Thermal Conductivity of Castable Refractories in Relation to Bulk Density

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Thermal conductivity measurements of castable refractories of widely different compositions and densities confirm that conductivity is related to bulk density. General equations have been derived by digital computer which allow prediction of thermal conductivity from the bulk density of the dried castables.

REFRACTORY CASTABLES, mostly based on grain aggregates of alumina-silica compositions, have developed widespread use in a great variety of industrial furnaces. With few exceptions the bonding constituents are calcium aluminate cements; these are available in several composition ranges. With various methods of installation, industry has at its disposal versatile materials that can be used for repairs or incorporated in original designs.

Reliable data on physical properties are necessary for applications under exacting conditions, but the situation is complicated by the diversity of both composition and installation methods.

In the present study of thermal conductivity of castable refractories it was possible to relate this property closely to bulk density of the dried product. The thermal conductivity of castables is a function of product thermal history and bulk density. This has previously been discussed in publications by Hansen and Livovich,[1] Ruh and Renkey,[2] Wygant and Crowley,[3] Bohling and Stanford[4] and Modern Refractory Practice.[5] We have here extended and studied in greater detail the generalization of product density as related to thermal conductivity.

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Description of Materials

Twenty-five commercially available castables were selected for thermal conductivity tests: twenty-one alumina-silica including high alumina and insulating castables, and four chrome based castables. Properties of these mixes are listed in Tables I, II and III. Of the chrome castables, mix *Y* was chemically bonded and mixes *V*, *W* and *X* were hydraulically bonded with calcium aluminate cements. Specimens were cast in 9 by $4^1/_2$ by $2^1/_2$ in. molds as described in ASTM designation C 268-65T. After curing 24 hr at 75°F in covered molds, the test specimens were removed and dried 18 hr at 230°F. Bulk density was then determined prior to testing in the thermal conductivity equipment.

Test Equipment

Measurments were made on the ASTM C 201-47 thermal conductivity equipment. This apparatus is a guarded calorimeter-furnace unit which is generally accepted to yield data with ±5% precision. Heat conducted from the furnace through the test specimen is quantitatively determined by a 3 by 3 in. test calorimeter.

Test Procedure

For refractory castables it is now generally agreed that tests on dried unfired specimens after heat treatment in the ASTM apparatus represent the proper method of obtaining thermal conductivity data for use in engineering design. By this method the castables are heated from one face only

Table I. Insulating Castable Properties and Test Results

Symbol:	*A*	*B*	*C*	*D*	*E*	*F* Extra strength type	*G*	*H*
Max service temp, °F:	1000	2000	2200	2200	2600	2300	2800	3300
Approx Al_2O_3 content, %:	9	40	32	37	53	34	51	90
Bulk density, pcf after drying at 230°F:	29	34	52	57	52	84	87	93

Thermal conductivity, *k* (Btu hr^{-1} ft^{-2} °F^{-1} in.)

°F	K	°F	K	°F	K	°F	K	°F	K	°F	K	°F	K	°F	K
173	0 85	249	1.61	399	2.80	400	1 68	275	2.72	395	3.24	426	4.17	**510**	**6.63**
280	0 86	370	1 44	801	2.21	783	1 78	435	2.10	868	2.90	916	3.42	**1216**	**4.90**
337	0 93	458	1.32	1280	1 80	1255	1 72	531	1.73	1400	2.67	1449	3.79	**1778**	**5.07**
478	0 96	657	1 37	1102	1.72	953	1.61	868	1.90	1198	2.63	1140	3.59	**1414**	**5.09**
559	1 00	1020	1.36	915	1 64	706	1.50	1131	1.73	933	2.54	830	3.37	**1048**	**5.40**
635	1 01	1374	1 48	610	1 56	469	1 42	1441	1 92	607	2 49	536	3.23	**686**	**5.90**
804	1 06	1063	1 31	304	1 50			1922	2 19	290	2 30	236	2.98	310	**6.97**
859	1 05	802	1 23					1503	1.92						
1098	1 14	698	1 21					1141	1.77						
		536	1 17					845	1.61						
		264	1 01					595	1.51						
								335	1 37						

resulting in the establishment of a temperature gradient through the castable as is the case in most industrial applications. Figure 1, mostly from Ruh and Renkey,[2] shows an example of different results obtained from the various methods of heat treatment.

It is clear from these curves that a significant difference in thermal conductivity occurs if the specimens are preheated to temperatures high enough to form ceramic bonding. In the work presented here, thermal conductivity measurements were taken both on heating and cooling after reaching equilibrium at a number of temperatures. The hot faces of the test specimens were heated to a maximum of 100°F below the recommended maximum service temperature of the castable or to 2500°F, whichever was lower.

Test Results

Results of these measurements are listed in Tables I, II and III. For their further study the data were plotted on large scale graphs. From these graphs thermal conductivity values were taken at 500°, 1000°, 1500° and 2000°F along the cooling curve and at 300° and 600°F along the initial heating curve. These data for 20 alumina-silica castables were then analyzed

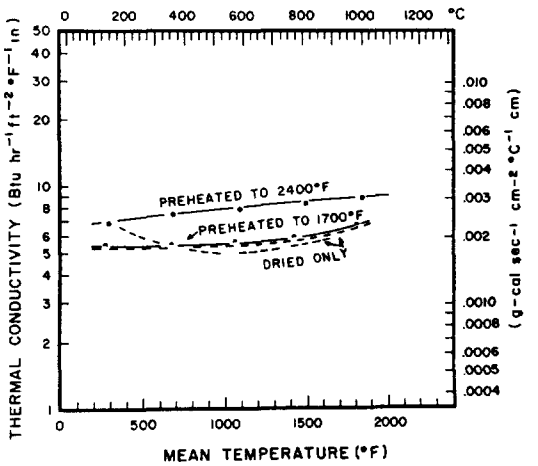

Fig. 1. Thermal conductivity of extra-strength type fireclay castable after various heat treatments.

Table II. Alumina-Silica and High Alumina-Castable Properties and Test Results

Symbol:	*I*	*J*	*K*	*L*	*M*	*N*	*O*
Type of castable:	High alumina	Extra high alumina	Extra high alumina abrasion resistant	Fireclay	Fireclay	Fireclay extra strength type	Fireclay extra strength coarse
Max service temp, °F:	3100	3200	3200	1000	2500	2400	2400
Approx Al_2O_3 content, %:	62	94	93	34	40	40	41
Bulk density, pcf after drying at 230°F:	140	159	160	126	123	129	140

Thermal conductivity, *k* (Btu hr^{-1} ft^{-2}°F^{-1} in.)

°F	K	°F	K	°F	K	°F	K	°F	K	°F	K	°F	K
458	10 8	437	21.8	563	13 3	279	8.08	489	5.89	300	7.12	495	9 42
1137	7 56	1173	9.73	1159	11.1	399	7.63	1063	5.15	912	5.50	998	8.53
1735	8.16	1744	9 74	1814	10 4	557	7.40	1646	5 77	1784	6.25	1663	8.03
1358	7.58	1360	10 0	1435	10 8	465	7.37	1360	5.70	1426	6.15	1435	8.13
990	8.00	980	10.9	1034	11 5	364	7.03	1002	5.54	1056	6.01	1049	8.04
626	8 02	622	11.7	637	13 0	261	7.24	642	5 50	681	5.91	660	8.03
283	8.00	269	13.1	274	13.3			292	5.13	306	5.50	293	7.95

Symbol:	*P*	*Q*	*R*	*S*	*T*	*U*
Type of castable:	Fireclay extra strength Low iron	Fireclay	Fireclay abrasion resistant	Fireclay	Fireclay	Fireclay coarse
Max service temp, °F:	2600	2700	2800	2800	2800	2800
Approx. Al_2O_3 content, %:	46	44	55	46	44	44
Bulk density, pcf after drying at 230°F:	127	125	142	129	129	135

Thermal conductivity, *k* (Btu hr^{-1} ft^{-2}°F^{-1} in.)

°F	K	°F	K	°F	K	°F	K	°F	K	°F	K
492	7.85	527	6 44	473	11.8	524	8.86	263	10.95	513	9.54
1064	6.11	1183	6 25	1192	9.3	1167	6.18	564	8.34	1163	7.32
1719	6 86	1754	6.93	1794	10 0	1768	7.02	1012	6.12	1749	7.92
1362	6.80	1388	6.72	1405	10.1	1391	7.00	1370	6.18	1394	7.87
1010	6.66	1015	6 44	1021	10.1	1019	6 70	1747	6.78	1029	7.60
645	6.61	647	6.38	636	10.3	650	6.70	1384	6 64	655	7.53
268	6.46	286	6 33	276	10.4	293	6.57	1025	6 43	298	7.75
						1761	7 16	651	6 38		
								287	6.18		

Table III. Chrome Castable Properties and Test Results

Symbol:	*V*		*W*		*X*		*Y*	
Type of castable:	Chrome high strength		Chrome 2600		Chrome abrasion resistant		Chrome chemically bonded	
Max service temp, °F:	2600				2600		3000	
Bulk density, pcf after drying at 230°F:	166		170		176		174	
Thermal conductivity, *k* (Btu hr^{-1} ft^{-2} °F^{-1} in.)	°F	*K*	°F	*K*	°F	*K*	°F	*K*
	555	7.49	464	8.84	497	11.4	548	9.41
	1125	6.30	1163	6.53	1215	9.70	1202	8.97
	1819	6.66	1789	7.06	1870	9.85	1800	9.06
	1458	6.82	1436	7.10	1500	10.2	1448	9.22
	1092	6.90	1066	7.14	1092	10.7	1063	9.50
	699	6.87	687	7.22	689	11.4	664	9.89
	310	6.56	304	6.87	298	11.1	286	9.81

by a least squares regression routine on a digital computer* to obtain the relation of dried bulk density to thermal conductivity. Based on the degree of fit of the higher order equations generated, it was seen that the third order equations adequately generalized the data. These equations are shown in Table IV. In Fig. 2 the equations from the measurements made on cooling are plotted. The four lower curves represent a generalization of all such measurements made at this laboratory on alumina-silica and high alumina castables with the single exception of mix *H*, a 3300°F insulating castable containing electrically fused bubble alumina (see Table II). This accounts for a higher conductivity than that of ordinary alumina-silica castables of equal bulk density. The other alumina-silica mixes tested, however, showed exceptionally good agreement with the computed curve. The average coefficient of variation of these curves was 6.4%. It is perhaps interesting to note that all of the alumina-silica curves passed through a common point at 137 pcf. This has a dual significance; namely, this is the density at which the slopes of the conductivity-temperature curves change from positive to negative and also, that an alumina-silica castable with this density would be predicted to have a thermal conductivity that is constant with temperature. The chrome curves shown in Fig. 2 will be discussed later.

In instances where castables are to be used at temperatures so far below their recommended service temperatures that appreciable hydraulic bonding remains, the data and equations obtained from measurements made on cooling, and shown in Fig. 2, do not apply. For this situation the data obtained on heating were considered. The thermal conductivity values at 300° and 600°F from the heating curves were analyzed by computer. Equations which resulted from this analysis are shown in Table IV and plotted in Fig. 3 along with the 500°F cooling curve from Fig. 2. It is apparent that with very low service temperatures, the remaining hydraulic bond causes appreciable elevation of the conductivity-density function. In addition, due to the variable nature of the hydraulic bond we are not able to predict conductivity based on bulk density with as great an accuracy as we could had the refractory been heated to a higher temperature.

Mixes *V*, *W*, *X* and *Y* were chrome based castables and consisted of hydraulically bonded as well as chemically bonded materials. Although it is clear that additional data are called for to properly analyze a conductivity-density relation it was decided to see if a reasonable curve would result from computer analysis. For this purpose the data taken at various

* Honeywell 120 digital computer, Honeywell Inc.

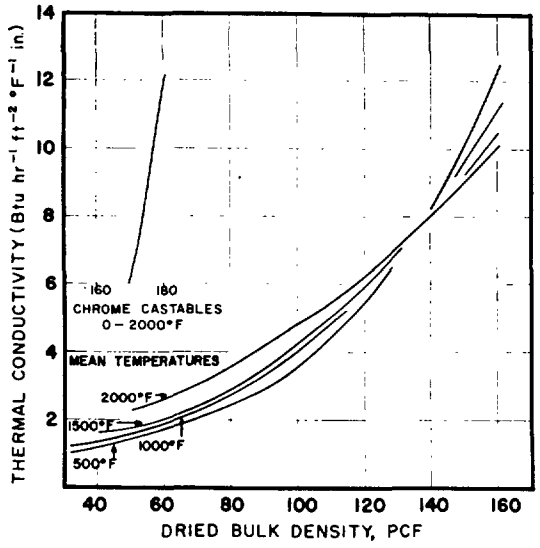

Fig. 2. Thermal conductivity vs. bulk density of dried castables for various mean temperatures. (Data was derived from cooling curves.)

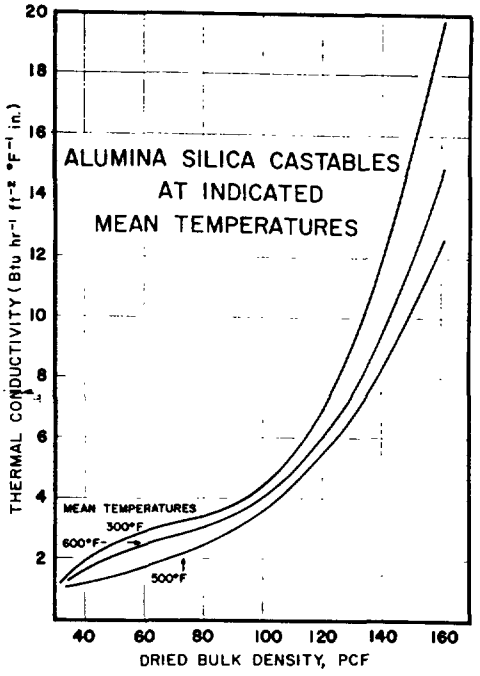

Fig. 3. Thermal conductivity vs. bulk density of dried castables for various mean temperatures with heating curve data compared with 500°F cooling curve.

Table IV. Equations for Deriving Thermal Conductivity from Bulk Density of Dried Alumina-Silica and Chrome Castables

General equations:

For alumina-silica castables: $K = Ad^3 + Bd^2 + Cd + D$, Third order equation

For chrome castables: $K = A'd^2 + B'd + C'$, Second order equation

where K = Thermal conductivity, Btu/ft² hr °F/in.

d = Bulk density, pcf

A, A', B, B', C, C', and D = Constants

Constants at various temperatures	A $\times 10^{-6}$	B $\times 10^{-4}$	C $\times 10^{-2}$	D	Coefficient of variation (%)
On cooling					
500°F	+5.569	−7.572	+5.870	−0.280	7.5
1000°F	+1.858	+0.831	+0.369	+0.955	7.1
1500°F	−0.859	+7.642	−5.015	+2.455	5.7
2000°F	+0.171	+2.891	+0.496	+1.242	5.4
On initial heating					
300°F	+21.62	−45.23	+33.73	−5.720	25.0
600°F	+11.91	−23.83	+18.72	−2.805	12.7
	A' $\times 10^{-3}$	B'	C'		
On cooling					
0° to 2000°F	+5.201	−1.385	+92.911		6.7
On initial heating					
0° to 1000°F	+2.109	−0.3843	+12.927		14.1

temperatures were averaged and a single analysis performed for both initial heating and cooling measurements. From a comparison of coefficients of variation, the second order formulas obtained from this analysis appear to be reasonable. These two formulas are shown in Table IV and the formula from the data taken on cooling plotted in Fig. 2.

Summary

Thermal conductivity measurements on 21 alumina-silica and four chrome castables have been presented. These data were generalized into formulas that can be used to predict thermal conductivity from the bulk density of dried castables. These formulas apply within the density range tested, namely, from 29 to 160 pcf for the alumina-silica castables and from 166 to 176 pcf for the chrome castables.

Bulk densities on dried rather than burned castables were used in this study for two reasons: (1) these values will be easier to obtain in the field and (2) exact duplication of the thermal history experienced by the specimens measured in this study would be difficult.

Other monolithic materials such as ramming and plastic mixes would not necessarily be expected to show agreement with the curves for castables presented in this paper. Although some measurements have been made on these materials, no relation has yet been established except that the data for plastic refractories seem to fall somewhat below those for castables.

Acknowledgment

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References

[1] W. C. Hansen and A. F. Livovich, "Thermal Conductivity of Refractory Insulating Concrete," *J. Am. Ceram. Soc.*, **36** [11] 356–62 (1953).

[2] Edwin Ruh and A. L. Renkey, "Thermal Conductivity of Refractory Castables," *ibid.*, **46** [2] 89–92 (1963).

[3] J. F. Wygant and M. S. Crowley, "Effects of High-Conductivity Gases on the Thermal Conductivity of Insulating Refractory Concrete," *ibid.*, 41 [5] 183–88 (1958).

[4] W. C. Bohling and J. C. Stanford, "Relationship of Thermal Conductivity Versus Bulk Density of Alumina-Silica Castables"; presented at the 65th Annual Meeting, The American Ceramic Society, Pittsburgh, Pa., May 1, 1963 (Refractories Division, No. 26-R-63); for abstract see *Am. Ceram. Soc. Bull.*, **42** [4] 243 (1963).

[5] Modern Refractory Practice, 4th ed.; pp. 323–24. Harbison-Walker Refractories Company, Pittsburgh, Pa., 1961. ☆

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3 14 - 1

B&W DENSE CASTABLES

AVERAGE PROPERTIES

Attached are average properties released by the B&W Technical Development Laboratory covering B&W Dense Castables.

This property sheet should be used in conjunction with Product Information Sheet 3 14 - 4 which covers the Factors Effecting the Use of Castable Refractories.

Supersedes 3 14 - 1 dated August 30, 1972

B&W DENSE CASTABLES

AVERAGE PROPERTIES

		Kaocrete A & A-BF	Kaocrete B	Kaocrete D	Kaocrete 28-LI	Kaocast	Kaocrete 30	Kaocrete 32-C	Kaocrete 32-G	Kao-Tab	Kao-Tab CS	Kaocrete HS (As Cast)	Kaocrete HS (As Gunned)	Kaogun BF (As Gunned)	Kao-Tuff C	Kao-Tuff G	Kao-Phos 30	Basic Gun Mix P (As Gunned)
Recommended Methods of Application (X):																		
Cast or Rammed		X	X	X	X	X	X	X	Rammed Limited Repairs	X	X	X	X	X	X	–	Rammed	Rammed
Troweled		–	X	–	X	–	X	–	X	X	X	X	X	X	–	X	X	X
Gunned		X	X	–	X	X	–	–	X	X	–	X	X	X	–	X	X	X
Lbs. Req'd. to Place One Cu. Ft.		126	100	128	126	123	135	144	135**	150	165	123	126**	128**	138	130**	170	152**
*Required Water, U.S. Qts. Per Bag																		
Vibrating		6.5-7	12-13	6.5-7	6.5-7	5.5-6.5	6.0-6.5	4.5-5.0	–	5.5-6	4-4.5	6-6.5	–	6.5-7	4-4.5	–	–	–
Casting and Rodding		7-7.5	13-13.5	7-7.5	7-7.5	6.5-7	6.0-6.5	4.5-5.0	–	6-6.5	4.5-5	6.5-7	–	7-7.5	4.5-5	–	–	1.25
Ramming		3-4	5-6	3-4	3-4	3-4	3-4	3-4	–	2-3	2-3	3-4	–	3-4	2-3	–	1.25-1.5	3-4
Recommended Use Limit, °F		2300	2300	2500	2800	3000	3000	3200	3200	3300	3300	2600	2600	2800	2400	2400	3000	2800
Melting Point, °F		2760	2725	2725	3100	3200	3200	3400	3400	3400	3400	3100	3100	3135	3000	3000	3800	3425
Density, Lbs./Cu. Ft. Fired		128	100	129	126	126	135	146	136	152	166	122	124	128	134	138	174	152
Modulus of Rupture, PSI (ASTM C 268-70)																		
Dried 18 to 24 Hrs. ●	220F	1000	400	1200	900	900	800	800	550	1700	1850	1300	1400	1300	1600	1200	2400	400
Cured 24 Hrs. ●	450F	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	400
Fired 5 Hrs. ●	1000F	550	350	600	600	350	600	–	–	1100	1400	850	950	650	1600	1200	2000	250
	1500F	180	160	600	400	250	500	–	–	900	1000	700	900	550	1600	1200	1800	250
	1750F	–	–	–	–	–	–	500	400	–	–	–	–	–	–	–	–	–
	2000F	140	140	320	300	270	400	–	–	700	1200	700	900	500	1100	980	2300	400
	2200F	1000	240	700	450	300	500	–	–	700	900	900	1100	900	1600	1200	–	–
	2400F	–	–	1200	600	550	850	750	650	700	900	–	–	1200	2000	1400	–	–
	2500F	–	–	–	–	–	–	–	–	–	–	1400	1600	–	–	–	–	700
	2600F	–	–	–	1500	1200	1000	–	–	700	1000	–	–	1800	–	–	–	–
	2800F	–	–	–	2000	1400	1200	–	–	800	1200	–	–	2150	–	–	–	600
	3000F	–	–	–	–	1400	1200	1700	1600	1200	1400	–	–	–	–	–	2900	800
	3200F	–	–	–	–	–	–	3800	2600	1600	1800	–	–	–	–	–	–	–
Cold Crushing Strength, PSI (Per ASTM C 133-55)																		
Dried 18 to 24 Hrs. ●	220F	2500	1400	4000	3000	2100	4000	3600	1800	6000	6000	4200	5500	4000	6600	3000	5300	1800
Cured 24 Hrs. ●	450F	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1800
Fired 5 Hrs. ●	1000F	1500	700	2200	2400	1200	3300	–	–	3100	5600	4000	4800	2100	6000	3000	5800	1400
	1500F	500	700	1950	2000	1000	3000	–	–	2900	5200	2800	4400	1800	6000	4200	4700	900
	1750F	–	–	–	–	–	–	3000	1600	–	–	–	–	–	–	–	–	–
	2000F	400	300	1500	1400	1100	2000	–	–	2300	5000	2800	3200	1200	6000	3800	6000	1200
	2200F	1500	450	2700	1400	1200	2200	–	–	1850	4400	2800	3400	1800	8500	4600	–	–
	2400F	–	–	3600	1800	1400	4200	2800	1600	1900	4500	–	–	1800	8700	6000	–	–
	2500F	–	–	–	–	–	–	–	–	–	–	3200	4000	–	–	–	–	1400
	2600F	–	–	–	3200	3000	4500	–	–	1950	4800	–	–	4800	–	–	–	–
	2800F	–	–	–	4000	3800	4800	–	–	2800	5000	–	–	5500	–	–	–	1000
	3000F	–	–	–	–	4200	5000	5500	3200	2800	5200	–	–	–	–	–	6800	1500
	3200F	–	–	–	–	–	–	6000	4200	3000	5600	–	–	–	–	–	–	–
Permanent Linear Change, % (ASTM C 269-70)																		
Dried 24 Hrs. ●	220F	0.0	0.0	0.0	0.0	0.0	0.0	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.2	–0.2
Cured 24 Hrs. ●	450F	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–0.2
Fired 5 Hrs. ●	1000F	–0.1	–0.5	–0.1	–0.1	–0.2	–0.2	–	–	–0.2	–0.2	–0.2	–0.2	–0.2	–0.1	–0.1	–0.2	–0.2
	1500F	–0.1	–1.2	–0.1	–0.2	–0.2	–0.2	–	–	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.3
	1750F	–	–	–	–	–	–	–0.2	–0.2	–	–	–	–	–	–	–	–	–
	2000F	–0.2	–1.5	–0.2	–0.2	–0.3	–0.2	–	–	–0.2	–0.2	–0.3	–0.3	–0.3	–0.1	–0.2	–0.3	–0.3
	2200F	–0.2	–1.8	–0.2	–0.2	–0.3	–0.2	–	–	–0.3	–0.3	–0.2	–0.2	–0.3	–0.2	–0.2	–	–
	2400F	–	–	–0.3	+0.1	–0.3	–0.3	–0.4	–0.4	–0.3	–0.3	–	–	+0.3	–	–	–	–
	2500F	–	–	–	–	–	–	–	–	–	–	+0.2	+0.2	–	–1.4	–1.4	–	–0.6
	2600F	–	–	–	+1.0	–0.3	–0.3	–	–	–0.5	–0.5	–	–	+1.3	–	–	–	–
	2800F	–	–	–	+0.2	–0.3	–0.2	–	–	–0.8	–0.8	–	–	+0.3	–	–	–	–0.8
	3000F	–	–	–	–	+0.2	+1.2	+0.2	–0.2	–0.6	–0.3	–	–	–	–	–	–1.5	–2.0
	3200F	–	–	–	–	–	–	+1.2	+1.2	–0.2	–0.2	–	–	–	–	–	–	–
Porosity, %, Fired		28	42	30	31	32	–	–	–	32	–	29	–	27	–	–	–	–
Chemical Analysis, %, Fired	Basis (ASTM C 573-70)																	
Alumina	Al_2O_3	40	38	44	49	60	60	70	70	93	96	46	46	48	59	56	93	1.7
Silica	SiO_2	47	46	39	42	33	33	26	26	0.5	0.1	40	40	40	33	36	0.2	2.0
Ferric Oxide	Fe_2O_3	1.6	1.3	5.4	0.9	1.0	0.8	0.9	0.9	0.1	0.1	1.0	1.0	1.4	0.8	0.6	0.1	0.3
Titanium Oxide	TiO_2	1.4	1.3	1.7	2.4	1.9	2.2	1.8	1.8	0.1	Trace	2.0	2.0	3.0	1.3	1.4	0.2	–
Calcium Oxide	CaO	9.8	12.1	10.2	6.0	3.4	2.8	2.4	2.4	6.0	4.8	10.2	10.2	7.1	5.5	5.5	0.7	0.9
Magnesium Oxide	MgO	0.5	0.9	Trace	–	0.1	0.2	0.1	0.1	Trace	Trace	0.2	0.2	0.1	0.2	0.2	–	91
Alkalies, As	Na_2O	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.3	0.3	Trace	0.3	0.4	0.1	0.8
Boron Oxide	B_2O_3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.3
Phosphorus Penta-Oxide	P_2O_5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5.8	2.3
Thermal Conductivity (ASTM C 417-60) BTU, In./Hr. $Ft.^2$ °F		6.2	4.6	7.2	6.8	6.7	7.4	9.0	8.0	9.1	13.1	7.0	7.1	7.2	7.9	7.4	9.0	26.0
*Pounds Per Bag		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	50	100

**Without Rebound Loss

Data are average results of tests conducted under standard procedures with cast samples except as otherwise noted and are subject to variation. Results should not be used for specification purposes.

CURING REFRACTORY CASTABLES:

IT ISN'T THE HEAT, IT'S THE HUMIDITY

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RESEARCH AND DEVELOPMENT DEPARTMENT

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Research and Development Department, American Oil Company, Whiting, Indiana

ABSTRACT

Curing methods for refractory concretes placed at low water content were studied. Curing was done (1) in a damp room; (2) by water-spraying; (3) with saturated steam; and (4) by the application of impermeable surface membranes. Internal temperature rise caused by hydration of aluminous cements does not impair strength. The only requirement for satisfactory curing is the retention of moisture within the concrete. Properly selected organic resin or asphalt membrane coatings are economical and superior in performance to water-spray curing, provided they have low water-vapor permeability, adhere to moist refractory concrete, rapidly form films and dry, and are free from deleterious substances. Curing with membrane coatings has been used successfully for eight years in large-scale refinery operations.

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INTRODUCTION

The traditional method of curing troweled or pneumatically-placed refractory castables is frequent spraying with water from about 6 hours after placement to about 24 hours after placement. It is the only method generally recommended by refractories manufacturers. This procedure is costly and sometimes unreliable. Laborers must be employed for several consecutive shifts to do the spraying. Scaffolding cannot be removed, and vessels or furnaces cannot be closed up, until the spraying ends. In many locations the castable is inaccessible for repeated spraying. A less costly and more reliable curing method was desired.

The exclusive use of water spraying has been justified on two bases. One is the need to keep the exposed surface of the castable damp, so that moisture will be available continuously for the hydration of the cement. This need for moisture has been confirmed (1). The other basis rests on the beliefs that temperatures much above 90°F during hydration cause low strengths, and that the cooling effect of the water spray prevents temperature rise in the castable during hydration. The former belief was reinforced by the work of Hansen and Livovich (2), in which castable

(1) Venable, C.R., "Erosion Resistance of Ceramic Materials for Refinery Applications", Bull. Amer. Ceram. Soc., 38 (7) 363-368 (1959).

(2) Hansen, W. C., and Livovich, A. F., "Factors Influencing the Physical Properties of Refractory Concretes", Bull. Amer. Ceram. Soc., 34 (9) 298-304 (1955).

refractory materials were preheated, mixed, and cured at temperatures from 50°F to 110°F. They found reduced strengths after curing at 100°F and 110°F, and interpreted them to show that curing temperatures above 90°F caused loss of strength. Unfortunately, their water: cement ratio, held constant up to 90°F, was increased at 100°F and again at 110°F to retain constant slump. The consequent reduction of strength could have been caused by the increased water: cement ratio rather than by the increased curing temperatures.

However, in field installations, Cook et al. (3) observed no detrimental effect when castable temperatures were allowed to rise due to retained heat of hydration of the cement.

Most types of aluminous cements have high heats of hydration. It appeared reasonable, in view of Venable's work (1), that strengths would be reduced if the retained heat of hydration caused substantial drying of a castable. The evidence was not convincing that elevated temperature by itself was harmful, if drying could be prevented. This investigation had two purposes: to determine whether temperatures caused by heat of hydration were harmful when drying was prevented; and, if not, to develop simplified curing methods.

EXPERIMENTAL

The temperature rise, due to the heat of hydration, was measured by placing thermocouples in a freshly-molded castable. Slab specimens were

(3) a. Cook, M.D., Cook, C.P., and King, D.F., "Pneumatic Placement of Refractory Castables", Paper No. 9-R-62, Amer. Ceram. Soc. 64th Annual Mtg., New York, May 1, 1962.

b. Cook, M.D., "Pneumatic Placement of Refractory Castables, Part 2", Paper No. 4-R-62F, Amer. Ceram. Soc. Refr. Div. Fall Mtg., Bedford Springs, Pa., October 5, 1962.

formed by tamping the castable in molds at a stiff plastic consistency. Two slabs were made, 12 in. by 12 in. by 3 in., representative in thickness of many refinery applications. The castable was a high-strength commercial product containing about 25 wt.% aluminous cement and 75 wt.% calcined flint clay. Its density after heating at 1000°F was 128 to 130 lb/cu ft. The molds were insulated on five sides with 2 in. of polystyrene foam, leaving a 12 in. by 12 in. face exposed. One slab was cured in a damp room, at about 96% relative humidity and 80°F. The other was cured in the open at 50% relative humidity and 75°F, the exposed face being coated with a 1/16 in. layer of asphalt mastic. Another slab of the same material, 18 in. by 18 in. by 8 in., was insulated similarly and cured under a 1/16 in. layer of asphalt mastic. The mastic was a high-viscosity dispersion of asphalt and mineral pigments in a hydrocarbon solvent, sold as a vapor barrier coating.

To obtain a yet larger temperature rise, an 18 in. cube was molded of a 60 lb/cu ft insulating castable. This castable contained about 50 wt.% pure calcium aluminate cement and 50 wt.% perlite. The exceptionally high heat of hydration of the cement, together with the low thermal conductivity and low volumetric heat capacity of the castable, was expected to cause very high temperatures during curing. The mold was insulated on all sides with 2 in. of polystyrene foam. Thermocouples were inserted as the castable was placed at plastic consistency. Compressive strengths were determined on 2 in. cubes cut from the large cube.

To confirm the results of these tests, and to evaluate steam curing and other types of organic membranes, thirteen additional series of tests were made. Each series included three to eight castable slabs made on a single day. The castable used in each series was mixed and split to yield uniform samples. Nominally equivalent high-strength castables from four manufacturers were used. Day-to-day variations in ambient temperatures, tap water temperatures, and humidity were unavoidable, and there was a practical limit on the number of slabs to be handled simultaneously. The series arrangement provided identical ambient conditions for all the specimens in a given series.

Water spray curing, simulating conventional practice, was done automatically in a cabinet equipped with spray heads, timers, and solenoid valves. Slabs, in their molds, were placed vertically in the cabinet within 30 min. after forming, and the door was closed to cause the relative humidity to build up. Spraying began 6 hours after forming. A 30 sec. spray period followed at 30 min. intervals for 18 hours.

Damp room curing, the usual standard laboratory methods, was done in a room at about 96% relative humidity and 80^{o}F. Specimens were placed in the damp room shortly after forming and left there for 24 hours.

Steam curing was accomplished by building a hollow cube of 12 in. by 12 in. concrete panels. The specimens in their molds constituted one or two sides, with their exposed faces inward. Corners were sealed, and exhaust

steam at 5 to 15 psi was introduced, beginning 2 to 4 hours after forming and continuing for the remainder of the 24 hours after forming. The exhaust steam was ordinarily saturated, but up to about $10^{o}F$ of superheat occurred occasionally.

Some specimens were cured in open laboratory air, at about $75^{o}F$ and 50% relative humidity, with no measurable air movement.

For membrane curing, organic films were applied to the exposed surfaces of some specimens. Molded slabs were cured in this way in the laboratory for 1 day, then were removed from the molds for drying. The same asphalt mastic used for the earlier temperature tests was applied to a number of slabs by troweling, about 1/16 in. thick, 30 to 60 min. after the concrete was placed.

Other membranes also were used. Molten paraffin was brushed on one slab. (Paraffin solutions proved impractical.) Four commercial concrete curing compounds, solutions of resins in hydrocarbon solvents, were applied by spraying. Two of the resin compounds contained red dyes, but no pigment. The other two contained white titania pigments. Two water emulsions of resins were applied by spraying. These were a styrene co-polymer and an alkyd resin emulsion, stabilized and pigmented in commercial coating products. Brief experiments, but no strength tests, were made with a water emulsion and a ketone dispersion of asphalt.

Several tests were made with membranes of a special asphalt cut-back, containing appropriate additives and fast drying solvents, developed for this use in cooperation with a vendor. In most of the tests, only 12 in. by 12 in. by 3 in. slabs were formed, either by tamping a plastic mix or by use of a Cement Gun Co. Size 00 cement gun. Tamping mixes were placed at a uniform stiff ball-in-hand consistency. Gunning was done so as to obtain the temporary water sheen recently described as indicating the optimum water content (4).

After curing, these slabs were cut into two 12 in. by 6 in. by 3 in. specimens, each of which was broken as a simple beam to determine modulus of rupture. To measure compressive strength, 2 in. cubes usually were cut from the broken halves and crushed. In a few cases 2 in. cubes were molded separately to determine compressive strength. In all tests, strengths were determined after 24 hours of curing, 1 to 3 days of air drying, and 24 hours at 220°F. In some tests, duplicate slabs were heated to 1000°F, after drying at 220°F, before testing.

RESULTS

Effects of Temperature

Table I shows the temperatures developed in 3 in. and 8 in. slabs of dense refractory concrete when the concrete was not cooled by spraying with water. By analogy with the 3 in. slabs, the internal temperature in

(4) Wygant, J. F., "Effects of Variables in Pneumatic Gun Operation on Refractory Castables", Paper No. 3-R-62F, Amer. Ceramic Society Refr. Div. Fall Meeting, Bedford Springs, Pennsylvania, October 5, 1962.

the 8 in. slab probably was about 165°F. The similarity between center and bottom face temperatures in the 3 in. slabs is evidence that heat loss from the insulated sides of the molds was insignificant. Each slab therefore was approximately the equivalent of a semi-infinite slab, twice as thick, with both surfaces exposed or with the back surface in contact with an uninsulated vessel shell. The temperature was slightly higher in the surface-sealed 3 in. slab than in the unsealed, probably because of the insulating effect of the asphalt mastic.

In Table II, Series 2, 6, and 7, direct comparisons can be made between 3 in. slabs cured by water spraying and slabs that were not water sprayed. The strengths with damp room curing generally about the same as those with water spray curing. Asphalt mastic membranes gave results similar to water spraying in Series 2 and 6; in Series 7 asphalt membranes were superior. The small cooling effect of water spraying at 30 min. intervals did not lead to increased strengths. In fact, temperatures in the membrane-cured slabs must have approached 120°F, from retained heat of hydration, but did not adversely affect strengths. Under most plant conditions, gunned or trowelled castables would have to be about 6 in. thick to reach this temperature during curing.

Effects of even higher temperature are shown in Table III. The temperature of the large insulating castable cube reached the atmospheric boiling point of water, and 18 hours after molding the cube was still steaming

vigorously. Because of the high absorption of the perlite, the initial water content was high and only a small part of the water was driven off. In spite of the high curing temperature, strength was considerably higher than usual.

Results with the 18 in. cube are confirmed by those with steam curing in Series 7, 8 and 9, Table II. The castable temperatures during steam curing must have approached 200°F. In these series, strengths of steam-cured slabs ranged from about 20% to 80% higher than with water spray or damp room curing. The variability probably was due to varying vapor-tightness of molds. Under favorable conditions, strength increased with curing at steam temperatures.

Elevated temperatures, even though achieved by external heating therefore appear harmless. They may even be helpful with respect to strength, if evaporation of significant amounts of water is prevented. In plant practice, insulating castable sections 18 in. thick (and probably thinner) can reach steam temperatures. The usual high-strength dense castables, in thicknesses of 8 to 16 in., would ordinarily reach temperatures not exceeding 165°F.

New Curing Methods

Strengths of eleven series of slabs cured by various methods are summarized in Table II. Direct comparisons are possible within each series, but different series cannot be compared directly because of differences in

materials and placement conditions. However, either damp room or water spray curing can be used as an internal standard, against which other methods in a series can be compared. Damp room and water spray curing gave similar results in Series 2, 6, and 7. In these three series, the averages of damp room and spray curing results were used as standards for comparison. In each of the other series, only one of these two methods was included, and it was used for comparison.

Table IV shows the percentile strength effects of other methods of curing compared with strengths from damp room and/or spray curing. Open air curing caused reductions of strength in most specimens. But steam curing caused increased strengths, except in Series 1, 2, and 3. The variable effects of steam curing in the first three curing cycles were traced to 5 to 10°F superheat in the steam. The use of unsaturated steam results in less than 100% relative humidity, and moisture evaporates rapidly from the wet refractory.

Asphalt mastic and paraffin wax membranes, with two exceptions, yielded strengths superior to, or statistically indistinguishable from, those resulting from damp room curing. These membranes contain thin spots and defects, permeable to water vapor, unless they are applied very carefully. Nevertheless, these tests showed the potentially excellent performance of impermeable membranes.

The ketone dispersion of asphalt (not shown in Table IV) showed no advantage over the asphalt mastic except the absence of low flash point solvents. Coatings of asphalt emulsion (not shown), and of alkyd and styrene

emulsions, are not sufficiently impermeable to water vapor. The high water vapor permeability of similarly formulated water-base paints is well known in paint technology.

The resin solution curing compounds gave uniformly good results. This was also true with the asphalt cutback curing compound, as shown in Tables II and IV, Series 11, and in Table V. The average results of all membrane curing tests were superior to those of damp room and/or spray curing. The results with resin solutions and the asphalt cutback in Series 10 and 11 average 21% higher than with spray curing.

The tests in Tables II and IV were completed in 1955; those in Table V in 1956. Hundreds of additional test slabs, made and cured with membranes since then, confirm the results shown here. A considerable number of 2 in. cubes and 2 in by 4 in. cylinders also were made during the same period, and cured by the use of membranes under the semi-adiabatic conditions recently described by Treffner and Williams (5). The temperatures reached were like those in Table I, and the strengths were normal.

PRACTICAL APPLICATIONS

Several petroleum refineries have been using membrane curing, with selected resin solution and asphalt cutback membranes, since early 1955. It has been eminently successful in curing refractory castable vessel linings and filler sections up to 12 in. thick. Hairline surface cracking, often observed

(5) Treffner, W. S., and Williams, R. M., "Heat Evolution Tests with Calcium Aluminate Binders and Castables", Paper No. 5-R-62F, Amer. Ceram. Soc. Refr. Div. Fall Meeting, Bedford Springs, Pa., October 5, 1962.

after water spray curing, usually is absent. Cured surfaces are notably hard. Lining service has been good. Substantial savings have been made by the elimination of two or three shifts of water spraying labor. Earlier start-ups are permitted by removal of scaffolding as soon as the membrane is applied. No special precautions are necessary in the initial heating cycle, and the membranes are not deleterious to refractories, metals, or catalysts when burned off.

The first requirement of a curing membrane is that it be nearly impermeable to water and water vapor. This can be judged according to ASTM Des. C309-58, "Liquid Membrane-Forming Compounds for Curing Concrete" and ASTM Des. C156-55T, "Water Retention Efficiency----", except that 24 hour water retention efficiency is a better index than 72 hour efficiency for the curing of aluminous cements.

Curing membranes preferably are applied within 30 min. after installation of the refractory. White pigmented compounds usually are used on dark castables made with iron-containing cements. Black asphaltic compounds are preferred when the castables contain white- low-iron cements. The contrasting membrane colors permit easy inspection for complete coverage. Hand sprayers of the garden tank type or conventional power paint sprayers are most convenient, but membranes can be applied with a soft full paint brush.

Membrane curing compounds should be selected with caution. Some drying oils, surfactants, inorganic salts, and other compounds cause soft surfaces or interfere with the setting of aluminous cements. Curing membranes often must be sufficiently viscous or thixotropic to form continuous films, preferably 0.010 to 0.015 in. thick, on vertical and overhead surfaces. The membrane materials must adhere to moist refractory surfaces. They should dry quickly--in 30 minutes, for example--to a tack-free condition, so that inadvertent contact with workers or tools will not cause damage. They should have good storage life.

The solvents are volatile hydrocarbons, and the safety precautions usual with paints are necessary. Severely toxic or dangerously combustible solvents should be avoided. Membrane compounds should be reasonable in cost. Suitable commercial materials range in cost from about $0.80 per gallon for the special asphalt cutback product to $2.25 per gallon for some white-pigmented resin solutions, or $0.01 to $0.02/sq ft of treated surface at about 100 sq ft/gallon coverage. This is insignificant compared to the labor cost of spray curing for three 8-hour shifts. The assured quality of curing and the early availability of the equipment for startup are additional advantages.

CONCLUSIONS

Moderately elevated curing temperatures, per se, do not cause reduced strengths in hydraulically-setting refractory castables. Either retained heat of hydration or external heating with saturated steam may be

TABLE I

TEMPERATURE RISE IN SLABS OF
REFRACTORY CONCRETE DURING HYDRATION

Curing Conditions	Slab Thickness, in.	Elapsed Time to		Max Temperature at:			Compressive Strength, psi after heating at 220F
		Initial Temp Rise	Maximum Temperature	Exposed Face	Center	Bottom Face	
No surface sealer; Damp room (a)	3	1-2 hr	7 hr	119 F	124 F	127 F	2830
Surface sealed with asphalt mastic, open air (b)	3	1-2 hr	6 hr	126 F	134 F	135 F	3530
Surface sealed with asphalt mastic, open air (b)	8	1-2 hr	7 hr	---	---	164 F	----

(a) 96-100% relative humidity, 80°F.

(b) 50% relative humidity, 77°F.

somewhat beneficial to strength, if escape of moisture is prevented. Curing with steam is risky, because slight superheating of the steam can cause drying and loss of strength.

The essential condition for good curing is maintenance of an adequate moisture content. In dense castables, placed with low water contents, it is necessary to prevent evaporation almost entirely. Curing by application of organic membranes, impermeable to water vapor, yields uniformly good results when the membrane curing compounds are carefully selected and applied. This practice has been proven by eight years of plant use.

TABLE II

EFFECTS OF CURING METHODS ON STRENGTHS OF REFRACTORY CONCRETES

Series	Refractory	Forming Method	Curing Method	Compressive strength, psi, after heating at 220 F	Compressive strength, psi, after heating at 1000 F	Modulus of Rupture, psi, after heating at 220 F	Modulus of Rupture, psi, after heating at 1000 F
1	A	Plastic tamped	Damp room	3320		670	
			Steam	3390		550	
			Asphalt Mastic	3630		530	
2	A	Plastic tamped	Damp room	4070	3730	790	430
			Water spray	4070	4000	530	410
			Steam	3660	3000	670	270
			Asphalt Mastic	4140	3290	710	430
3	A	Dry gun (d)	Damp room	8360		955	
			Steam	10120		770	
			Asphalt Mastic	7800		945	
4	B	Plastic tamped	Damp room	2770	3060		
			Open air	2320	2540		
			Asphalt Mastic	3030	3270		
			Paraffin wax	3060	2680		
5	B	Plastic tamped	Damp room	2830			
			Asphalt Mastic	3530			
6	B	Dry gun (d)	Damp room	7630		610	
			Open air	7090		540	
			Water spray	7170		670	
			Asphalt Mastic	7180		580	
7	B	Plastic tamped	Damp room	1960	1750	430	210
			Spray (1)	1860	1850	490	150
			(2)	1800	1760	400	100
			Steam (1)	3100	3260	610	270
			(2)	1920	2030	360	120
			Asphalt Mastic	2790	2470	480	270
8	C	Plastic tamped	Damp room	2920		660	
			Steam	4070		920	
			Asphalt Mastic	3730		610	
9	D	Plastic tamped	Damp room	3890		800	
			Steam	4700		920	
			Asphalt Mastic	4200		630	

TABLE III

NEAR-ADIABATIC CURING OF INSULATING REFRACTORY CONCRETE

Cube Size:	18 in. x 18 in. x 18 in.
Material:	60 lb/cu ft (100 F), perlite-IFB*-aluminous cement
Forms:	3/4 in. wood with 2 in. foamed polystyrene insulation on all sides
Consistency:	Spading
Thermocouples:	Center and top center
Temperatures:	210-230 F at center, reached 11-1/2 hr after pouring; 190 F at center, 167 F at top center, 19 hr after pouring
Compressive strengths, 220 F:	Blank:
	2 in. cubes, damp room cured in brass molds:
	Operator A (3 cubes) - 380 psi
	Operator B (3 cubes) - 349 psi
	2 in. cubes cut from 18 in. cube:
	adjacent to center (3 cubes) - 503 psi
	505 psi
	400 psi
	center of side (2 cubes) - 535 psi
	523 psi

*IFB = insulating fire brick

TABLE IV

PERCENTILE EFFECTS OF CURING METHODS ON STRENGTHS

Series	Curing Method	Compressive Strength, psi, after heating at: 220 F	1000 F	Modulus of Rupture, psi after heating at: 220 F	1000 F
1	Steam	+ 2		-12	
	Asphalt Mastic	+ 9		-21	
2	Steam	-10	-22	0	-36
	Asphalt Mastic	+ 2	-15	+ 1	0
3	Steam	+20		-19	
	Asphalt Mastic	- 7		- 1	
4	Open air	-16	-17		
	Asphalt Mastic	+ 9	+ 7		
	Paraffin Wax	+10	-12		
5	Asphalt Mastic	+24			
6	Open air	- 4		-15	
	Asphalt Mastic	- 4		9	
7	Steam	+27	+49	0	+16
	Asphalt Mastic	+47	+39	+ 1	+60
8	Steam	+36		+39	
	Asphalt Mastic	+28		- 8	
9	Steam	+21		+15	
	Asphalt Mastic	+ 8		-21	
10	Open air	-24		+12	
	Steam	+79		+ 7	
	Resin Solution A	+32		+38	
	Resin Solution B	+40		+45	
	Styrene Emulsion			-13	
	Alkyd Emulsion			-22	
11	Resin Solution C				
	Light Coat	0	- 5	+10	+12
	Heavy Coat	- 2	- 5	+13	+20
	Resin Solution D				
	Light Coat	- 1	- 3	+ 7	+ 4
	Heavy Coat	+20	+13	+13	+29
	Asphalt Cutback	+35	+16	+19	+65
Average Effects					
	Open Air	-15	-17	- 2	
	Steam	+25	+13	+ 4	-10
	Membranes (a)	+16	+ 4	+ 6	+27

(a) Excluding emulsions in Series 10.

TABLE II (Cont'd.)

Series	Refractory	Forming Method	Curing Method	Compressive strength, psi, after heating at 220F	Compressive strength, psi, after heating at 1000F	Modulus of Rupture, psi, after heating at 220F	Modulus of Rupture, psi, after heating at 1000F
10	B	Plastic tamped	Water spray	2690		550	
			Open air	2040		690	
			Steam	4160		590	
			Resin Solution A(a)				
			(1) vertical	3560		760	
			(2) horizontal	5590		830	
			Resin solution B(a)				
			vertical	3750		800	
			Styrene Emulsion	----		480	
			Alkyd Emulsion	----		430	
11	B	Dry gun (d)	Water spray	5100	5300	740	485
			Resin Solution C(a)				
			(1) Light coat (b)	5080	5010	812	542
			(2) Heavy coat (c)	4980	5050	839	581
			Resin Solution D(a)				
			(1) Light coat (b)	5040	5160	795	505
			(2) Heavy coat (c)	6120	5970	839	625
			Asphalt Cutback (c)	6880	6160	878	800

(a) Resin Solutions A and B were unpigmented commercial concrete curing compounds containing fugitive red dyes. C and D were commercial white-pigmented concrete curing compounds.

(b) Approximately 300 sq.ft./gal. coverage.

(c) Approximately 100 sq.ft./gal. coverage.

(d) Each value is the average of two slabs, and of four compression cubes and two moduli of rupture per slab.

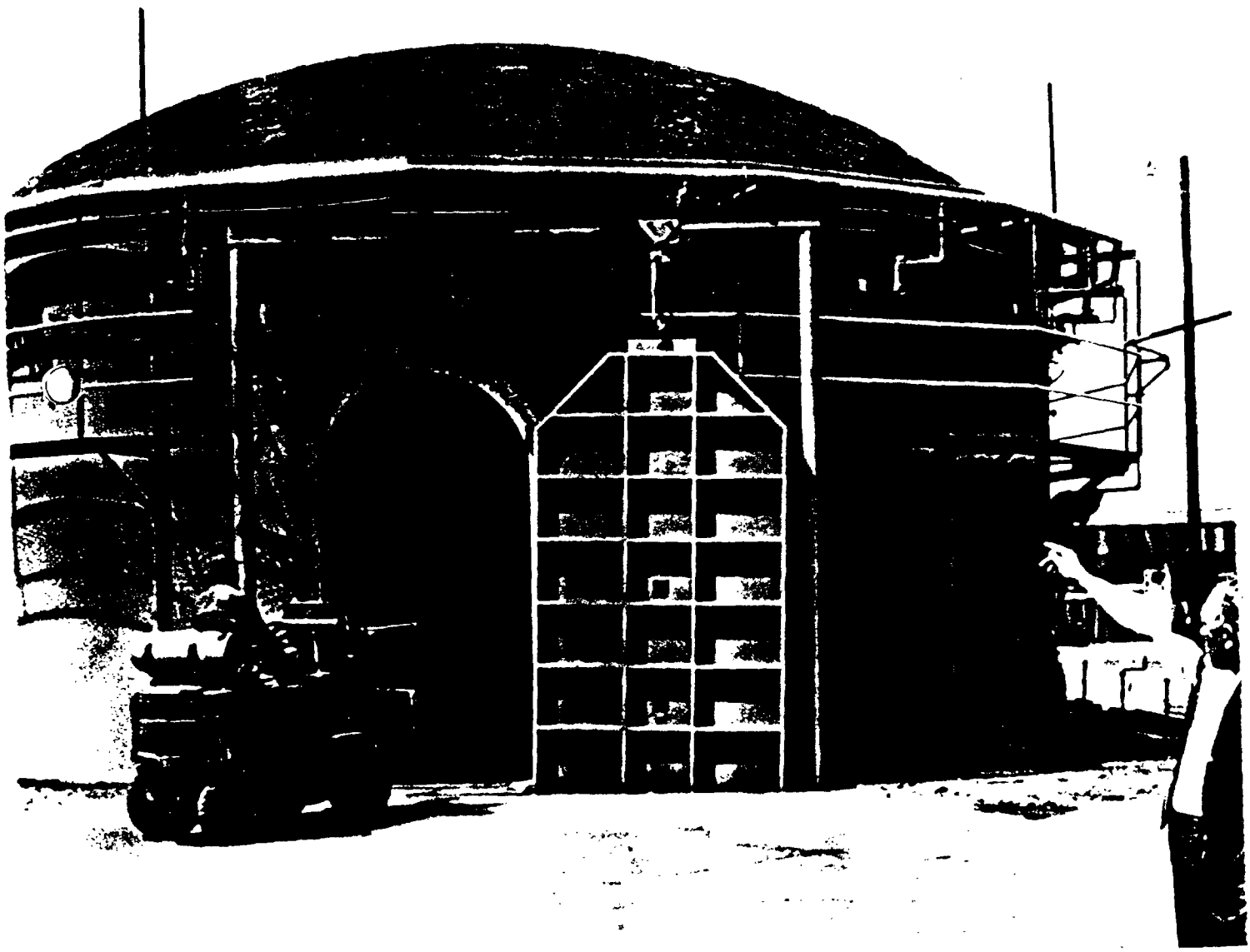
TABLE V

COMPARISON OF ASPHALT CUTBACK AND RESINOUR CURING MEMBRANES ON PNEUMATICALLY-APPLIED REFRACTORY CONCRETE (a)

Type of Cure	Compressive Strength, psi, after heating at 220 F	Compressive Strength, psi, after heating at 1000 F	Modulus of Rupture, psi, after heating at 220 F	Modulus of Rupture, psi, after heating at 1000 F
Series 12 - (1 slab each)				
Resin Solution D	5000	4400	937	837
Special Asphalt Cutback	5210	3890	682	607
Series 12 - (4 slabs each)(b)				
Resin Solution D	6610		1026	
Special Asphalt Cutback	6450		1098	
Series 14 - (4 slabs)(b)				
Special Asphalt Cutback	7780		1183	

(a) Applied at approx. 100 sq ft/gal coverage, or about 0.015 in. wet film thickness. Material was Refractory B of Table III.

(b) Gunned with new design water ring in nozzle.



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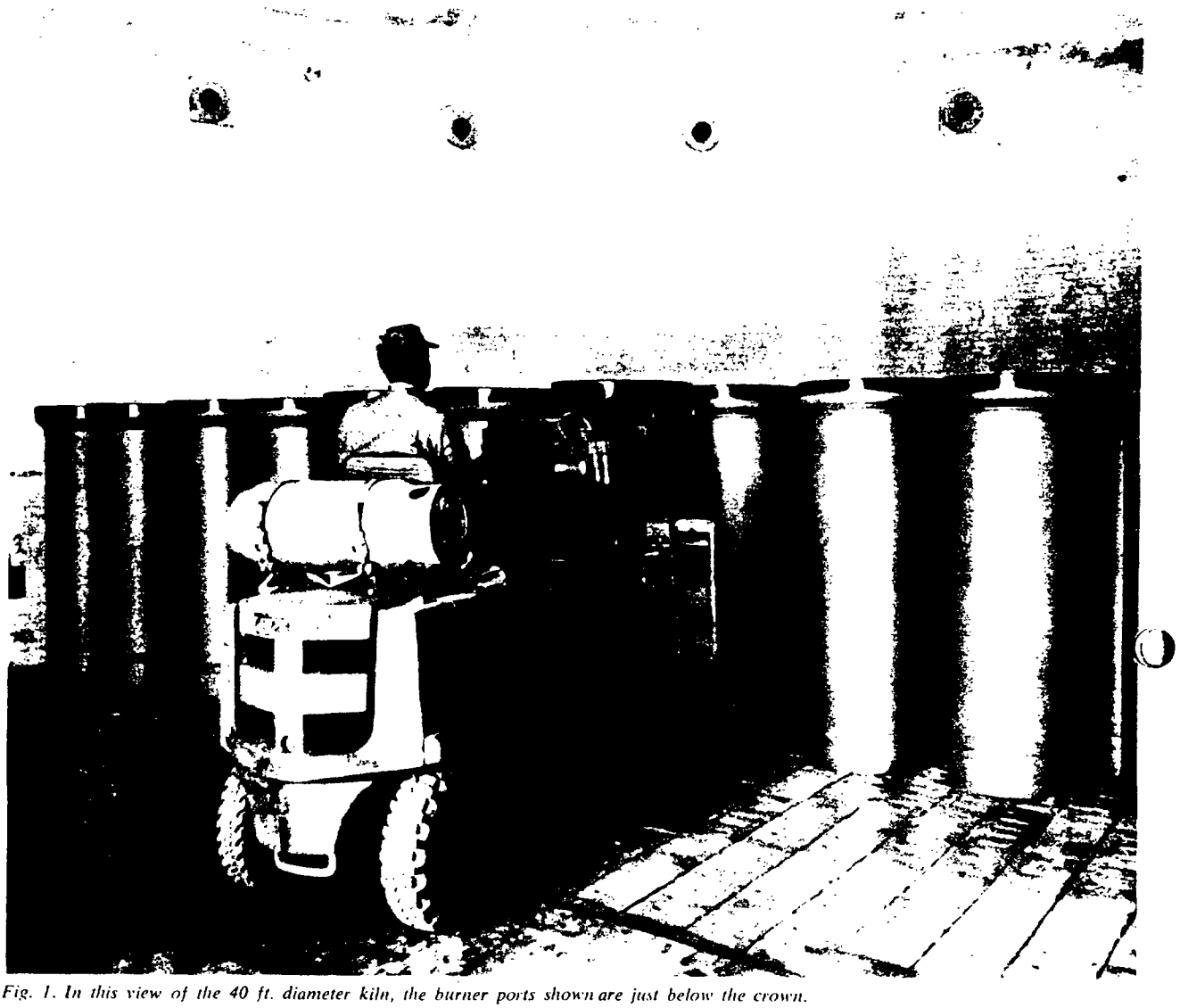


Fig. 1. In this view of the 40 ft. diameter kiln, the burner ports shown are just below the crown.

Unique kiln design can save up to 75% fuel costs

IFB construction saves time and money. Clay pipe fired two-high. Turn-over time up 60%.

By: LAWRENCE J. MIDKIFF, JR., *Production Mgr., Pomona Pipe Products Co. and* GORDON THOMAS, *District Sales Representative, Refractories Div., The Babcock & Wilcox Co.*

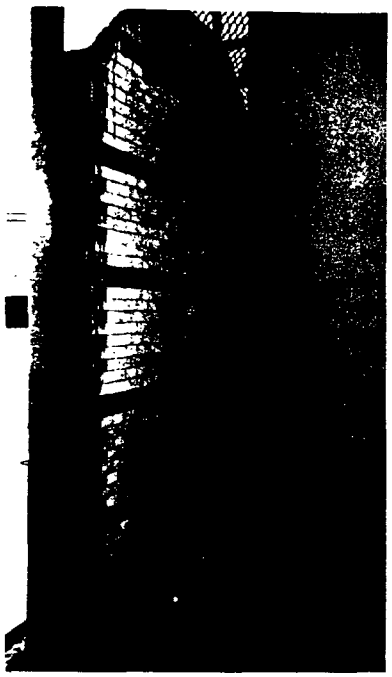


Fig. 2. The sliding door has the same IFB construction as the kiln.

In the past year, Pomona Pipe Products put in what is believed to be the largest periodic kiln in the country to fire structural clay sewer pipe, and they are about to start construction on a second insulating firebrick kiln of equal size.

In addition to its size and insulating firebrick construction, the kiln is unusual because it has a top-fired premixed, fuel burner system, and a flue system with individual damper controls. Because of these systems, Pomona has realized substantial savings in construction costs and construction time. Furthermore, the kiln has proven much more economical to operate than the thick-wall units, and has provided significant savings in ware recovery.

The thin-wall kiln cost exactly half as much as a thick-wall kiln required to produce equal ware. The thin-wall unit costs a total of $40,000 for all material, labor, and equipment. At Pomona a conventional thick-wall, heavy firebrick kiln, with equal ID, would have cost about the same. But the thin-wall unit has twice the capacity of the thick-wall unit because it can be set with ware two-high, whereas heavy duty firebrick kilns cannot, as will be explained later. Two of them, of course, would cost twice as much as one insulating firebrick kiln. Also, it would take one month longer to put up a single thick-wall kiln and four months longer to build two such kilns.

From an operational point of view, this thin-wall kiln, when compared with heavy firebrick units, saves more than 75% in fuel in some cases, and can be loaded in 60% less time. In addition to these economies, better control and efficiency of the thin-wall insulating firebrick kiln reduces loss of ware by 10 to 15%, and reduces each firing cycle by 10 hours. Basically, three main factors account for these advantages:

1. The insulating firebrick used in construction.
2. The burner system.
3. The flue control system.

Pomona's large diameter pipe was being produced in 30 heavy firebrick kilns. After a thorough investigation of the performance of other existing thin-wall kilns, there were enough facts to show the advantages of constructing a single thin-wall insulating firebrick kiln. For example, the proven slower heat transmission and lower heat storage of insulating firebrick meant faster heat-up and faster cooling. It could also be shown that periodic kilns of larger size kilns produce[1] greater quantities of ware per dollar of capital investment.

After careful consideration, Pomona gave the go-ahead for construction of the 40-ft. ID insulating firebrick periodic kiln with walls 17 ft. high as shown in Figure 3. The walls were lined with headers of 9-in. insulating firebrick recommended for service to 2000°F, backed up by a 1-in. layer of 1900°F block insulation and a ¼-in. plate of carbon steel for structural support. Although

[1] *E. J. Dickson "Kiln Designing advances using characteristics of Insulating Refractories" American Ceramic Society Bulletin, 46 (12) 1178-1181 (1967).*

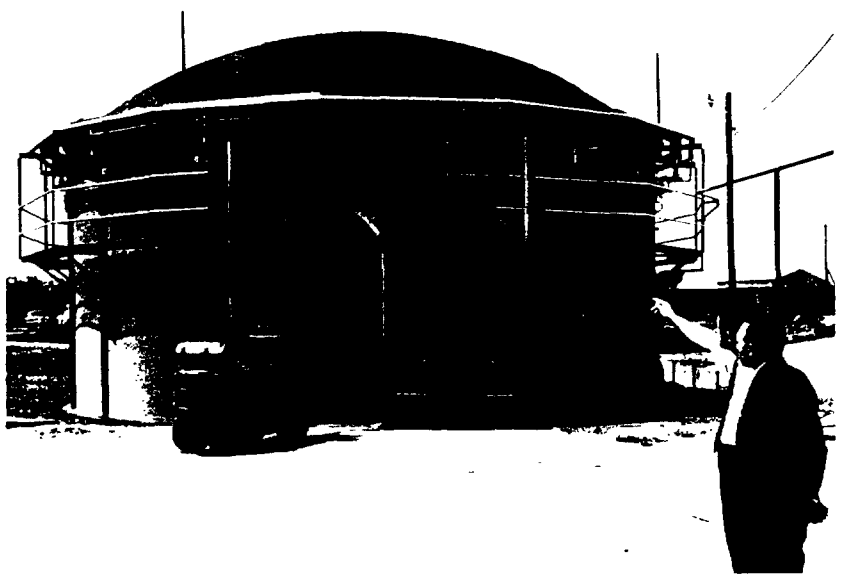


Fig. 3. This overall view of the kiln shows the clean lines of the shell and the burner system.

the cost of insulating firebrick is higher than that of firebrick, the total insulating firebrick cost was lower because fewer brick were required than for two thick-wall heavy firebrick units with the same ID. The thin-wall kiln used 50,000 insulating firebrick compared with 150,000 high duty brick that two thick-wall units would have required. At $220 per M, insulating firebrick cost $11,000. High duty firebrick, at only $150 to $160 per M, would have cost between $22,-500 and $24,000. The insulating firebrick kiln has a sliding door as shown in Figure 2 of the same thin-wall construction as the kiln itself. This simplifies operation, compared with the old way of bricking up and taking down the door opening with each firing.

The crown of the thin-wall kiln has a 2½-in. rise, one layer of insulating firebrick is coated on its top side with refractory paint to reduce gas permeability through the porous insulating firebrick. This is covered with 2 in. of 2000°F insulating castable, and a layer of coarse woven glass cloth, painted with an asbestos impregnated bitumastic compound.

In addition to savings in construction costs and time, insulating firebrick walls help reduce operating fuel costs because heat storage and heat loss are lower than that of dense firebrick as illustrated in Figure 4. The heat storage of the thin-wall kiln is less than 9% that of the conventional heavy wall construction. This is a major factor in reducing fuel consumption with insulating firebrick.

Also, a firebrick kiln loses additional heat through cracks in the lining, a constant problem with thick-wall construction. The thin-wall kiln's steel jacket prevents gas flow either in or out and thereby prevents heat loss through cracks.

Burner system precision set

Pomona's second major advance in kiln construction in the clay pipe industry was the installation of the burner system. This system shown in Figure 6 fires the kiln through 16 ports which are located 14 ft. 6 in. above grade, instead of the conventional ports 1-ft. above grade. The bottom ports in the thin-wall kiln are bricked up, having been installed before it was known that top-firing would work.

Pomona uses a wide-range burner premixing system to maintain a proper 10 to 1 air-gas ratio throughout the burning cycle. This is a high-pressure premix burner system which Pomona modified so that the kiln lights off on four burners, then goes to eight burners, and finally to all 16.

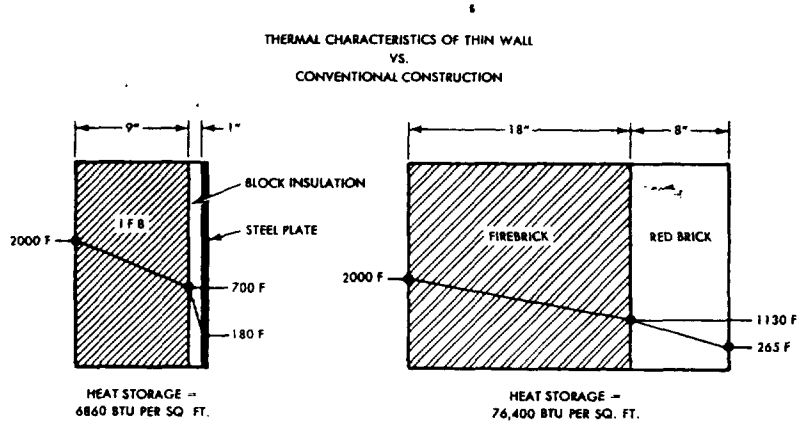


Fig. 4. This chart shows some of the advantages of the wall IFB constructions.

By top-firing, Pomona eliminated bag walls, which are necessary for bottom-firing kilns. Bag walls take up valuable setting space, add to construction costs, and cause many maintenance problems. Top-firing also eliminated the need for fire box arches and the maintenance problems that go with them. Figure 1 shows an interior view including burner locations and setting efficiency.

Combined with the kiln's unusual flue system, high pressure top-firing produces a complete change in the concept of heating periodic kilns. The pressure within the thin-wall kiln has proven to be sufficient for exhausting the kiln without either a stack or an exhaust fan. This eliminates the need for the exhaust stacks required for most other periodic units. Such stacks are usually either 40 to 50 ft. units that create a draft to draw heat through the kiln, or 17 ft. units with induced-draft fans. Not sure that top-firing would create sufficient positive pressure, Pomona had a 17 ft. exhaust stack constructed and illustrated in Figure 5 when the kiln was built, but the induced-draft fan has never been installed. The new thin-wall kiln now being constructed does not have a stack, only a gas collection exit placed 6 ft. above grade to protect personnel.

Flue system provides efficiencies

The flue system in the thin-wall kiln is a key factor in the efficiency of the heating system. It is a system with several control points and, along with the kiln's burner system, size, and insulating firebrick construction provide efficiencies not previously approached by any periodic kiln.

The two main benefits of the flue system are:

1. It controls the pressure differential between the skew line at the top and the bottom of the kiln.
2. It exerts greater control over the amount and distribution of heat in the kiln.

When the insulating firebrick kiln is at 2000°F. the crown is 40 de-

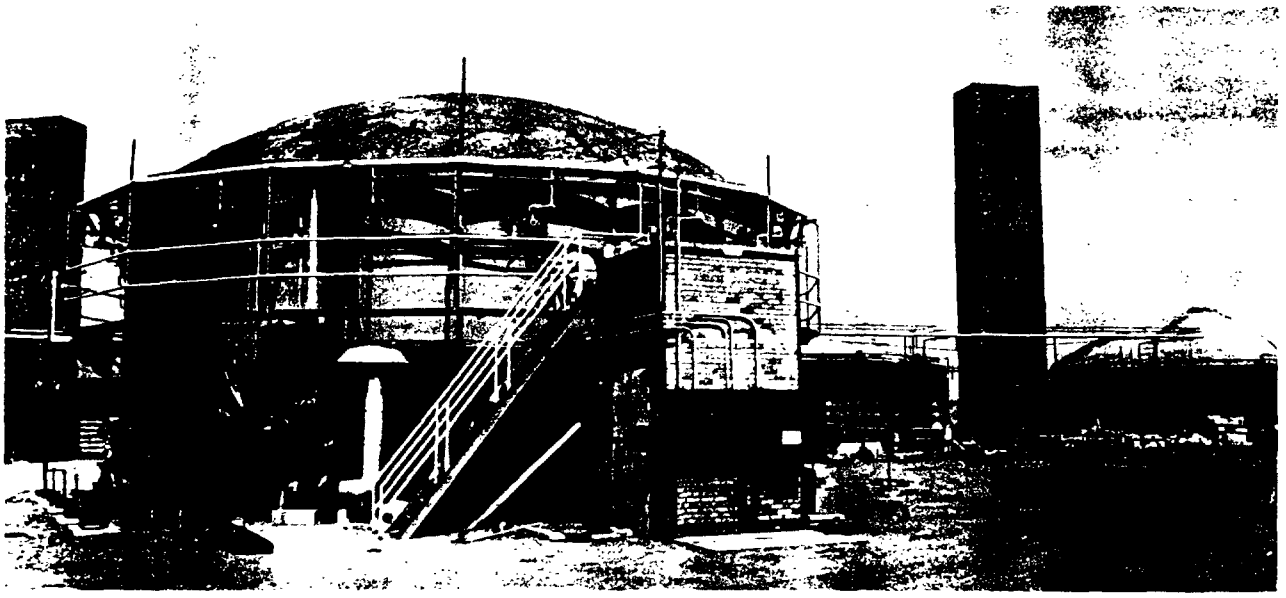


Fig. 5. The stack and service walkway are shown in this view from the back of the kiln.

". . . Quick turnover & high recovery are kiln features . . ."

grees cooler than the side walls 12-ft. above grade. The crown of a thick-wall kiln, by comparison, is 400°F *hotter* than the walls 12-ft. above grade during its early burning cycle, and 75°F to 100°F hotter when the kiln reaches maturing temperature of 2000°F.

The new kiln also shows a remarkable vertical temperature uniformity in the ware measured by chromel-alumel thermocouples. At the end of the burn, the temperature is 2000°F at the top of the ware and 1980°F at the bottom or a difference of only 20°. In a thick-wall heavy firebrick kiln the difference between top and bottom is approximately 70°F with a setting only half as high.

Controls in the flues permit close regulation of the amount and direction of heat going through the system. Each damper can be completely opened, completely closed, or adjusted to any intermediate point.

With these controls and this flue system, the kiln is never significantly hotter at the skew line than at the bottom of the ware.

Firing ware two-high is successful

As a result of these tight controls over heating, Pomona can set sewer pipe two-high in the kiln and thereby double the kiln's capacity. Increasing the capacity results in greater fuel economy. Since the controls reduce dimensional variation, a greater percentage of saleable ware can be recovered.

At one time it was common at Pomona to fire ware two-high in thick-wall heavy firebrick kilns. But as specifications for ware became tighter, this practice became extremely impractical. When the pipe was set two-high, it was extremely difficult to obtain correct shrinkage on the bottom pipe without over burning the top pipe. This caused high losses of saleable ware. To increase its recovery rate, Pomona turned to firing ware only one-high.

But in the new thin-wall insulating firebrick kiln, because of the close control of heating, ware can be successfully fired two-high.

Pipes from 12 to 18 in. ID cannot be set two-high because the dry strength of their thin-cross section is not sufficient to support the top load; but Pomona fires 5 ft. pipes with ID's from 21 to 36 in. two-high to obtain the increased efficiencies such setting makes possible.

Firing two-high in the thin-wall, Pomona recovers 85 to 90% of saleable ware. This compares with a 60% recovery firing two-high in a thick-wall kiln of equal ID. The insulating firebrick kiln, while firing two-high, reduces ware losses 10 to 15% below the heavy firebrick unit with only one-high. This is accomplished while contending with the inherent higher ware load pressures associated with higher settings.

Loading the kiln for two-high setting is much more economical than for one-high setting. Most loading time, in either case, is spent placing and leveling the setting rings. It takes very little more time to set the ware in two layers. Pomona cuts loading time 60% by setting pipe two-high.

Firing cycle 6½ days

The firing cycle in this thin-wall insulating firebrick periodic kiln runs about six and a half days from light to light.

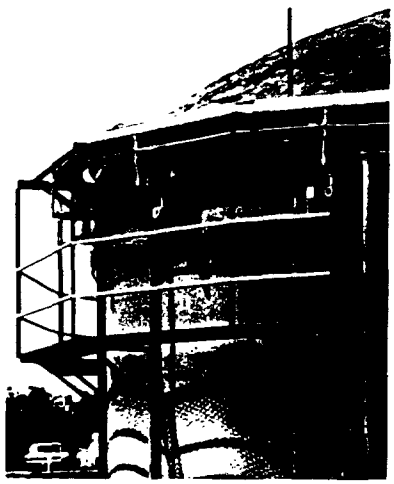


Fig. 6. This closeup view of the high pressure premix burner system.

First, the ware is set two-high. After light-off, kiln temperature is raised to 2000°F during an 85 hour period using the top-fired burner system. During the heat-up period the flue system can control differences in temperature, from one side of the kiln to the other or from top to bottom. The dampers are adjusted to regulate heat flow and to equalize temperatures throughout the kiln.

Fuel economies realized

Perhaps the greatest economies of the thin-wall insulating firebrick kiln are in savings on fuel. Because fuel efficiency increases as tonnage increases, setting ware two-high increases kiln tonnage and, therefore, fuel efficiency. A larger kiln, with even greater tonnage, would yield greater efficiency. Other ways to accelerate fuel efficiency as exemplified by the Pomona kiln are reduction of heat loss through insulating firebrick walls, and elimination of heat loss caused by wall cracking.

In controlled tests, Pomona determined the fuel consumption rates of an insulating firebrick kiln and a heavy firebrick kiln, each with a 40 ft. ID and firing to 2000°F, as charted in Figure 7.

The insulating firebrick kiln, loaded with 148 tons of 30 in. clay pipe set two-high, consumed 3730 cu. ft. of gas per ton of ware. The heavy firebrick kiln, loaded with 72 tons of 30 in. ware set one-high, used 12,000 cu. ft. of gas per ton of ware, more than three times as much fuel per ton.

The best fuel efficiency was obtained with 24 in. pipe because the greatest tonnage of that size pipe could be loaded into the kiln. With the 24 in. pipe set two-high, the insulating firebrick kiln held 174 tons of ware and consumed 3000 cu. ft. of gas per ton. In the heavy firebrick kiln, 84 tons of 24 in. pipe set one-high consumed 12,800 cu. ft. of gas per ton, more than four times the rate of the insulating firebrick kiln.

Of course, the greater capacity of the insulating firebrick kiln is a significant factor in achieving these fuel savings, but it is not the only factor. Even when firing equal tonnage, the overall efficiency of the insulating firebrick kiln results in lower fuel comsumption.

Pomona fired its 12 in. and 18 in. pipe one-high in each kiln. Firing 70 tons of 12 in. pipe, the insulating firebrick kiln consumed 4300 cu. ft. of gas per ton of ware. The thick-wall kiln used up almost twice that amount—8000 cu. ft. per ton.

Firing 80 tons of 18 in. pipe required 3750 cu. ft. of gas per ton in the insulating firebrick kiln and 9000 cu. ft., more than twice as much, in the thick-wall kiln.

After reaching maturing temperature, the kiln is cooled to ambient temperature. Because temperature variation between the top and bottom of the ware varies by no more than 20°F, it is not necessary to have a soaking period at the end of the burn to equalize temperature, as is required for the heavier kiln. The 155 hours for the complete cycle is 10 hours less than with a thick-wall kiln. This time is gained in reaching the maturing temperature.

Summary

With the thin-wall kiln at Pomona the following results have been realized:

1. Lower capital expenditure per ton of ware.
2. Lower gas consumption per ton of ware.
3. Lower labor cost per ton of ware.

Based on the success of the thin-wall insulating firebrick kiln during its first year of operation, Pomona has begun construction on a similar kiln with the same dimensions and burner and flue system. In fact, Pomona plans to construct thin-wall insulating firebrick kilns whenever any of its existing periodics require replacement. ■■

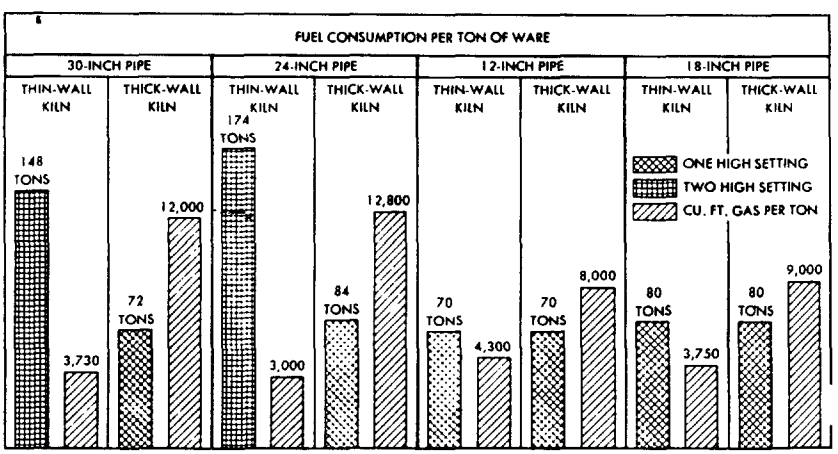
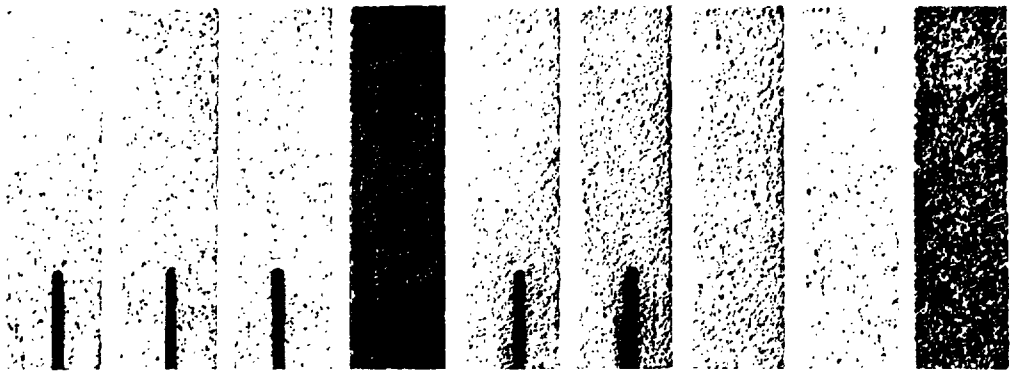
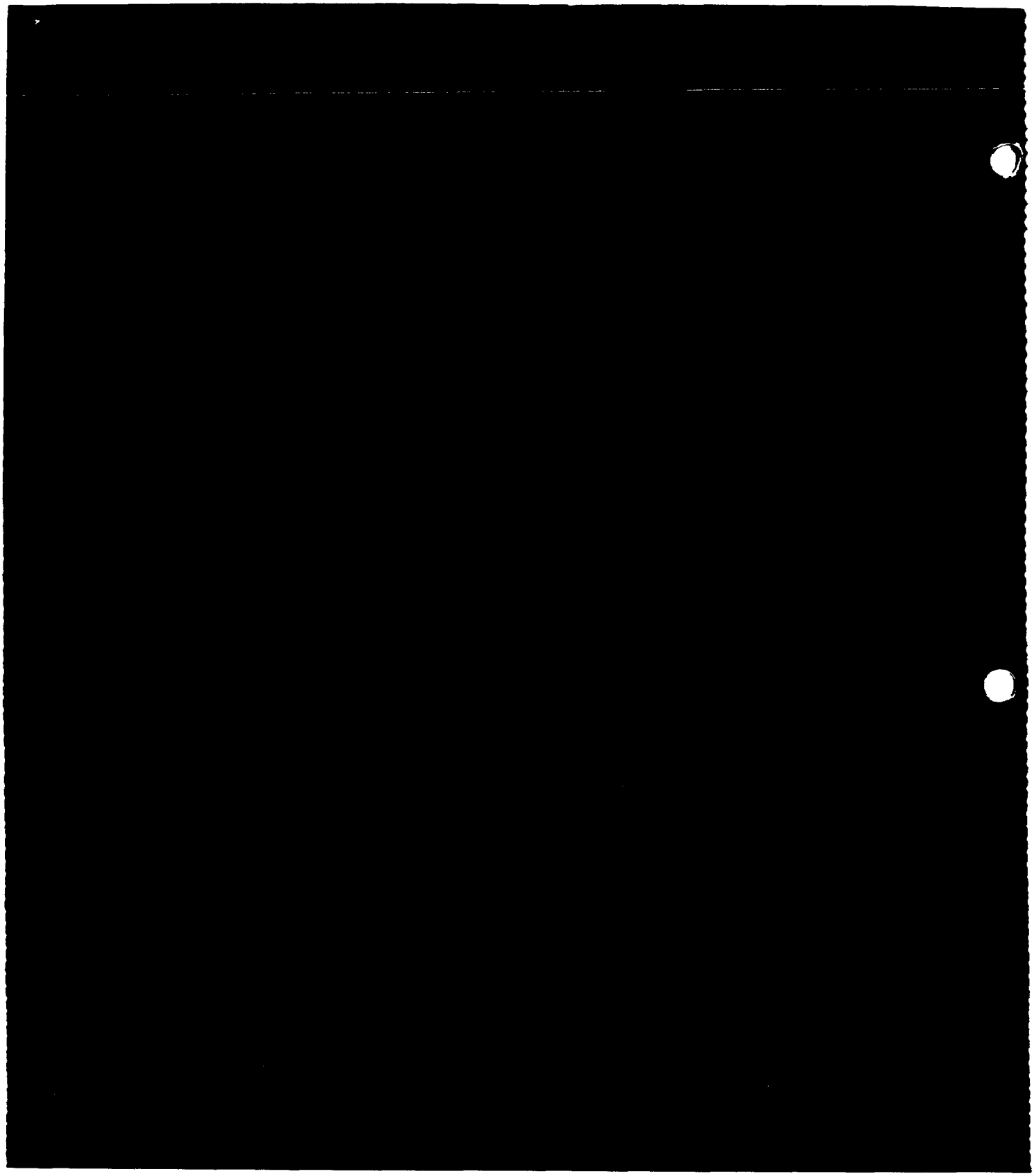


Fig. 7. Typical fuel consumption figures charted here show the kiln's economy.



	K-1620	K-20	K-23	K-26	K-28	K-30	K-3000	Insulpure	Insalcor
Service Temperatures, F									
Exposed	1600	2000	2300	2600	2800	2900	3000	2800	3250
Backup	2000	2000	2300	2600	2800	2900	3000	2800	3250
Density									
Lb/9 in. str.	1.60	1.70	1.85	2.60	2.70	3.06	3.25	2.9	4.60
Lb/cu ft	27.3	29.1	31.6	44.5	46.2	52.3	55.5	49.5	78.7
Fusion Point, F	2700	2750	2750	3100	3190	3190	3350	3475	3350
Thermal Conductivity, Btu/sq ft in. thickness, hr F									
500 F	0.91	0.97	1.07	1.70	1.82	2.04	2.13	2.03	6.03
1000 F	1.19	1.25	1.32	2.10	2.16	2.36	2.37	2.07	5.87
1500 F	1.49	1.55	1.59	2.71	2.64	2.96	2.83	2.26	6.30
2000 F	—	—	1.91	3.43	3.20	3.80	3.44	2.56	7.30
2400 F	—	—	—	—	—	—	4.00	2.86	8.40
Hot Load Strength % Deformation 10 psi, 1½ hr at									
1600 F	0	—	—	—	—	—	—	—	—
2000 F	0	0	—	—	—	—	—	—	—
2200 F	—	—	0.1	0.3	0.3	0.2	0.5	—	—
12.5 psi, 1½ hr at 2730 F	—	—	—	—	—	—	—	—	0.1
10 psi, 1½ hr at 2640 F	—	—	—	—	—	—	0.5	0.5	—
Reheat Shrinkage at Temp, F	1550	1950	2250	2550	2750	2800	2950	2750	3250
	0	0	0	0.2	0.6	0.5	0.6	0.3	+0.4
Cold Crushing Strength, psi	90	110	145	195	190	295	275	220	900
Modulus of Rupture, psi	90	110	150	200	200	280	230	200	350
Chemical Analyses %									
Alumina, Al_2O_3	38.7	39.6	40.1	40.1	46.1	45.3	64.8	94.5	76.6
Silica, SiO_2	44.1	43.0	43.3	54.6	50.8	51.4	33.2	0.3	21.5
Iron Oxide, Fe_2O_3	0.5	0.7	0.6	2.4	1.0	0.9	0.6	—	0.4
Titanium Oxide, TiO_2	1.5	1.1	1.1	1.2	1.4	1.4	0.7	—	0.6
Calcium Oxide, CaO	14.9	15.0	14.4	1.5	0.3	0.5	0.3	5.2	0.1
Magnesium Oxide, MgO	0.1	0.1	0.1	0.1	0.1	0.1	Trace	—	0.1
Alkalies, as Na_2O	0.2	0.3	0.4	0.4	0.3	0.4	0.4	—	0.3
Coefficient of Linear Reversible Thermal Expansion, in./in./F	3.0×10^{-6}	3.0×10^{-6}	3.0×10^{-6}	2.9×10^{-6}	2.9×10^{-6}	2.9×10^{-6}	2.9×10^{-6}	5.2×10^{-6}	3.8×10^{-6}

Data are average results of control tests and are subject to normal variation. Results should not be taken as maximum or minimum requirements for specifications.



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