings show quite high color retentions. Enamels PA–3 and PA–4, in particular, have color retentions after 3 yr that are comparable to the best of the glossy enamels (table 3). All of the mat enamels included in the earlier test [2] were exceptionally poor with respect to color stability. It follows that some of the mat enamels that have been produced since World War II are much more stable.

The mat aluminum enamels, as a group, show the second best color retention of all of the enamel types (table 8), and some of the glossy aluminum enamels showed good stability at some sites. A recent paper by Sopp, Wallace, and Picker [12] gives the color change of three glossy green aluminum enamels after about 3 yr on a roof at New Kensington, Pa. The measured color change for a class A enamel was 4.0 NBS units. This value is in fair agreement with the color change reported in table 3 for three class A green glossy aluminum enamels exposed at Pittsburgh, where similar exposure conditions might be expected (average ΔE—2.2 NBS units). The average change for the same three enamels exposed at Kure Beach, 80 ft, however, was 10.5 NBS units while at KB–800 ft it was 8.5 units.

8. Effect of Exposure Angle

A comparison of the color retention and percentage gloss retained of the 45 enamels that were exposed (a) vertically facing south and (b) at a 45° angle facing south at the Washington site suggested that the difference in the degree of attack was related to the weather resistance of the enamel. As a check on this possible relationship, the enamels were placed into five groups based on an arbitrary weather resistance rating of the enamels when exposed at 45°. The following summarizes the rating system:

Weather resistance rating	Limits of percentage gloss retained, G_R	Limits of color retention, C_R
1	80 to 100	97.5 to 100
2	65 to 80	95.0 to 97.5
3	50 to 65	92.5 to 95.0
4	35 to 50	90.0 to 92.5
5	0 to 35	0 to 90.0

For an enamel to receive a No. 1 rating it would need to have both an average G_R between 80 and 100 and an average C_R between 97.5 and 100; however, if the values for either G_R or C_R fell outside these limits, the enamel would be given the lowest applicable rating. Thus, an enamel with a G_R of 89.0 and a C_R of 91.3 would be given a No. 4 rating.

Table 9. *Comparison of percentage gloss retained, C_R, and color retention, C_R, for representative glossy enamels exposed on vertical and 45° racks at Washington, D.C. site*

Weather resistance rating on 45° Rack [a]	No. of enamels averaged	Average G_R		Average C_R [b]	
		Vertical	45°	Vertical	45°
1	6	82.9	85.7	99.2	98.9
2	15	74.4	78.0	98.0	97.6
3	12	66.5	60.5	97.2	96.0
4	4	54.3	42.1	95.1	93.5
5	8	63.2	59.3	88.4	79.7

[a] See text for method used for assigning ratings.
[b] White enamels not included in averages.

The results (table 9) show that the enamels with No. 1 and No. 2 ratings lose slightly more gloss (lower G_R values) when exposed vertically than when exposed at 45°. Those with No. 3, 4, and 5 ratings, however, lose more gloss when exposed at 45°. The loss in color (lower C_R) was always greater when the enamels were exposed at 45° than when they were exposed vertically. Another observation of interest is that as the weather resistance rating decreases, and the difference in color retention values between the 45° and vertical exposure tends to increase. This is brought out by figure 4.

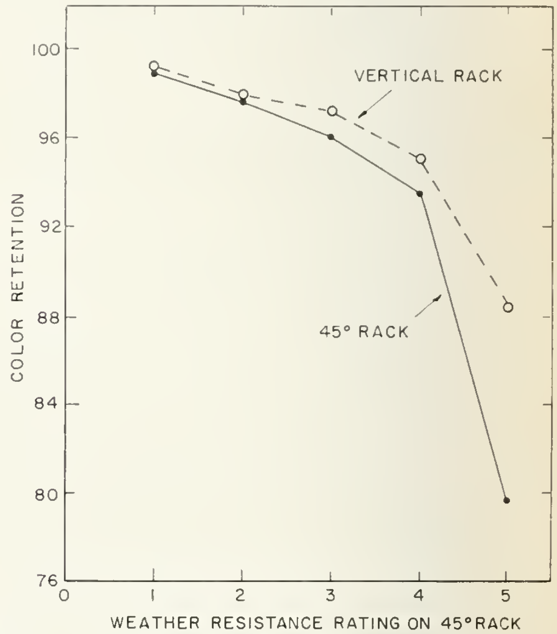

Figure 4. *Effect of exposure angle on the color retentions of enamels exposed at Washington, D.C.*
Method used for assigning weather resistance ratings is given in text.

The only conclusion on exposure angle that seems safe to draw at 3 yr is that exposing the specimens at 45° rather than vertically accelerates the weathering action of those enamels with poor weather resistance. The increased attack, while significant, is not so large that an enamel that was considered to have poor weather resistance (No. 4 and 5 ratings in table 9) when exposed at 45° would not also be considered to have rather poor resistance when exposed vertically.

9. Correlation of Weather Resistance with Citric Acid Spot Test

A number of earlier investigations of weather resistance of porcelain enamels have shown that a direct relationship exists between acid resistance and weather resistance [2, 12, 13, 14]. As can be seen from tables 5 and 6, this same general type of relationship was noted in the present investigation. However, as in the 15-yr study [2], the correlation exists only when averages are considered and there are many individual exceptions to the pattern.

Figure 5, which is a plot of the individual values for the regular glossy steel enamels at Washington, is typical of the color retention results. The dashed line drawn through the average for each acid resistance class shows that a correlation exists between the citric acid spot-test rating and the weather resistance as measured by color retention. Although the points show a high scatter, it will be noted that all class AA and class A enamels have color retentions of 97.0 or above, which might be considered as reasonably good color stability after 3 yr of exposure. However, there is one class C (E–1 in table 3) and one class D enamel (E–4 in table 3) that show equally as good color retention as any of the class AA or class A enamels. The percentage gloss retained for these two enamels at Washington is also high (71.7 and 74.2, respectively). Thus, on the basis of short-time tests only, these two enamels might be considered as suitable for architectural use even though they fail the citric acid spot-test requirement of the architectural specification [10].

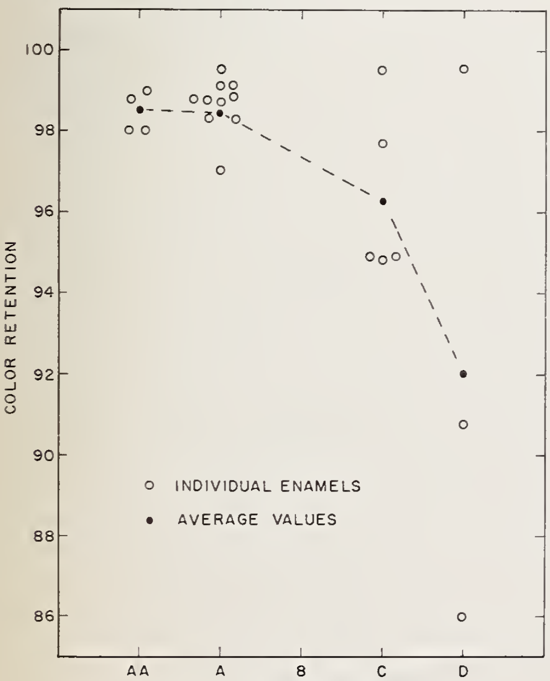

FIGURE 5. *Color retentions at Washington, D.C. for enamels with different citric acid spot test ratings.*

A shortcoming of the citric acid spot test is that it fails to predict the relatively poor color stability of the 1,000 °F steel, the screening-paste steel, and some of the glossy aluminum enamels (see table 6). Obviously a test that gives a better prediction of weather resistance than does the citric acid spot test is needed and one of the long-range goals of the study is to develop such a test.

10. Copper Sulfate Test for Predicting Color Stability of Red and Yellow Enamels

Many of the red and yellow enamels with high citric acid spot-test ratings lacked good color stability (table 3). The red and yellow screening-paste enamels, for example, had the lowest color retentions of any of the enamels tested. During laboratory examination of these particular enamels, it was discovered that the least stable compositions would change in color when spot tested with a saturated solution of cupric sulfate for one hr at room temperature. Because of the potential value of such a treatment for predicting color stability of red, yellow, and orange enamels, subsequent work was carried forward in which a number of possible variables in the testing were investigated. This work led eventually to the following test procedure:

A saturated solution, prepared by adding 50 g of cupric sulfate ($CuSO_4 \cdot 5H_2O$) to 100 ml of water, was allowed to stand for 16 hr at room temperature. A few drops were withdrawn from the upper part of this solution and placed on the cleaned enamel surface to form a small pool which was covered immediately with a 1-in.-diam watch glass. The specimen with the watch glass in position was then placed under a plywood box painted white on the inside. The inside dimensions of the box were 20x6x12 in. A 15 w "white" fluorescent lamp, 1 in. diam x 18 in. long, was centered 3 in. from the top of the box so that its center line was 9 in. from the specimen. With this arrangement, the light intensity at the specimen surface was 300 foot candles. [6]

After 20 hr at room temperature, the specimen was removed, the copper sulfate solution rinsed away with water, and the treated area examined for evidence of a visual change in chromaticity. If a change could be detected by visual examination, the enamel failed the test; otherwise it passed.

Table 10 compares the results obtained with this test for all class A and class AA red and yellow porcelain enamels included in the test with their average 3-yr color retention values. All enamels of this type that pass the cupric sulfate test have color retentions of 98.2 or above; all enamels that fail have color retentions of 92.9 or below. Thus, the test appears to be effective in separating those class AA and class A red and yellow enamels of good color stability on weathering from those of

[6] Experiments showed that the reaction between the cupric sulfate solution and the enamel surface was partly photochemical in nature and that a controlled light source was essential to obtain a suitable separation of enamels.

Table 10. *Cupric sulfate test ratings and average 3-yr color retentions of red and yellow enamels with class A and class AA citric spot test ratings*

Enamel designation	Enamel type	Enamel color	$CuSO_4$ test rating	Average color retention
L–2	Reg. glossy steel	Yellow	Pass	98.4
L–3	do	do	do	98.3
L–4	do	do	do	98.2
L–1	do	do	do	98.2
D–4	do	Red	do	98.3
G–1	Screening-paste steel	Yellow	Fail	92.8
G–2	do	do	do	88.8
G–3	do	do	do	92.9
G–4	do	do	do	92.5
GA–1	do	do	do	80.4
GA–2	do	do	do	81.9
GA–3	do	do	do	83.4
GS–4	do	do	do	82.8
F–2	do	Red	do	84.2

poor stability.[7] Although the test also separates red and yellow enamels with citric acid spot-test ratings of class B and lower, such enamels would have already been eliminated for architectural use (10) because of their lack of acid resistance.

11. Discussion

An analysis of the 3-yr data suggests that the factors responsible for changes in surface appearance of enamels with weathering are:

(1) Moisture.

(2) Atomospheric pollution by acidic substances.

(3) Sea spray and sea air at ocean sites.

Although sea air can cause rapid weathering of some enamel types, neither moisture nor atmospheric pollution by acidic gases, of itself, appears to cause a rapid change in enamels. However, moisture in combination with air pollution apparently can produce a fairly fast weathering action of some types of porcelain enamel.

The relatively large effect of exposure location on the measured changes in gloss and color was not observed in the 15-yr investigation [2]. In this earlier study, however, there were no sites comparable to New Orleans, Dallas, and Los Angeles. The comparatively mild conditions that exist at these sites suggest that either (a) a less resistant enamel can be used to achieve equally as good color and gloss retention as at the more severe sites, or (b) the same enamel will show less change in surface appearance in any given time period. However, because there is usually a lack of exact knowledge as to severity of conditions at a proposed building site, and also because the producer does not always know where his product will be used, the safest approach might be to consider as architectural enamels only those compositions that give the best resistance to all types of weather conditions.

Most installations of porcelain-enameled metal are intended to maintain good appearance for 20 yr or longer. It cannot be stated with certainty that those enamels that show good resistance to weathering at 3 yr will also be good at 20. However, from the results of the 15-yr study [2], it seems probable that there will be very few deviations from the observed pattern with continued testing.

The most recent specification for architectural enamels on steel [10] requires that the enamel pass a citric acid spot test that is described in the specification. Any enamel that passes this test will have a citric spot-test rating of either class A or class AA by the system of grading used in the present investigation. Practically all of the steel enamels with these ratings, and which also pass the cupric sulphate test for red, yellow, and orange enamels, as required by the specification, had good weather resistance at the 3-yr inspection. The only exception was enamel Y–1, which is a green class AA enamel fired at very low temperature (1,020 °F). This enamel, which showed a color change of more than 10.0 NBS units at some sites in only 3 yr, does not have sufficiently good color stability to be considered for architectural use. Obviously, a new test is needed that will predict the poor color stability of enamels of this type. In addition, the new test should be capable of predicting the rather large color changes that occurred with the class A and class AA glossy aluminum enamels at some of the more severe exposure sites.

12. Summary

An examination of 2,160 porcelain enameled specimens of 28 types was made after exposure for 3 years at Dallas, Tex.; Los Angeles, Calif.; New Orleans, La.; Pittsburgh, Pa.; Washington, D.C.; and two sites at Kure Beach, N.C. A summary of the findings follows:

(1) Enamels exposed at all test sites except Pittsburgh could be cleaned reasonably well by washing with a detergent.

(2) With one exception all enamels protected the metal base from corrosion. The exception pertained to specimens to which an unusual type of low-fired steel enamel had been applied. At the Kure Beach sites, these specimens showed rust stains on the face surface. These stained areas were adjacent to pinholes in the enamel coating.

(3) For enamels of one type, a direct relationship was observed between the citric acid spot-test rating and the weather resistance as measured by changes in gloss and color. This relationship, however, existed only when averages were considered. Also, relatively large variations in weather resistance were observed between different types of enamel with the same spot-test rating.

(4) The exposure conditions were found to be least severe, on the average, at Dallas, Los Angeles, and New Orleans; of intermediate severity at Pittsburgh, Kure Beach–800 ft, and Washington;

[7] Although table 10 implies that all screening-paste steel enamels will fail the copper sulfate test and all regular steel enamels will pass extensive testing of production enamels has shown that there are some yellow and orange regular steel enamels of good acid resistance that will consistently fail the test; also, one architectural enamel producer has demonstrated that it is possible to prepare red and yellow screening-paste enamels that will consistently pass the test.

and most severe at Kure Beach–80 ft. The low average resistance at Kure Beach–80 ft was caused, for the most part, by the low resistance of certain types of enamels to the sea spray environment.

(5) Comparison of gloss and color changes with data from the National Air Sampling Network indicated that air pollution by acidic contaminants is an impgrtant factor at those urban sites that have annual rainfalls of 34 in. or greater.

(6) On the average, the regular glossy steel porcelain enamels showed the best weather resistance of any of the types tested.

(7) Class AA steel porcelain enamels fired at 1,300 °F showed a comparable weather resistance to the Class AA steel enamels fired in the range 1,450–1,550 °F. Class AA steel enamels fired at 1,000 °F, however, showed relatively poor resistance at all sites.

(8) The class A mat steel porcelain enamels included in the test displayed a color stability that was comparable to the class A glossy steel enamels.

(9) The glossy aluminum porcelain enamels, as a group, were not as resistant as the regular glossy steel or the 1,300 °F steel enamels but they were somewhat more resistant than the 1,000 °F steel enamels. The class AA mat aluminum enamels, on the other hand, had a color stability that was comparable to the class AA regular glossy steel enamels.

(10) All red and yellow screening-paste porcelain enamels in the test showed relatively low color retentions at all sites. It was found, however, that this poor color stability could be predicted by a specially developed cupric sulfate spot test.

(11) Specimens with enamels of poor weather resistance that were exposed vertically at Washington, D.C., showed significantly smaller changes in gloss and color than similar specimens that were exposed at 45°. Enamels with good weather resistance, on the other hand, showed only minor differences in the degree of attack with exposure angle.

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WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-Ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics. Electrolysis and Metal Deposition.

Mineral Products. Engineering Ceramics. Glass. Refractories. Crystal Growth. Physical Properties. Constitution and Microstructure.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Solid State Physics. Electron Physics. Atomic Physics.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Molecular Kinetics. Mass Spectrometry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

Radio Physics.

Circuit Standards.