TESTING OF FIRE-CLAY BRICK WITH SPECIAL REFERENCE TO THEIR USE IN COAL-FIRED BOILER SETTINGS.

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ABSTRACT

Following a conference of Government representatives, users, and producers of fire-clay refractories, held at the Bureau of Standards, a voluminous field survey report was obtained through the cooperation of Stone & Webster, and refractories of 42 brands representative of the product as manufactured in the United States were submitted to an extended investigation in the laboratory.

The investigation was confined to a study of brick used in the settings of coal-fired boilers and to that class of installation in which the so-called first quality fire brick can be economically used. In the laboratory refractories were subjected to an endurance test, a reheating test, quenching tests, load tests, softening points were determined, and the brick analyzed chemically and petrographically. As a result of the field survey data were obtained covering the boiler rating and load factor, the actual life and mode of failure of the refractory in the several locations of the setting, the kind and quality of fuel used, the fusion point of the ash, and the type of stoker.

As a result of this work the qualifications of high-grade refractories for coal-fired boiler settings are believed to have been established. It was found that a close relation existed between data obtained in the endurance, reheating, quenching, and softening point tests, and that the behavior of brick in these tests depended to a remarkable extent on the chemical composition. The results indicate that a refractory which will successfully withstand 15 quenchings from 850° C. to running water has a softening point equivalent to at least that of cone 32; that the linear change in the endurance test will not exceed 2 per cent, and when transversely loaded the deflection will not exceed 10/32 of an inch; that the per cent absorption after the reheating test will lie between 6 and 10 per cent; and also that the refractory should be composed of raw materials containing not more than 4 per cent flux and 20 per cent uncombined quartz. The results favor the dry-press process for manufacturing brick.

It was found that refractories which appeared of highest quality in the laboratory did not always give the highest service, but this was to be expected since no two brands of refractories were subjected to similar service conditions. The field survey showed, however, that in practically every instance brick fail primarily through erosion, indicating lack of refractoriness and resistance to the fluxing action of molten coal ash. The one exception is the suspended arch in which the refractories fail mainly by spalling. In addition, the data from the survey indicate that where the life is relatively long the brick fail by erosion, while with a short life the failure is due to combined erosion and spalling.

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Part I.—RESULTS OF LABORATORY WORK

I. INTRODUCTION

It is becoming increasingly evident to consumers and producers of refractories that specialization, which is the outstanding feature of our age, must also be applied to this type of product. One grade of this material can no longer be expected to meet the requirements of every type of installation and, with the rapid advance which is being made in the economical combustion of fuel and the general speeding up of manufacturing processes, the demands of the industry are becoming more and more urgent for the very best refractories which can be made with the materials provided by nature.

The ceramic literature is replete with papers and discussions on the subject of fire-clay refractories, but a search of the same will show that those papers which are devoted to a presentation of results of investigative work cover grades of material which have long been known as number one, number two, and number three refractories. The principal purpose of this past work has been to determine physical and chemical properties characterizing these various grades and usually without considering a particular industrial application.

II. SCOPE OF WORK

In the investigation reported here it was decided to limit the field to one grade of fire-clay refractory and the application of the results to one type of installation. With this idea in mind a meeting of manufacturers and users of refractories, acting as an advisory board, was called at the Bureau of Standards on March 8, 1922, to discuss the problem and outline a method of procedure. It was decided to confine the first phase of the investigation to brick used in the settings of coal-fired boilers and to that class of installation in which the so-called first quality fire brick can be economically used.¹

In order to further enhance the value of the work, it was determined to correlate the laboratory data with records of the behavior of the several brands under service conditions. Accordingly, 60 samples of brick were submitted to the Bureau of Standards from 60 power plants representing all of the important industrial districts of the country. Some of the shipments were duplicates, but the final count showed 42 different brands of standard 9-inch brick.

III. ACKNOWLEDGMENTS

The author wishes to express his appreciation, for assistance in carrying out the work, to E. B. Powell, of Stone & Webster, through whose cooperation the material for test was obtained and who also

¹ In parts of some furnaces and with some types of fuel conditions arise which no known refractory can withstand and which are met with special devices, while other types of service demand special refractories. There is, however, a large class of installations to which the so-called first quality fire brick can be adapted.

collected and correlated the data comprising the field survey, and to the following members of the bureau staff: Dr. H. Insley for petrographic examinations, H. C. Stecker for chemical analyses, and W. L. Pendergast and B. J. Woods for assistance in the laboratory.

The samples, obtained through the cooperation of Mr. Powell, were submitted by the following companies:

Companies	Brands of specimens submitted
Halls & Sons-----	Hall & Sons Extra and XX.
United Light & Power Co-----	Woodland.
Savannah Electric Co-----	H. W. R. Co. 10-21.
Boston Woven Hose & Rubber Co-----	Mount Savage.
Torresdale Pumping Station-----	R. C. Remmey Sons Co. No. 1.
Pennsylvania-Ohio Power & Light Co.	Niles No. 10.
Beech Bottom Power Co-----	Osceola.
Narragansett Electric Light Co---	Valentine and Waco.
Nebraska Power Co-----	Hybrand Flint.
Pennsylvania Power and Light Co-----	B-264 and McHose & Co.
New York Steamboat Corp-----	A. P. Green Empire H. M.
Commonwealth Edison Co-----	Evens and Howard, Acme, H. W. Furnace, Electric Furnace, Osceola, Walsh XX, Steel King, and Superior.
Buffalo General Electric Co-----	Hall & Sons XX.
Adirondack Power & Light Co----	Hayes Run.
Public Service Electric Co-----	Walsh, Henry Maurer No. 1 A, New York, and M. D. Valentine XX.
Edison Electric Illuminating Co---	P. S. W. Oil and P. S. W. Co. Oil.
New York Steamboat Corp-----	Walsh XX and Henry Maurer No. 1, New York.
Texas Power & Light Co-----	Empire D. P.
The Transit Supply Co-----	Laclede King.
Consolidated Gas, Electric Light & Power Co.	Mount Savage and Q. R. Glass.
Tampa Electric Co-----	Tiger Steel.
The Lowell Electric Light Corp---	Henry Maurer No. 1, New York.
Milwaukee Electric Railway & Light Co.	Walsh XX.
Idaho Fire Brick Co-----	Troy Idaho Dense and Troy Idaho White.
Union Electric Co-----	Walsh XX.
Blackstone Valley Gas & Electric Co.	Woodland.
Monarch Fire Clay Co-----	Monarch.
Philadelphia Electric Co-----	Q. R. Glass and R. C. Remmey Sons Co. R. M.
Brooklyn Rapid Transit Co-----	Penn-Acme.
Interborough Rapid Transit Co---	Hayes Run.
United Gas & Electric Co-----	L. F. B. Works No. 1.
Edison Electric Illuminating Co---	Woodland.
El Paso Electric Railway Co-----	Do.
Nebraska Power Co-----	Walsh XX.
N. B. Gas & Edison Light Co----	Woodland.
Pennsylvania Power & Light Co---	Henry Maurer No. 1 A., New York.
Texas Power & Light Co-----	Hybrand Flint.

Companies	Brands of specimens submitted
Commercial Edison Co-----	Empire D. P.
Denver Gas & Electric Light Co--	Golden.
Narragansett Electric Lighting Co.	Q. R. Glass. and P. S. W. Co. Oil.
Meridan Light & Railway Co-----	Standard S. M. and Empire D. P.
Puget Sound Power & Light Co---	Renton.

IV. METHODS OF TESTING

The following tests were decided on at the conference composed of the advisory board and bureau representatives: (1) Endurance test, (2) reheating test, (3) quenching test, (4) softening-point test, and (5) load test.

1. ENDURANCE TEST

The endurance test is made in two ways: (a) The brick is placed on end in a gas-fired furnace and subjected to a temperature of $1,450^{\circ}$ C. for 72 hours. Two bricks of each brand are used in this test.

(b) The brick is laid flat, supported at the ends, leaving 7 inches clear span, loaded at the center with a brick cut to weigh 5 pounds, and subjected to a temperature of $1,450^{\circ}$ C. for 72 hours. Two bricks of each brand are used in this test.

In the endurance test the following heat schedule was followed. The kiln (fig. 1a) was started in the afternoon and allowed to reach from 900 to $1,000^{\circ}$ C. overnight. The temperature was then carried up to $1,350^{\circ}$ C. at a uniform rate of 50° an hour, and from $1,350$ to $1,450^{\circ}$ C. at the rate of approximately 10° an hour. As measured by pyrometric cones, this heat treatment was equivalent to the softening point of cone 19.

2. REHEATING TEST

The reheating test consists in subjecting a brick to a temperature of $1,400^{\circ}$ C. for five hours. Seven bricks of each brand are used in this test.

The kiln (fig. 1) was allowed to reach approximately 800° C. overnight, and was then carried up to $1,400^{\circ}$ at a uniform rate of approximately 60° per hour. In this way the test was completed at about midnight following the day on which the kiln was set. As measured by pyrometric cones, this heat treatment was equivalent to the softening point of cone number 15.

3. QUENCHING TEST

The quenching test is conducted on brick which have been reheated at $1,400^{\circ}$ C. for five hours. The advantages of this preheating have been discussed by Howe,² and it is recognized that it

² R. M. Howe and R. F. Ferguson, J. Amer. Cer. Soc., 3, 1921.

produces decidedly better comparative results. The quenching itself followed in principle the tentative A. S. T. M. method, which consists in heating the bricks at one end in a kiln door and plunging them half way into running water. The bricks are allowed to remain in the water for three minutes, taken out, allowed to steam in the air for five minutes and then returned to the kiln door. The process is repeated in hourly cycles until the entire end of the brick has spalled off or can be removed easily with the fingers, which is interpreted as failure. Three kiln temperatures are used, viz, 850, 1,100, and 1,350°, and five bricks of each brand are quenched from each temperature.

A counterweighted door (fig. 1a) was used for the purpose of closing the panel while the test bricks were being quenched. In this way the heat was retained in the kiln, so that not more than 10 minutes were required to reach the required temperature after the specimens were replaced in the kiln door.

4. SOFTENING-POINT TEST

The softening-point test is carried out according to the method approved by the bureau, and known as the A. S. T. M. standard method, serial designation C 24-20.

5. LOAD TEST

The load test is carried out according to the method developed by the bureau and accepted by the A. S. T. M. as their standard method for heavy-duty brick (serial designation C 16-20). This test was also given the following variations: (a) The brick were held under load at 1,350° C. for 10 hours instead of one and one-half hours. (b) Brick preheated at 1,400° C. for five hours were held under load at 1,350° C. for one and one-half hours. (c) Brick preheated at 1,400° C. for five hours were held under load at 1,450° C. for one and one-half hours.

6. SUPPLEMENTARY TESTS

In addition to the above tests, a series of absorption determinations were made, a representative number of brands were examined petrographically, specimens of four brands were submitted to an erosion test, and a sample of each brand was analyzed for iron oxide (Fe_2O_3), alumina (Al_2O_3) and silica (SiO_2).

(a) For the absorption determinations 15 brick of each brand were used. Five of these were tested as received, 5 had been subjected to the reheating test, and the remaining 5 had been subjected to the endurance test. The absorption was determined on irregular fragments weighing not less than 100 g and calculated from the formula

$$A = \frac{W-D}{D} \times 100$$

in which

A = per cent absorption.

W = weight of specimen after having been boiled in water for two hours and allowed to cool with the water.

D = weight of specimen after having been dried to constant weight at 110° C.

(b) The petrographic examinations were made to determine the approximate amounts of free quartz, mullite, cristobalite, and glass present in the brick and to determine the successive effects of (1) the commercial burn, (2) burning at 1,400° C. for five hours, and (3) burning at 1,450° C. for 72 hours.

V. APPARATUS USED

1. FOR HEATING

The kiln used in making the endurance, reheating, and quenching tests is shown in Figure 1a. It is of the gas-fired, recuperative, semi-muffle type. The walls are constructed of 9 inches of refractory brick, 2½ inches of insulating brick, and 4 inches of face brick. The fuel used is carburated manufactured water gas, the same as that supplied to the city for domestic use, and usually under a pressure varying from 3½ to 4½ inches of water. It is of the following average composition, given in per cent: CO₂, 4.8; O₂, 0.7; CO, 25.4; H₂, 33.5; CH₄, 15.4; illuminants, 12.3; N (by difference), 7.9; and has an average heating value of 600 B. t. u. per cubic foot. The products of combustion pass downward from the hearth of the kiln to a flue leading to the stack, and in doing so heat the incoming air which is admitted at the front of the kiln and at the bottom of the recuperative chamber (not shown in the figure), rising from there through baffled chambers on either side of the exhaust flue and then to the burner port.

The furnace used for softening-point determinations is of the carbon resistance type, details of which are shown in Figure 1b.

The kiln used in making the load test determinations is that prescribed by the American Society for Testing Materials, detailed drawings of which can be found in the Standards of the Society published in 1924, opposite page 738.

2. FOR MEASURING TEMPERATURE

For all temperatures not exceeding 1,350° C. platinum-platinum rhodium thermocouples were used in connection with a recording potentiometer, and in all cases the hot junction was placed as near as possible to the center of the area occupied by the specimens. For temperatures above 1,350° C. an optical pyrometer was used. To insure good black body conditions³ the pyrometer was sighted into

³ B. S. Tech. Paper, No. 170, Pyrometric Practice.

was encountered in the widths. It was found that about 25 per cent of the brick measured ran $4\frac{1}{4}$ inches or less in width. This would be equivalent to a variation of almost 6 per cent. The complete data are shown in Table 1.

TABLE 1.—Average dimension of 15 brands showing variation from standard $9\frac{1}{2}$ by $4\frac{1}{2}$ by $2\frac{1}{2}$ inch size

Test number of brand	Mean length of 10 specimens	Maximum percentage deviation from mean length	Maximum percentage deviation from 9 inches	Mean width of 10 specimens	Maximum percentage deviation from mean width	Maximum percentage deviation from 4.5 inches	Mean thickness of 10 specimens	Maximum percentage deviation from mean thickness	Maximum percentage deviation from 2.5 inches
3-----	8.96	0.45	0.89	4.24	4.50	7.11	2.57	1.94	4.80
10-----	8.90	1.12	2.22	4.45	1.12	2.23	2.48	3.22	4.00
11-----	8.81	1.25	3.34	4.27	2.34	7.33	2.40	1.66	5.60
13-----	8.97	.78	1.11	4.35	2.30	5.56	2.44	3.69	6.00
15-----	9.11	.55	1.78	4.39	2.74	4.45	2.50	.80	.80
18-----	9.10	1.21	2.33	4.37	1.83	3.56	2.53	3.55	4.80
19-----	8.96	.67	1.11	4.20	1.19	7.78	2.56	1.56	4.00
33-----	8.89	.67	.78	4.40	.45	2.67	2.46	3.25	4.80
35-----	8.75	.68	3.11	4.26	1.88	6.23	2.37	3.37	8.40
37-----	8.84	1.58	3.12	4.43	2.73	4.00	2.54	2.37	4.00
38-----	8.82	1.13	3.10	4.39	.91	3.34	2.44	3.28	4.00
39-----	9.00	.33	.33	4.33	1.63	4.45	2.40	.41	4.00
40-----	8.93	1.45	1.78	4.35	2.07	5.33	2.42	2.48	5.00
41-----	8.85	1.13	3.00	4.35	1.84	5.00	2.50	6.40	6.40
42-----	9.07	1.21	1.22	4.43	1.58	3.55	2.53	2.77	4.00
Average-----		.95	1.95		1.94	4.84		2.72	4.70

VII. DESIGNATION OF BRANDS

Since the behavior of refractory brick under load at high temperatures has long been recognized as a test of considerable value,⁴ it was determined to conduct this test, first, following the method previously described. As shown in Figure 2, the brands were numbered according to the results of this test, and the same system of designations used throughout the investigation. In this way the results of other tests can easily be compared with the behavior of the brick in the standard load test.⁵

VIII. RESULTS

1. ENDURANCE TEST

The first results discussed are those obtained in the endurance test, which was developed in the commercial field. The data obtained are shown in Figure 3 and in Table 2. It is obvious from the curves (fig. 3) that no relation exists between the reaction of brick to the standard-load test and the endurance tests. However, brick placed on end during the endurance test show results agreeing, in

⁴ B. S. Tech. Papers Nos. 7 and 159; Jour. of the Am. Ceramic Soc., February, 1920; Trans. Am. Ceramic Soc., 12, p. 337; 13, p. 210; Trans. English Ceramic Soc., 17, part 2.

⁵ It will be noted that brands 42 and 43 are omitted from the curves. This was done, due to the fact that they failed consistently in every type of load test.

general, with brick transversely loaded during the same heat treatment. For example, brands designated by numbers 2, 5, 6, 17, 18,

FIG. 2.—Results of load test

19, and 32 show a large deflection under transverse load and also a comparatively large shrinkage when placed on end under no load

FIG. 3.—Results of endurance test

but their own weight. On the other hand, brick showing the least deflection also show comparatively little change in length, there

being only two exceptions where this change is not well within a 2 per cent limit. These two brick were both very high initially in free quartz, and consequently retain a high viscosity to a point nearing their deformation temperature, thereby accounting for the low deflection under transverse load, while the transformation of the quartz accounts for the exceptional change in length.

The results of the endurance test compare quite favorably with the results of quenching, fusion point, and constant volume determinations (fig. 17). While they do not appear to differentiate between brick which are in practice classified as No. 1 quality, the two brands (42 and 43) which failed completely in the load test also failed in the endurance test when transversely loaded. Typical

FIG. 6.—Changes in absorption produced by the reheating and endurance tests

results are shown in Figure 4, brands 36 and 26 being considered as meeting the test requirements satisfactorily, while brands 28 and 43 are typical of so-called failures.

Figure 5 shows the appearance of five brick before and after the endurance test when placed in the kiln on end and under no load. In each group the brick to the left has been tested, while the other has received no treatment in the laboratory. Brands 6 and 29, both of fine uniform structure, shrunk slightly, and the structure has become very dense. Brand 7 has expanded, very probably due to the high free quartz content which was estimated petrographically at approximately 75 per cent. The structure, originally of uniform texture and composed of fine-grained material, has become more porous, but shows no signs of fusion. Brand 39, considered as an

FIG. 4.—*Typical examples of brick after subjection to endurance test when transversely loaded*

FIG. 5.—*Typical examples of brick after subjection to endurance test when placed on end without loading*

aluminous brick, has a very coarse structure and will shrink considerably in the load test, while without load a noticeable expansion will take place. After the endurance test this brick shows a well-marked and uniform iron discoloration, and the structure appears puffed. The explanation for the expansion is not evident, although it would appear that the plastic clay bond overfires and swells. Brand 40 is a handmade clay brick of somewhat low refractoriness for first quality. The expansion in this case is obviously due to overfiring, the structure being bloated and vesicular.

From a study of the data at hand it would appear that the method of manufacture does not affect the behavior of brick in the endurance

FIG. 7.—Showing the relation between the amount of deflection and the change in absorption in the endurance test

test, but there is an interesting relation between the change in absorption during the endurance test, the resistance to deflection, and also (as will be shown later) the resistance to spalling. The absorption data are shown in Table 3 and Figure 6. Table 4 shows the respective changes in absorption after the test for two groups of brick having good and poor resistance to deflection, and Figure 7 shows the relation between change in absorption and deflection.

(a) DEFLECTION VS. CHANGE IN ABSORPTION.—Since change in absorption is a measure of the rate of vitrification it can be said that the curves (fig. 6) afford a rough picture of the rate at which the several bricks are vitrifying, and it is evident that the burning behavior of brick varies considerably in the range from the temperature

of the commercial burn (about 1,225° C.) to the maximum temperature of the endurance test (1,450° C.).

TABLE 2.—Results of endurance test

Test number of brands	District represented	Average linear change	Average deflection in thirty-seconds inch	Test number of brands	District represented	Average linear change	Average deflection in thirty-seconds inch
		<i>Per cent</i>				<i>Per cent</i>	
2.....	Eastern.....	-2.70	16	23.....	Central.....	-0.11	10
3.....	Western.....	+1.22	9	24.....	Central.....	-0.61	9
4.....	Eastern.....	+3.09	4	25.....	Eastern.....	+0.28	(1)
5.....	Eastern.....	-1.32	14	26.....	Central.....	+1.36	10
6.....	Eastern.....	-3.74	15	27.....	Central.....	-1.58	6
7.....	Eastern.....	+4.82	4	28.....	Western.....	(1, 4)	(2)
8.....	Eastern.....	-0.78	9	29.....	Central.....	-1.43	21
9.....	Central.....	-0.77	12	30.....	Western.....	-1.28	21
10.....	Central.....	+0.36	12	31.....	Central.....	-1.85	12
11.....	Eastern.....	-0.80	10	32.....	Central.....	-3.01	17
12.....	Central.....	+0.44	8	33.....	Eastern.....	-0.27	8
13.....	Central.....	-0.34	8	34.....	Western.....	(3)	10
14.....	Central.....	-1.34	12	35.....	Eastern.....	+1.94	11
15.....	Eastern.....	-0.78	9	36.....	Central.....	-0.12	10
16.....	Central.....	+1.07	8	37.....	Central.....	+2.57	11
17.....	Western.....	-4.38	21	38.....	Central.....	+0.93	13
18.....	Central.....	-0.28	16	39.....	Central.....	+1.70	14
19.....	Western.....	-2.94	20	40.....	Central.....	+2.64	12
20.....	Central.....	+1.55	14	41.....	Central.....	-2.45	12
21.....	Eastern.....	-1.06	15	42.....	Central.....	+0.70	22
22.....	Eastern.....	-2.74	10	43.....	Central.....	(2)	(3)

¹ Wedge shape, no test

² Squatted badly.

³ Failed.

⁴ No measurements.

⁵ No brick.

TABLE 3.—Showing absorption of brick as received and after subjection to the reheating and endurance tests

Test number of brands	Absorption of brick			Test number of brands	Absorption of brick		
	As received	After reheat test at 1,400° C. for five hours	After endurance test at 1,450° C. for 72 hours		As received	After reheat test at 1,400° C. for five hours	After endurance test at 1,450° C. for 72 hours
	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>		<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>
2.....	17.5	15.8	10.1	23.....	8.5	8.0	6.0
3.....	16.8	15.6	13.1	24.....	8.2	7.2	6.6
4.....	16.1	15.9	15.9	25.....	9.9	8.7	8.9
5.....	17.4	17.3	12.8	26.....	10.1	7.2	7.8
6.....	13.4	12.2	7.8	27.....	9.2	8.1	7.8
7.....	16.1	15.9	20.9	28.....	17.3	13.7	2.9
8.....	15.4	13.2	10.7	29.....	10.6	4.2	2.0
9.....	10.7	9.5	5.5	30.....	10.2	5.5	5.2
10.....	7.2	3.3	2.3	31.....	11.2	8.8	5.9
11.....	15.1	12.5	6.0	32.....	10.3	8.7	6.2
12.....	7.3	6.8	5.5	33.....	15.0	13.3	10.8
13.....	9.4	8.2	7.1	34.....	10.6	8.3	4.5
14.....	11.0	7.6	5.7	35.....	9.2	5.5	5.1
15.....	16.7	15.8	13.6	36.....	11.1	7.7	5.0
16.....	4.1	3.3	2.3	37.....	10.4	5.2	5.5
17.....	13.4	12.1	4.4	38.....	9.5	8.7	7.7
18.....		11.3	10.8	39.....	10.2	10.3	11.8
19.....	14.9	12.2	4.8	40.....	11.9	11.9	12.7
20.....	9.9	9.2	9.1	41.....	12.5	5.1	4.4
21.....	9.4	7.4	5.2	42.....	12.1	9.4	10.5
22.....	18.1	15.9	10.3	43.....	11.8	10.8	4.0

TABLE 4.—Showing relation between the amount of deflection, change in absorption, and final absorption in the endurance test

Test numbers	Change in absorption	Absorption after the endurance test
Test number of brands showing less than 8/32 deflection when transversely loaded in the endurance test:	<i>Per cent</i>	<i>Per cent</i>
4.....	0.2	15.9
7.....	4.8	20.9
13.....	2.3	7.1
27.....	1.4	7.8
38.....	1.8	7.7
Average.....	2.1	11.9
Test number of brands showing more than 15/32 deflection when transversely loaded in the endurance test:		
2.....	7.4	10.1
17.....	9.0	4.4
18.....		10.8
19.....	10.1	4.8
21.....	4.2	5.2
28.....	14.3	3.0
29.....	8.6	2.0
30.....	5.0	5.2
32.....	4.1	8.7
Average.....	7.8	6.0

The brick which deflected the least (Table 4 and fig. 7) show an average difference in absorption of 2.1 per cent, while those deflecting the most have an average change in absorption of 7.8 per cent. Consequently, a large deflection is indicative of low refractoriness not only because it in itself indicates a decrease in viscosity, but because the brick are rapidly approaching complete vitrification as evidenced by a decrease in absorption, and it is reasonable to assume that such brick, under service conditions where they are held continuously at a high temperature, would in a comparatively short time become vitrified or at least reach a state of incipient vitrification resulting either in deformation if the brick are under load, or in spalling if they happen to be in a place where frequent and rapid changes in temperature take place.

(b) DEFLECTION VS. FINAL ABSORPTION.—Disregarding brands 4 and 7, which because of their quartz content act more like silica brick and have a high expansion with a resultant high absorption, it is evident that the final absorption of both the best and the poorest brick of the transverse test have no noteworthy differences. This would seem reasonable since the final absorption is dependent on a number of factors, such as method of manufacture, per cent grog and its sizing, and the per cent plastic clay used and its nature; that is, an open burning body may still show considerable absorption at its minimum porosity stage preceding the overburned state.

These data would indicate, therefore, that the reaction of brick to transverse load in the endurance test is a measure of what the brick

is doing at the maximum temperature of the test rather than a measure of the condition of the brick at the end of the test.

(c) PETROGRAPHIC EXAMINATIONS.—The brick were examined with the petrographic microscope, because this method of examination will give information that can be obtained in no other way. The change in the structure of the brick, the solution of quartz, and the development of mullite and glass after increased heat treatment can be observed and the percentage of uncombined quartz in the brick estimated much more rapidly than could be done by calculation based on chemical composition.⁶

In this investigation the examinations were made on crushed and ground samples of the brick immersed in an oil of known index of refraction. An effort was made to obtain samples of the brick that would be representative of the whole brick, and where there was a marked difference in the composition of the grog and the bond in the burned pieces the grog was picked out, crushed, and examined separately. No attempt was made to determine the percentage of quartz accurately, the values obtained having been estimated after a visual inspection of two or three fields in the microscope. They checked fairly well, however, with the values for free quartz obtained by calculation from the chemical compositions (Table 9).

TABLE 5.—Results of petrographic examination of brick as received and after subjection to the reheating and endurance tests

Test number of brand	Results of petrographic examination of brick—		
	As received	After being held at 1,400° C. for five hours	After being held at 1,450° C. for 72 hours
3-----	About 50 per cent quartz; grog particles are quartz grains, somewhat shattered; clay altered in part to mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$).	Slight alteration of quartz to cristobalite; extensive development of mullite.	At least 40 per cent cristobalite, 10 per cent or less of unaltered quartz, and remainder mullite (well developed) with a little glass.
6-----	35 per cent quartz; quartz somewhat shattered, but not inverted to cristobalite; some development of mullite in clay matter.	Small inversion of quartz to cristobalite; slightly more mullite than in commercial brick.	Stained black due to iron oxide; 20 to 35 per cent cristobalite, 5 per cent quartz, and remainder clay matter extensively altered to mullite.
7-----	About 75 per cent quartz; some quartz grains slightly shattered, but not inverted; no visible alteration of clay matter to mullite; grog particles are quartz.	Some shattering of quartz; slight formation of cristobalite; development of mullite not prominent, but slightly greater than in commercial brick.	About 70 per cent cristobalite, 5 per cent quartz, and remainder fairly well-formed crystals of mullite with little glass.
13-----	About 10 per cent quartz; no cristobalite; small amount of mullite; considerable glass and amorphous material.	About same in quartz and mullite content as untreated, but very different in appearance; color darker and iron stains more pronounced.	
23-----	Less than 5 per cent quartz; considerable glass; slight change of clay matter to mullite, no cristobalite.	Much glass; clay matter largely transformed to mullite; large mullite crystals present and many small ones.	

⁶ For a summary of the applications of the petrographic microscope in ceramics see an article by A. B. Peck in Jour. Amer. Cer. Soc., 2, p. 659; 1919.

TABLE 5.—*Results of petrographic examination of brick as received and after subjection to the reheating and endurance tests—Continued*

Test number of brand	Results of petrographic examination of brick—		
	As received	After being held at 1,400° C. for five hours	After being held at 1,450° C. for 72 hours
27-----	Less than 5 per cent quartz; no cristobalite; considerable glass; largely amorphous material; little crystalline mullite.	About same amount of quartz; no cristobalite; considerable glass; moderate quantity of small crystals of mullite.	
38-----		10 to 15 per cent quartz; no cristobalite noted; moderate amount of glass; well developed small crystals of mullite abundant.	
39-----	About 10 per cent or less quartz; no inversion to cristobalite, but clay matter is extensively changed to crystals of mullite; grog particles unusually coarse; quartz mostly in bond clay.	Very similar to "commercial" both in mineral composition and development of mullite; very small amount of cristobalite present.	Quartz inverted to cristobalite; fairly large crystals of mullite; all of clay changed to mullite and glass.
41-----	20 to 25 per cent quartz; no cristobalite; considerable alteration of clay to mullite; mullite in fine intermeshed crystals; grog particles contain more quartz than the bond does.	Large part of quartz inverted to cristobalite; remnants of quartz grains surrounded by rims of cristobalite; clay extensively altered to mullite; mullite crystals well formed and large.	Quartz entirely inverted to cristobalite; mullite development very extensive.
42-----	About 10 per cent quartz; apparently not shattered; no cristobalite; considerable mullite development.	Bond clay an olive yellow, grog particles white; except in color differs little from commercial brick; a small amount of cristobalite; little, if any, more mullite than in commercial brick.	Quartz almost completely changed to cristobalite; mullite development very extensive.

As shown in Table 5, the structure of the bricks examined had changed materially during the heat treatment of the endurance test. In every case where a petrographic examination was made it was found that the free quartz had been almost completely changed to cristobalite while the clay matter was transformed into mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) and glass, and it may be said that one no longer has the same brick after this test. The value of these data will be brought out more clearly in a discussion of the quenching test.

It will be noted that the needles of mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) vary in size and abundance in the different brick as received. The variation may be due not only to the burning temperatures of the brick, but also to the amounts of flux present. The needle-like crystals have been called mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), since recent experimental work⁷ has shown that mullite and not sillimanite can exist at these temperatures and under these conditions.

⁷ Bowen and Greig, The system $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Jour. Amer. Cer. Soc., 7, p. 244; 1924.

2. REHEATING TEST

This test was conducted to determine, if possible, the relation between the linear change and absorption of a brick when reheated and its value as a refractory. The brick were carefully measured before and after the test for average length and the difference expressed as the per cent linear change. The determination of actual volume change would have involved much more work and, because of the nature of the material, would very probably have yielded data of no greater value than that afforded by the measurement of linear change.

FIG. 8.—Showing the relation between the per cent absorption of brick after the endurance test and the number of quenchings required to produce failure

The results obtained are shown in Table 3 and by the dotted curve in Figure 3. There is no evident relation between these results and the results of the other tests, which may be due to the fact that the changes produced are not sufficiently large to be significant, but the final absorption proved to be of considerable interest and probable value. The results are plotted in Figure 8 and will be discussed later in connection with the quenching test.

3. QUENCHING TEST

The two main results to be considered in this test are (a) the loss in weight, and (b) the number of quenchings required to produce failure. As previously stated, the brick were first reheated at

FIG. 9.—*Typical examples of brick after subjection to the quenching test*

1,400° C. for five hours, allowed to cool slowly with the kiln, and were weighed to the nearest ounce. Fifteen brick of each brand were prepared in this way, five being used for the quenching work from each temperature; that is, from 850, 1,100 and 1,350° C. Quenchings were repeated until the end of the brick had completely spalled away (see specimens 6, 28, and 19 in fig. 9), and each brick was then reweighed and the per cent loss in weight calculated. In nearly all cases the first spall carried away the entire end of the brick, but occasionally only a corner was lost, requiring one or two more quench-

FIG. 10.—Showing the relation between the number of quenchings required to produce failure when using 850, 1,100, and 1,350° C., respectively, as the furnace temperature

ings before the brick failed. The complete results of quenchings from the three temperatures are shown in Figure 10 and Table 6. The brick shown in Figure 9 are typical of the appearance of specimens after the quenching test. Brands 6 and 28 were decided failures after six and nine quenchings, respectively. Brand 19, although a failure after three quenchings according to the definition used in this work, had actually lost very little in weight. Brand 23, with a somewhat shattered structure, showed no actual failure after 34 quenchings.

TABLE 6.—Results obtained in the quenching test

Test number of brand	Quenched from 1,350° C. to running water		Quenched from 1,100° C. to running water		Quenched from 850° C. to running water	
	Number of quenches required to produce failure	Spalled off	Number of quenches required to produce failure	Spalled off	Number of quenches required to produce failure	Spalled off
		<i>Per cent</i>		<i>Per cent</i>		<i>Per cent</i>
2.....	2	17.8	3	11.4	5	48.4
3.....	2	8.6	3	14.2	13	7.2
4.....	1	23.0	1	26.2	2	18.4
5.....	2	20.4	3	13.8	7	15.0
6.....	1	13.4	1	7.4	4	17.2
7.....	2	32.6	2	13.2	13	28.6
8.....	1	30.8	2	30.5	5	24.4
9.....	5	31.0	5	15.0	14	43.0
10.....	1	22.8	1	23.7	1	26.8
11.....	3	27.6	3	18.4	15	18.5
12.....	3	23.0	2	26.2	15	26.8
13.....	2	27.8	4	14.2	18	26.0
14.....	3	23.2	5	19.6	12	20.8
15.....	2	19.4	2	27.0	8	18.0
16.....	2	8.6	2	23.0	2	19.4
17.....	2	8.0	2	18.0	6	10.2
18.....	5	23.4	4	17.5	15	22.6
19.....	2	6.8	2	8.8	3	7.8
20.....	2	26.8	2	21.0	3	33.6
21.....	7	27.2	3	7.8	4	28.0
22.....	1	31.6	4	15.4	5	5.0
23.....	8	20.2	24	14.2	34	30.0
24.....	5	12.8	7	14.6	18	18.8
25.....	1	37.5	2	14.8	5	16.6
26.....	3	13.0	6	16.3	30	22.5
27.....	4	18.2	9	15.8	39	27.2
28.....	2	13.4	2	12.4	9	13.0
29.....	5	23.0	2	11.0	5	12.0
30.....	1	9.4	1	12.0	1	9.2
31.....	2	26.2	2	10.2	5	22.0
32.....	3	24.4	2	8.0	6	11.0
33.....	2	13.8	3	7.4	14	12.4
34.....	1	24.7	1	8.6	5	14.6
35.....	2	24.4	3	21.6	4	24.7
36.....	4	13.5	4	6.5	6	20.8
37.....	4	35.0	1	17.4	2	10.4
38.....	3	34.2	9	18.2	59	24.5
39.....	4	13.0	5	9.0	19	14.2
40.....	2	22.6	1	8.0	2	17.4
41.....	2	37.5	1	8.4	3	22.2
42.....	2	30.2	3	9.6	4	25.0
43.....	1	35.0	1	21.3	1	22.6

The loss in weight of the several brands (Table 6) does not bear any relation to the behavior of the brick in other tests, and the temperature from which quenches were made also had very little effect on the loss in weight. The number of quenches to produce failure does show decided differences, however, when temperatures are considered. A study of the curves (fig. 10) shows that, while quenching from 1,350° C. will undoubtedly indicate brick of low resistance to temperature change, it does not show sufficient difference between the best and the poorest to enable one to make good comparisons. Quenching from 1,100° C. did not increase the value of

the test very much, if at all. Brands 23, 27, and 38 withstood this test appreciably better, but in most cases the number of quenches was either the same or differed by not more than one. In fact, some brick, as the curves will show, appeared better in the 1,350° test. From this it would appear that if quenching from 1,100° C. has any advantage over that from 1,350° C. the gain lies within the limits of error of the test.

FIG. 11.—Showing variations in thermal expansion of clay bodies as produced by variations in clay and quartz content

Prepared by Dr. H. Kohl, "Die Wärmeausdehnung und einige andere physikalische Eigenschaften von Steingut in Abhängigkeit von der Zusammensetzung und Brenntemperatur." Vol. 3, No. 6, December, 1922, Ber. der Deut. Keramischen Gesell. The quartz and cristobalite curves were developed by Le Chatelier (La Silica, Revue. l. p. 90; 1913) and express expansions in terms of mm per 100 mm. The work of Doctor Kohl included the determination of expansion coefficients of bodies fired to temperatures varying from cones 0.08 to 7, and the results indicate that for bodies low in quartz the coefficient is increased with higher temperature burns. This would mean that the slope of the curve for bodies D and E would be somewhat decreased. The materials used by the author of this work were also purer, and corresponding curves for refractory specimens would not be exactly the same, but it is reasonable to assume them sufficiently close for purposes of discussion.

Quenching from 850° C. produced a marked change in the nature of the results. Although some brands still failed in the first quenching, there is a much wider range between the best and poorest brands. The data show a range of 1 to 59 quenches, with a general average of 6.7, for the 850° test and a range of 1 to 8, with a general average of 2.0 for the 1,350° test.

(a) RESISTANCE TO SPALLING VS. THERMAL EXPANSION.—A study of the curves shown in Figure 11 suggested an explanation which may account for the fact that the temperature interval from 1,350

to 1,100° C. did not effect a change in the quenching behavior of the brick, while the equal temperature interval from 1,100 to 850° C. produced the decided difference which has been noted.

The inversion point of α quartz to β quartz (573.3° C.)⁸ lies well below the furnace temperatures of the test, and it is therefore evident that the difference in behavior is due to some other cause. It would appear that the coefficient of expansion of brick in the range from 20 to 1,100° C., or higher, produces a stress which greatly exceeds the ultimate tensile strength irrespective of the composition and structure of the specimen, while in the range from 20 to 850° C. the stress produced in brick containing small amounts of free quartz is only great enough to produce a gradual weakening of the structure, although for those containing large amounts of free quartz the stress is still comparatively large.

There are two factors which may account for the rapid spalling of some brick in the 850° quenching: (a) The brick may contain a comparatively large amount of free quartz, and the sudden change in volume of this material at its transformation point may produce a shattering of the structure. (b) The brick may contain 10 per cent or less of free quartz, but be composed largely or entirely of plastic clay. In this case the structure will be very dense, and because of the lower refractoriness of plastic clays it is probable that vitrification and partial conversion to glass takes place. This condition will result in a brittleness of structure tending to reduce the resistance of the brick to thermal shock.

Let us assume that a change in length of 0.75 mm per 150 mm between the suddenly cooled and the hot portions of the brick produces a strain which exceeds the tensile strength of all of the refractories under test. For bodies quenched from 1,100 and 1,350° C. to running water (fig. 11) the body having no quartz undergoes a change in length of at least 0.8 mm per 150 mm ($C'-A'$), while the values for the bodies of medium and high quartz content are appreciably higher, and therefore, according to the assumption, all will spall. On the other hand, quenching from 850° has produced an entirely different set of conditions. The body high in quartz undergoes practically the same change in length ($C-F$) as when quenched from 1,100° C. ($C'-F'$), while the one containing 30 per cent quartz lies near the border line with a linear change of approximately 0.72 mm ($C-E$). Those still lower in quartz can be considered as in the area where failure is brought about by a gradual weakening of the structure through repeated thermal shocks. As previously explained, the beneficial effects of using material low in quartz may be lost by using

⁸ As reported by Bates and Phelps, of the polarimetry section of the Bureau of Standards. Their work further shows that the inversion from β to α quartz, while not as sharply defined as the inversion from α to β , probably lies between 572 and 573° C.

clays which will result in a brick of low refractoriness. The method of application of this explanation to the test results is shown in Figures 8 and 12.

The second conclusion which was drawn from the data presented in Figure 11,⁹ viz, that materials containing less than 30 per cent quartz fail through a gradual weakening of the structure, is verified by the data in Figure 12, which shows that, with but one exception, no material containing more than 20 per cent uncombined quartz withstood more than 15 quenchings. Of the six brands containing less than 4 per cent flux and 20 per cent uncombined quartz, but which did not successfully withstand 15 quenchings, two failed after

FIG. 12.—Showing relation between chemical composition and resistance to spalling

12 and 14 quenchings, respectively, and the other four were considerably higher in absorption than the information given in Figure 8 would indicate to be desirable.

(b) RESISTANCE TO SPALLING VS. ABSORPTION.—While the relation between the absorption of reheated brick and their quenching behavior (fig. 8) is not evident, a comparison of the absorptions of the nine brands highest in resistance to thermal shock (brands 38, 27, 23, 26, 39, 24, 13, 12, and 11) will show that, with one exception, this value lies between 6 and 10 per cent. Although the evidence ob-

⁹ The uncombined quartz was calculated from the chemical analyses. The flux was determined by difference.

tained does not warrant the assertion that a good brick, after reheating at 1,400° C. for five hours, will have an absorption between these limits, it is undoubtedly of significance. In addition, a comparison of the data on change in absorption during the endurance test with those obtained in the quenching test shows that with but one exception (brand 11, which was very high in silica content) all of the brands which satisfactorily withstood 15 or more quenchings underwent a change in absorption of less than 3 per cent, while (with the exception of brands 4, 16, 20, 25, 40, and 42, the structure of which indicated overfiring) the remaining 33 brands which did not withstand 15 quenchings showed a change in absorption of more than 3 per cent.¹⁰ However, since the endurance test involves a considerable expenditure of time and money, it is not thought that the information obtained warrants its adoption as a check method for the determination of resistance to quenching.

(c) RESISTANCE TO SPALLING VS. LIFE IN SERVICE.—During the course of the experiments reported here a list of the brands under examination was submitted to R. M. Howe, senior fellow of the Refractories Manufacturers Association, with the request that he submit available data relative to the raw materials used in the manufacture of the several brands, the method of manufacture, and, if possible, the consensus of opinion in the trade as to the relative value of the brands as boiler-setting refractories. The comments received regarding the serviceability of the nine best brands, as determined by the quenching test, are worthy of note:

11. Envable reputation.
12. Good reputation.
13. Very good reputation.
23. Very good brick.
24. Good reputation.
26. Good reputation.
27. Good grade.
38. Good reputation.
39. Very good brick.

While it does not necessarily follow from this that a refractory which will not withstand 15 quenchings will be unsatisfactory in service, it does indicate that the quenching test is valuable as a measure of the life of fire-clay brick in boiler settings.

(d) RESISTANCE TO SPALLING VS. METHOD OF MANUFACTURE.—While there is no conclusive evidence to show the advantage of any one method of manufacturing over that of another, it is interesting

¹⁰ Observation has shown that refractories which tend to overfire resist quenching tests very poorly, although the final absorption change would indicate a satisfactory structure. Fortunately an overfired structure can be readily detected by visual inspection. For a detailed discussion of the effect of overfiring on the structure of clays see B. S. Tech. Paper No. 22.

FIG. 13.—Showing typical appearance of refractories after subjection to the standard load test

FIG. 14.—*Showing effect of preheating on resistance to deformation under load at high temperatures*

to note that of the 10 first brands, as shown in Figure 17, seven were made by the dry-press process, two were handmade, and one stiff mud.

4. LOAD TEST

The data obtained in the investigation dealing with the behavior of refractories when subjected to high temperatures while under direct load are presented in Figure 2 and in Table 7, while Figures 13 and 14 illustrate some of the results obtained.

It was not expected that the load test would produce any new information, since the investigations by means of which this test was developed were very thorough and comprehensive.¹¹ However, due to its general acceptance by the trade, as well as research laboratories, it was considered advisable to make this test for comparative purposes.

The most noticeable feature of the load-test results is that they can not be correlated with the results of any other test used. It serves to differentiate between refractories which remain rigid at high temperatures and those whose viscosity is appreciably lowered, but apparently has no value as a means for grading refractories which fall in any one group as determined by such other accepted tests as softening point, quenching test, endurance test, and chemical analysis. Regarding the composition of a refractory and its relation to the load test, it has long been known that a material high in quartz will withstand load at high temperatures, due to the fact that the decrease in viscosity of this substance is not a gradual one, but takes place rapidly at temperatures approximating the softening point.¹² This fact tends to minimize the value of the test due to the difficulty of adapting it to brands of both high and low silica content which are accepted as satisfactory by the trade. It has also been shown by previous investigators¹³ that the behavior of the so-called aluminous refractory in the load test is affected appreciably by the previous thermal history of the specimen, as a result of which this test can only be used as an indirect measure to determine the extent to which the material has been burned, and which again increases the difficulty of establishing a common standard.

¹¹ See footnote 4, p. 106.

¹² This is demonstrated by the fact that the 16 brands which deformed 2.6 per cent or less in the standard load test had an average uncombined quartz content of 33.4 per cent, while in the balance of the brands this was equal to 18.4 per cent.

¹³ A. V. Bleining, *Jour. Amer. Ceramic Soc.*, 3, No. 2; 1920.

TABLE 7.—Load-test results

Laboratory number	Standard A. S. T. M. method for No. 1 fire brick (25 pounds per square inch at 1,350° C. for one and one- half hours		25 pounds per square inch at 1,350° C. for 10 hours	25 pounds per square inch at 1,450° C. for one and one-half hours
	Brick as received	Brick pre- heated at 1,400° C. for five hours	Brick as received	Brick pre- heated at 1,400° C. for five hours
	<i>Per cent deformation</i>	<i>Per cent deformation</i>	<i>Per cent deformation</i>	<i>Per cent deformation</i>
2	0.23		1.38	
3	.35	0.23	1.50	2.57
4	.45		1.10	
5	.55	.77	3.34	3.74
6	.65			
7	.70		1.12	
8	.85	.00		
9	.90			
10	1.30			
11	1.60	.23	1.13	1.32
12	1.70			
13	2.20		7.31	
14	2.40		4.30	
15	2.50	.33	2.70	8.80
16	2.50			
17	2.60		7.73	
18	2.70	2.95	5.24	7.20
19	2.90		3.01	
20	3.00			
21	3.10	1.66		3.45
22	3.20		7.02	
23	3.30		4.23	
24	3.40	3.04		7.85
25	3.60			
26	3.80		8.30	
27	4.50	.57	5.50	3.90
28	4.50			
29	4.50			
30	4.80		11.69	
31	5.10	1.85	6.99	9.85
32	5.24	1.81	9.20	7.57
33	5.50	.45	5.60	1.71
34	6.50		7.12	
35	6.60			5.10
36	6.90	1.49	12.40	1.74
37	7.50		11.40	
38	7.80	3.62	13.10	5.03
39	8.30	1.66	8.20	5.58
40	8.40		13.85	(3)
41	8.60	3.20	10.90	2.33
42	(3)		(3)	
43	(3)		(3)	

¹ Tends to deform.² Deformed.³ Failed.

In an endeavor to meet these objections, several brands were subjected to the previously-described modifications of the A. S. T. M. standard method of test.

As the data given in Figure 2 show the first modification, consisting in holding the specimen under load at 1,350° C. for 10 hours, did not essentially alter the results, and the curve in general follows that obtained with the standard test. The brands high in silica with-

stood the 10-hour exposure to heat while under load practically the same as for the shorter period, while the greater deformation of aluminous refractories makes the test less valuable for classification purposes than the present standard method.

It is customary in the industry to burn fire clay refractories to temperatures corresponding to the softening points of pyrometric cones 4 to 8, depending on the raw material used and the service which they are to render. It is obvious that reheating the specimens in the laboratory preparatory to further testing produced results decidedly different in character, and it was logical to assume that it would, since this reburning of aluminous refractories affords further opportunity for reaction between the highly refractory flint clay and the plastic bond (naturally lower in refractoriness), resulting in averaging their resistance to heat. This is verified by the results (Table 7 and fig. 2) and is plainly shown by the photographs of typical specimens presented in Figure 14. In the lower group of brick the specimen to the left (41.9 per cent Al_2O_3 and 53.8 per cent SiO_2), which had been preheated, deformed 3.62 per cent, while the untreated brick had deformed 7.80 per cent.

To further demonstrate this point, three specimens were preheated and subjected to the transverse endurance test. In the upper group (fig. 14) the specimen to the left had been preheated and deflected 9/32 of an inch, while the untreated brick, shown to the right, deflected 20/32 of an inch. The detailed results obtained are shown in Table 8.

TABLE 8.—Deflection of brick in thirty-seconds inches, showing effect of preheating

Brand	As received	Preheated at 1,400° C. for five hours
	Thirty-seconds	Thirty-seconds
2.....	15	4
26.....	9	5
30.....	20	9

To determine what effect, if any, this preheating had on the reaction of refractories to load at temperatures considerably higher than those usually employed, 17 brands were subjected to a temperature of 1,450° C. for one and one-half hours under a load of 25 pounds per square inch. This is a very severe test and one in which, under ordinary conditions, a fire-clay refractory of satisfactory quality would undoubtedly fail. The preheated specimens (Table 7 and fig. 2) in nearly every instance not only withstood the test, but actually in several cases (brands 11, 21, 27, 33, 38, 39, and 40) were compressed less than in the standard test. This is interesting and valuable evidence showing that higher burning

of refractories, particularly of the aluminous type, greatly increases their ability to withstand load under service conditions.

Another point of interest is illustrated by results obtained on two specimens of brand 8 (central brick in the upper and lower groups, fig. 13). The upper one withstood the test satisfactorily, while the lower one failed. This failure was not due to the inherent qualities of the raw material, but rather to a large flint pebble, which can be plainly seen in the photograph and which happened to be so placed as to materially decrease the mechanical strength of the specimen in the plane of maximum shearing stress. The specimen emphasizes the necessity for taking proper measures to prevent the incorporation of excessively large grog particles in the batch mix.

TABLE 9.—*Softening point and chemical analysis*

Test number of brands	Softening point in cones	Chemical analysis			Rational analysis		
		Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	Clay	Uncombined quartz	Flux
		<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>
2.....	31	21.0	77.8	1.2	49.3	49.5	1.1
3.....	31-32	21.5	76.0	1.1	50.7	47.1	2.3
4.....	30	19.0	79.8	1.2	45.1	53.8	1.1
5.....	31	22.3	76.5	1.5	51.8	46.8	1.4
6.....	31	33.4	64.3	2.0	75.6	22.3	2.1
7.....	+31	16.5	82.7	1.1	39.4	59.6	1.0
8.....	30	20.1	77.9	1.4	47.5	50.6	1.9
9.....	30-31	43.6	54.3	1.2	95.6	2.6	1.9
10.....	+30	34.8	61.7	3.6	78.4	18.4	3.2
11.....	30-31	20.4	77.8	1.0	48.2	50.1	1.7
12.....	32	34.9	61.4	1.7	78.5	18.1	3.4
13.....	32-33	41.2	55.4	1.5	91.0	6.0	3.0
14.....	32	35.4	61.1	1.5	79.6	17.3	3.1
15.....	31-32	27.9	70.5	1.4	59.0	39.7	1.3
16.....	29-30	36.6	60.1	2.4	81.2	15.8	3.0
17.....	30-31	26.3	71.5	2.1	60.9	37.1	2.0
18.....	33	43.2	53.4	2.4	94.9	2.2	2.9
19.....	29	21.7	74.1	2.1	51.0	45.1	3.9
20.....	32-33	43.9	51.2	2.8	95.9	0.0	4.1
21.....	32	36.7	60.0	1.5	82.2	14.9	2.8
22.....	31	30.7	66.2	2.2	70.1	27.1	2.8
23.....	33	48.0	48.2	1.8	91.9	0.0	2.8
24.....	32-33	39.2	57.4	2.0	87.3	9.9	2.8
25.....	30	39.4	55.3	2.4	87.5	7.9	4.6
26.....	33	40.4	57.9	1.6	89.4	9.1	1.5
27.....	33	44.8	51.6	1.8	97.0	0.0	3.0
28.....	26	24.1	71.9	2.4	56.3	40.0	3.7
29.....	30	26.8	70.1	1.7	61.8	35.3	2.8
30.....	26	33.5	61.1	4.5	75.8	19.4	4.8
31.....	29	32.9	64.3	2.3	74.4	23.0	2.5
32.....	+32	41.0	56.3	2.4	90.6	7.1	2.3
33.....	32-33	31.9	65.2	1.7	72.5	24.9	2.5
34.....	27-28	29.2	67.3	2.1	66.1	30.7	3.2
35.....	29-30	34.2	61.5	2.9	69.3	27.4	3.3
36.....	30	34.3	61.4	2.4	69.2	27.4	3.4
37.....	30	38.8	56.2	2.0	86.2	9.3	4.4
38.....	33	37.7	58.8	2.0	84.2	12.7	3.1
39.....	33	41.9	53.9	1.9	92.2	4.0	3.7
40.....	28	41.2	51.2	5.6	91.0	2.3	6.6
41.....	29	36.4	57.4	2.3	81.5	13.0	5.5
42.....	30	41.8	52.0	3.4	92.0	2.6	5.4
43.....	-26	26.1	66.8	3.0	60.5	33.0	6.5

¹ 5.3 per cent uncombined Al₂O₃.

While the standard load test, as previously stated, can undoubtedly be used to good advantage in judging refractories, the results obtained can not be interpreted properly without a knowledge of the nature of the material, its softening point, and its previous thermal history. It is possible, therefore, that the test, if conducted on preheated brick, will be considerably improved as a method for classifying the so-called high quality fire-clay refractories.

5. SOFTENING POINT AND COMPOSITION

(a) **SOFTENING POINTS.**—Although the user of refractories is not directly interested in their softening points, because such materials are not as a rule subjected in service to temperatures which would cause them to flow under their own weight, they are, nevertheless, values of primary importance. This is true not only because they indicate resistance to heat, but because of their close relation (as will be shown later) to composition, volume change, and resistance to quenching, all of which are factors affecting the life of brick in service.

Softening points are usually given in terms of cone numbers, but in this work both the cone number and the actual temperature corresponding to the softening point of the material tested were determined. It is realized that temperature measurements by means of the optical pyrometer are subject to experimental error with the most refined methods known (probably plus or minus 10° for temperatures equivalent to the softening point of refractories). The determinations (Table 10), obtained by sighting an optical pyrometer through the top of the magnesite muffle (fig. 1b) and on the cone pat as the cone was going down, were made in an oxidizing atmosphere and were checked repeatedly within the limits of error stated above.

TABLE 10

Cone number	Degrees centigrade
28.....	1,590
29.....	1,605
30.....	1,630
31.....	1,650
32.....	1,670
33.....	1,690

(b) **CHEMICAL ANALYSES.**—The chemical analysis of these refractories consisted of the determination of SiO_2 , Al_2O_3 , and Fe_2O_3 by the A. S. T. M. standard method, serial designation C 18-21. Other constituents were not determined, but the difference between 100 per cent and the sum of the percentages of SiO_2 and Al_2O_3 was regarded as the percentage of flux.

(c) CHEMICAL VS. RATIONAL COMPOSITION.—If plotted on a triaxial diagram, the values would lie in the following field:

	Per cent
Al ₂ O ₃ -----	15-50
SiO ₂ -----	45-85
Total flux (by difference)-----	0-10

and if calculated to clay, uncombined quartz, and flux the compositions could be plotted in the field:

	Per cent
Clay-----	40-98
Uncombined quartz-----	0-60
Flux-----	0-10

The rational analyses, as given in Table 9, were derived by a slight modification of the method of computation usually applied to ceramic bodies assumed to contain only clay, quartz, and feldspar.¹⁴ In the present work the calculations were made by computing the amount of silica necessary to combine with all the alumina present to form a clay of the formula Al₂O₃.2SiO₂.2H₂O. The excess silica was regarded as uncombined quartz, and the flux was obtained by difference. The following factors were used:

Molecular weights: SiO₂ = 60; Al₂O₃ = 102; H₂O = 18.

Clay = 2.529 × per cent Al₂O₃.

Combined silica = 1.176 × per cent Al₂O₃.

Uncombined quartz = total silica - combined silica.

Flux = 100 - (per cent Al₂O₃ + per cent SiO₂).

The sum of the clay, uncombined quartz, and flux was then reduced to 100 per cent.

Example.—As an example, a calculation based on the analysis of number 17 is given:

Composition as determined by analysis = Al₂O₃ - 26.3 per cent; SiO₂ - 71.5 per cent; Fe₂O₃ - 2.1 per cent.

Clay = 26.3 × 2.529 = 66.5.

Silica required to satisfy Al₂O₃ = 26.3 × 1.176 = 30.9.

Excess silica = 71.5 - 30.9 = 40.6.

Total flux = 100 - per cent Al₂O₃ and SiO₂ = 100 - (26.3 + 71.5) = 2.2.

Adding clay, excess silica and total flux = 66.5 + 40.6 + 2.2 = 109.3.

Calculating to 100 per cent:

	Per cent
Clay-----	= 60.9
Uncombined quartz-----	= 37.1
Flux-----	= 2.0

(d) COMPOSITION VS. THERMAL PROPERTIES AND RESISTANCE TO SPALLING.—Several methods of correlating the chemical analyses

¹⁴ For description and references relating to other methods of analysis see 1, No. 6, Jour. Amer. Cer. Soc., "The calculation of the 'rational analysis' of clays." H. S. Washington.

with other physical properties suggest themselves, but that shown in Figures 12 and 15 was finally adopted.

Bleining and Brown, in their paper on the testing of clay refractories with special reference to their load carrying capacity,¹⁵ have clearly explained the relation of chemical composition to the viscosity of mixtures of clay, quartz, and flux at temperatures approximating the softening point. Since an empirical formula was used by these writers, a direct comparison of their results with those of the present investigation can not be made. From their discussion it is evident that composition is the most important factor determining softening points, and this is verified by the data in Table 9 and Figure 15. It

FIG. 15.—Showing relation between chemical composition and softening point

was not so evident, however, that resistance to quenching was as dependent on chemical composition as the data (fig. 12) indicate. In fact, it was thought that physical structure determined this quality, but, if these data are correct, any refractory having a softening point lower than cone 32, or which contains more than 20 per cent uncombined SiO_2 , and 4 per cent total flux, can not be expected to satisfactorily resist spalling.

6. DESCRIPTION OF EROSION TEST

The reason for, and application of, a test to determine the relative resistance of refractories to the combined action of molten slag, flue gases, and high temperatures is given in Part II in the discussion of service data. Preliminary runs were made in a test chamber shown

¹⁵ B. S. Tech. Paper No. 7.

in Figure 16 which was built into the kiln shown in Figure 1a. It was approximately 24 by 24 by 4½ inches inside. The test brick (marked A) formed a baffle wall against which the flame from the compressed air burner at *B* impinged. This flame carried with it finely ground slag introduced through the refractory tube *C*.

The entire interior of the kiln was brought to a red heat and maintained at this temperature (900 to 1,000° C.) throughout the test by means of the burners at the side and which are used regularly in firing the kiln. The temperature of the interior of the test chamber was raised to 1,450° C. by means of burner *B* and maintained there for one and one-half hours, during which time 1½ pounds of slag was gradually introduced through tube *C*.¹⁶

FIG. 16.—Sketch of furnace used in testing resistance of refractories to erosion and slagging

The finely ground slag, falling into the flame, was picked up, the finer grains melted almost instantly, and the entire charge carried against the test bricks in the cover of the test chamber. The slag then flowed down across the face of the test panel at the back and was retained in the pocket at *E* while the flame swept on and down to the recuperator through a flue at *D*.

Brands 13, 23, 31, and 40 were used in the test. The results obtained were not sufficiently pronounced to warrant conclusions, but indicate that valuable information can be derived by a method of this type if the runs are continued for a sufficient length of time, probably not more than 24 hours.

¹⁶ The slag had a softening point of 1,100° C. and was prepared in the laboratory by calcining and grinding (to pass a 40-mesh sieve) the proper raw materials to approximate a low fusing coal ash of the following composition:

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	SO ₂
30.7	19.6	18.9	1.1	11.3	3.7	1.9	0.5	12.2

The analysis was obtained from Bureau of Mines Bulletin 209, p. 2.

IX. CONCLUSIONS

A comprehensive picture of practically all of the laboratory results is given in Figure 17, in which there are correlated the softening points of the refractories, the per cent linear change, and the deflection in 1/32 inch during the endurance test, the absorption after reheating, and the number of quenchings from 850° C. required to produce failure.

The brands have been arranged in the order of their relative behavior in the quenching test.

Considering the first 8 brands which required 15 or more quenchings to produce failure, it was found that in every case the softening point was equivalent to, or higher than, pyrometric cone number 32, while among the balance of 29 brands only 6 were equally refractory.

The endurance test is a measure of the rapidity with which a refractory approaches vitrification at high temperatures. Excellent interrelation between the linear change, absorption change, and deflection in the transverse load test were obtained. As the graph shows, no refractory requiring 15 or more quenchings underwent a linear change of more than 2 per cent and, with but one exception, they did not deflect more than 10/32 of an inch. The exception (brand 39) was a light burned, open structure aluminous brick which showed practically no deflection when preheated at 1,400° C. Although this information, obtained by testing refractories at 1,450° C. for 72 hours, is of interest and value, it involves a difficult and expensive procedure in the laboratory and offers no better data than other and simpler tests. For an industrial plant, where a constant heat of the required degree is available, the test is to be recommended.

The reheating test did not produce sufficient linear or absorption change to be of value, but the final absorption lay between comparatively narrow limits for brands of high resistance to quenching. As the graph shows (fig. 17), the absorption for the first 10 brands was, with one exception, between 6 and 10 per cent, while for the balance this value was in almost every case considerably higher or lower, due to vitrification, overfiring, or a high content of uncombined quartz. In brief, the data obtained indicate the following:

1. The endurance test, while furnishing results of undoubted interest and value, is difficult and expensive and offers no better means of testing refractories than other and simpler methods.

2. The reheating test, used as a preliminary step to quenching, offers a means for obtaining valuable absorption data.

3. The quenching test, using 850°C. as the furnace temperature, is an excellent means for judging comparative resistance to thermal shock.

4. Although the relation between resistance to sudden temperature change, softening point, and chemical composition is close it does not warrant the complete replacement of the quenching test by either or both of the latter.

5. The load test justifies itself as a means for determining whether or not an aluminous refractory is sufficiently well burned to resist considerable load when that load is applied during the initial heating of the installation and to extreme temperature.

6. Evidence indicates that for classifying high heat-duty refractories the load test could be improved by preheating the specimens.

FIG. 17.—Correlation of pertinent data obtained by means of the softening-point determination and the endurance, reheating, and quenching tests

7. Chemical composition is a source of very interesting and important information, since the evidence at hand indicates that it serves as an indirect measure of the softening point and resistance to spalling.

8. Petrographic examination can generally be substituted for chemical analysis, especially if the softening point is determined.

9. The erosion test described will produce valuable results if the proper slag is used and if the test is continued for several hours.

10. The data indicate that refractories made by the dry-press process have the highest resistance to failure in laboratory tests.

Part II.—RESULT OF FIELD SURVEY

I. INTRODUCTION

As stated in the introduction to Part I, the field survey was made by Stone & Webster through the cooperation of E. B. Powell. The completed data comprised reports from 74 installations and furnished information on: The trade name of the refractory; year of purchase and average number purchased annually; the boiler type, rating, and load factor; the location of the brick in the setting (front wall, side wall, bridge wall, sprung arch, suspended arch); the type and relative per cent of failure (spalling, fusion, clinkering, erosion); the actual life in months for each location; the name, grade, analysis and B. t. u. value of the fuel; the ash analysis and fusion point; the type of stoker; the type of wall construction; the size of the special shapes used (if any); and the bonding material for the refractory.

The essential facts were condensed to the form shown in Table 11. In this table the brands are referred to both by the Bureau of Standards test number, if the brand in question was included in the work reported in Part I, and by the "case number" used by Stone & Webster. The tabulated data show the State in which the refractory was manufactured; the boiler rating and load factor; the actual life and mode of failure of the refractory in the several locations of the setting; the name, grade, and B. t. u. value of the fuel and its ash and sulphur content; the fusion point of the ash in degrees Fahrenheit; and the type of stoker employed.

II. RESULTS

1. CORRELATION OF SERVICE DATA

With the most carefully prepared field survey of the type under discussion there still remain many undeterminate factors which directly concern the life of the refractory and result in a large factor of error. The one most frequently mentioned is the effect of clinker removal from the side wall by means of the clinker bar. Worthy of mention also is the effect of the viscosity of the slag in the furnace and its chemical composition, which is not necessarily related to the composition of the fuel and the fusion point of the slag. The actual temperatures attained locally by the refractory setting are also unknown in practically every installation, due to the difficulty of determining them. The optical pyrometer, while highly efficient under favorable conditions, can not be depended upon where readings are made through flame or on surfaces reflecting light from other sources. Fluctuations in temperature, dependent upon the construction and operation of the installation, also materially affect the life of the refractory and, in addition, the personal factor introduced by the

plant official who describes the action of the brick in technical terms has an important bearing on the nature of the information which is obtained. In most instances it would be difficult, indeed, to say with any accuracy what percentages of the wall or arch had been removed, respectively, by fusion, erosion, and spalling, and what per cent had been removed from the wall by the fireman when breaking away clinker.¹

After a consideration of these facts it is obvious that information of value can be obtained only through a generalization of a large amount of detailed information such as is presented in Table 11. To do this it was determined to consider as failures only those instances in which the actual life of the refractory was less than one year and

FIG. 18.—Relation of type of failure as encountered in boiler settings to the type of stoker used and the location of the failure in the setting

the relative per cent of any one type of failure equalled or exceeded 50 per cent.

To facilitate comparison and study, the values obtained by this method are presented graphically in Figure 18. In the five vertical columns are plotted the failures occurring, respectively, in the sprung arch, the suspended arch, the side wall, bridge wall, and front wall. Each column is further divided to show the number of failures for each location occurring in a boiler fired by means of an underfeed stoker, chain grate, or by an unrecorded means. Horizontally the columns are divided into four sections, the designations on the left

¹ The reader is referred to the "Proceedings of the Electric Furnace Association," Oct. 6, 1920, for a further discussion of factors affecting the life of refractories in stoker furnaces.

TABLE II.—*Extract of more important data from field survey of boiler refractories made by Stone & White*

showing the cause of failure, while the numbers on the right are the number of failures reported in the field survey. As previously stated, a failure was defined as that instance in which the actual life of the refractory was less than one year and could be assigned to some one predominating cause.

The total failures (fig. 18) number 86, divided as follows:

Sprung arch.....	15	Erosion.....	39	Chain grate.....	49
Suspended arch.....	15	Clinkering.....	13	Underfeed.....	19
Side wall.....	29	Fusion.....	6	Unrecorded.....	18
Bridge wall.....	25	Spalling.....	28		
Front wall.....	2				
Total.....	86	Total.....	86	Total.....	86

Of the total failures 57 per cent occurred when using the chain grate and approximately 45 per cent were caused by erosion, while, as the data show, there were slightly more failures in the side wall than in any other one location.

It is evident that in the construction of a sprung arch material should be used which is primarily resistant to erosion, since nearly all of the failures are due to this cause. It is essential, therefore, that the refractory be dense to prevent the molten ash from penetrating to some depth and dissolving the less refractory bond (which in many cases has already been converted partly to glass by the action of the heat), and in this way permitting the structure of the brick to be destroyed and washed away by the slag. This density of structure must be attained at the expense of the resistance to spalling, but the latter quality is not of primary importance, since the individual brick, by the very nature of the construction, are held in place and continue to function after they have been ruptured.

In the suspended or flat arch the conditions are materially altered. The end of a brick which has broken off is no longer held in place by the neighboring brick, but is free to drop. The predominant quality of a refractory for the suspended type of arch construction is, then, a high resistance to spalling. This is verified by the results of the field survey, which show that of the 15 cases of failure in the suspended arch 12 were assigned to spalling.

The data obtained from the reported conditions of side and bridge walls are very similar. In both locations practically half of the reports indicate failure through erosion, a few through fusion (although erosion was probably meant), and the balance are equally divided between clinkering and spalling. Here, again, failures through spalling are not so noticeable, since the brick will be held in place if it is broken off at an appreciable depth from the surface and can not be told from erosion if the face breaks away a little at a time. In any case, it is evident that the refractory must be pri-

marily resistant to the action of heat. Fifty-two per cent of the installations were unsatisfactory because the brick fused or eroded and fusion must undeniably facilitate erosion. This large percentage of failures by erosion indicated the desirability of the laboratory test (which is described in Part I) for the determination of resistance of refractories to this type of failure.

Of the 74 installations from which data were obtained 23 reported the use of the underfeed stoker and 24 the use of the chain grate. However, from the data given in Figure 18, it can be shown that 72 per cent of the failures, where the type of stoker is known, occurred with the use of the chain grate. This is to be expected as regards

FIG. 19.—Showing relation of life of refractory in service to type of failure

the arch failures, since an arch is rarely used in connection with the underfeed stoker, but that the majority of failures in the side walls occurred where the chain grate is used is not so easily explained. In this connection it should be borne in mind that only one factor has been taken into consideration, and that is the life of the brickwork. If the chain grate burns the fuel more efficiently and produces higher temperatures, the refractory must be improved to meet this condition or make way for other types of construction. It is also possible that the design of the setting is at fault, in which case a problem of interest and importance is presented to the engineer specializing in the design of boilers and boiler settings.

The results shown in Figure 19 further indicate that brick with an actual life of two years or less failed by either spalling or erosion

in the side wall. With one exception (No. 9, fig. 19) there were no cases where a refractory lining lasted longer than 24 months when the cause of failure could be definitely assigned to spalling. It will be noted that the boiler rating had no apparent effect on either the life of the refractory or the type of failure.

2. CORRELATION OF SERVICE AND LABORATORY DATA

To facilitate the comparison of service rendered with results as obtained in the laboratory, the essential data on every installation where information from both sources is available were compiled as shown in Table 12. An exhaustive study of these data failed to bring out any consistent relationship. The many factors introduced by variations in boiler rating, load factor, draft, fuel, clinker removal, and interpretation of the service results seem to preclude any possibility of comparing refractories on the basis of actual life rendered unless the brands are observed in the same boiler setting, or at least in a plant where the fuel and the methods of operation are similar within practical limitations.²

An investigation carried out under conditions as suggested should produce information invaluable to every individual and concern interested in the production and use of better fire-clay refractories.

² A series of plant observations and laboratory tests, conducted in a large industrial establishment requiring the production of steam power, resulted in the elimination of all but four of a number of brands of refractories. It should be noted that the four brands in question are included in the first 10 as shown in Figure 17.

TABLE 12.—Data obtained by Stone & Webster (on boiler settings in which refractories tested in the laboratory were used), together with the data obtained in the laboratory on these brands

Laboratory number	Case number	Boiler rating	Load factor	Life in months	Location of failure	Type of failure *				Softening point, in cones	Quenchings to produce failure	Analysis		
						Spalling	Fusion	Clinkering	Erosion			Al ₂ O ₃	SiO ₂	Fe ₂ O ₃
4	56	190		5	Side wall					30	2	Per cent 19.04	Per cent 79.85	Per cent 1.20
8	30	165	70	48	do.		100			30	5	20.10	77.88	1.40
8	28	175	165	60	Sprung arch			4		30	5	20.10	77.88	1.40
8	29	140	60	84	do.			50		30	5	20.10	77.88	1.40
8	30	165	70	60	do.					30	5	20.10	77.88	1.40
9	58	130	62	7	Bridge wall; side wall	6			100	30-31	14	43.56	54.28	1.24
9	58	130	62	18	Suspended arch		30			30-31	14	43.56	54.28	1.24
9	57	160	51	9.8	Sprung arch		10			30-31	14	43.56	54.28	1.24
9	60	150	50	6	do.	20	40			30-31	14	43.56	54.28	1.24
11	34	150	37.5	24	Side wall			80		30-31	15	20.42	77.77	.96
11	34	150	37.5	8.5	Sprung arch	20				30-31	15	20.42	77.77	.96
12	6	165	70	24	Side wall	60	25			32	15	34.89	61.36	1.72
12	12	165	70	12	Sprung arch	80	20			32	15	34.89	61.36	1.72
13	59	165	70	.5	Bridge wall; side wall					32-33	18	41.22	55.44	1.52
13	59	165	70	.5	do.		100			32-33	18	41.22	55.44	1.52
14	74	180		48	Side wall					32	12	35.41	61.14	1.48
14	74	180		8	Suspended arch					32	12	35.41	61.14	1.48
17	53	125	100	180	Side wall					30-31	6	26.28	71.53	2.08
17	53	125	100	60	Sprung arch	25	50	25		30-31	6	26.28	71.53	2.08
18	44	135		14	do.					33	15	43.24	53.38	2.40
20	46	135	30	60	Bridge wall; side wall			86	15	32-33	3	43.95	51.23	2.80
23	75	140	75	18	do.	50	35			33	34	48.05	48.22	1.80
24	22	150	50	12	Side wall		25	75		32-33	18	33.25	57.44	2.04
24	21	180	65	1.25	Suspended arch					32-33	18	33.25	57.44	2.04
24	22	150	50	18	Sprung arch	50	50			32-33	18	33.25	57.44	2.04
26	40	130	70	14	Side wall			20	70	33	30	40.40	57.86	2.40
27	1	160	48	2.4	do.			10		33	39	44.85	51.65	1.80
27	1	160	48	.6	Sprung arch	10				33	39	44.85	51.65	1.80
30	4		40	24	Bridge wall; side wall	10	45	30		26	1	24.15	71.88	2.40
30	4		40	12	Sprung arch	15	85			26	1	24.15	71.88	2.40
32	72	130	52	3	Side wall			10		32	6	41.01	56.30	2.44

33	7	250	24.5	72	do.	---	---	---	100	32-33	15	31.94	65.25	1.72
33	7	250	24.5	72	Bridge wall	---	---	---	100	32-33	15	31.94	65.25	1.72
34	73	135	65	54	Bridge wall, side wall	---	---	---	100	27-28	5	29.8	67.20	2.12
34	73	135	65	5	Suspended arch	---	---	---	---	27-28	5	29.8	67.20	2.12
35	43½	---	---	5	Side wall	100	---	---	---	29-30	4	34.29	61.55	2.88
35	45	---	---	18	Sprung arch	25	25	---	25	29-30	4	34.29	61.55	2.88
37	50	160	51	3	Side wall	---	---	---	90	30	2	38.77	56.17	2.00
37	50	160	51	7.4	Sprung arch	10	10	---	80	30	2	38.77	56.17	2.00
37	50	160	51	---	Suspended arch	60	10	---	40	30	2	38.77	56.17	2.00
38	37	180	76	12	Bridge wall, side wall	50	15	---	10	33	59	37.73	58.79	1.96
39	11	160	70	18	Side wall	---	---	---	---	33	19	41.89	53.86	1.88
39	18½	190	95	18	Suspended arch	100	---	---	---	33	19	41.89	53.86	1.88
39	11	160	70	24	Sprung arch	---	---	---	---	33	19	41.89	53.86	1.88
40	41	205	71	24	Side wall	5	5	---	---	28	2	41.20	51.19	2.64
40	41	205	71	12	Suspended arch	10	5	---	85	28	2	41.20	51.19	2.64
40	42	205	71	4.7	Sprung arch	10	10	---	80	28	2	41.20	51.19	2.64
41	9	150	50	36	Side wall	40	20	---	---	29	3	36.89	57.41	2.28
42	10	---	71	2.1	do.	---	---	---	90	30	4	41.70	51.90	2.44
42	10	---	71	---	Suspended arch	60	10	---	40	30	4	41.70	51.90	2.44
42	10	---	71	4.5	Sprung arch	10	10	---	80	30	4	41.70	51.90	2.44

Part III.—SUMMARY

Following a conference of Government representatives and users and producers of fire-clay refractories, held at the Bureau of Standards, refractories of 42 commercial brands representative of the product as manufactured in the United States were obtained for laboratory testing through the cooperation of Stone & Webster. A report of a field survey was also obtained through the same cooperation.

In the laboratory the refractories were subjected (1) to an endurance test in which brick were held at $1,450^{\circ}$ C. for 72 hours, both transversely loaded and placed on end without load; (2) to a reheating test in which the change in length and porosity was noted after having held the brick at $1,400^{\circ}$ C. for five hours; (3) to a quenching test in which specimens from each brand, which had previously been reheated at $1,400^{\circ}$ C. for five hours, were alternately subjected to heat in a furnace door, held at a specified temperature, and plunged into running water (the furnace temperatures used were $1,350$, $1,100$, and 850° C.); (4) to the standard A. S. T. M. load test and to modifications of this test; (5) the softening points were determined according to the standard A. S. T. M. method; (6) brick of each brand were analyzed chemically; (7) several were examined petrographically after various heat treatments; and (8) four were subjected to an erosion test.

Although the field survey did not include reports on all of the brands tested in the laboratory, it is a valuable source of information regarding the service rendered by a representative group of refractories. The data contain the following information: Year refractories were purchased and number purchased annually; the boiler type, rating, and load factor; the location of the brick in the setting (front wall, bridge wall, side wall, sprung arch, suspended arch); the type and relative per cent of failure (spalling, fusion, erosion, clinkering); the actual life of the refractory in months for each location; the name, grade, composition, and calorific value of the fuel used; the composition of the ash and its fusion point; the type of stoker; the type of wall construction; the size of the special shapes used, if any; and the bonding material for the refractory.

There is no apparent relation between laboratory and service results, since no two brands were subjected to the same conditions, and the desirability of placing various refractories in service in the same boiler setting (or under conditions which are known to be similar within practical limitations) for comparison and study is thereby evidenced.

The field survey furnished interesting information in itself, and the results obtained show that (1) refractories in the suspended

arch fail principally through spalling; (2) that in every other location in the setting the failures are due mainly to erosion; (3) that conditions in the side and bridge walls are very similar; (4) that walls lasting two years or longer show high resistance to spalling; and (5) the results indicate an abnormal number of failures in connection with the use of the chain grate, but it should be borne in mind that only the life of the refractory has been considered, and that this type of stoker may burn the fuel more economically (producing higher temperatures), or that the setting is not suited to conditions under which it is operated.

The results of the laboratory work (see fig. 17, Part I) seem to justify the following conclusions: (1) While the endurance test furnishes results of interest and value, the data obtained are no better than those derived by simpler methods and do not justify the greater difficulty and cost of the test; (2) the constant-volume test, as a preliminary step to quenching, provides valuable absorption data which have a bearing on the resistance of the brick to spalling; (3) the quenching test, using 850° C. as the furnace temperature, is an excellent means for judging comparative resistance to thermal shock and appears to have a direct bearing on the general value of a refractory as a boiler lining; (4) the field survey has shown that a large majority of failures are due to fusion and erosion, and the softening point of a refractory is therefore of primary importance. While refractoriness is not necessarily a measure of resistance to slag action, it is reasonable to assume that a brick relatively free from fluxing agents will be more resistant than one which contains a network of vitrified and glassy material produced by heat and the impurities inherent to the clays; (5) while the load test does not classify high heat-duty refractories it justifies itself as a means for determining whether or not an aluminous refractory is sufficiently well burned to resist a considerable load when that load is applied during the initial heating of the installation; (6) the tests favor brick made by the dry-press process; (7) the chemical composition has an important bearing on the resistance of a refractory to spalling, as well as on the softening point; and (8) the evidence obtained indicates that information obtained by means of the petrographic microscope assists greatly in judging refractories and encourages the increasing use of this method of test.

WASHINGTON, September 19, 1924.