CAPACITY OF 6-METRE COKE-OVEN WALLS TO RESIST UNBALANCED LATERAL PRESSURE

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ABSTRACT

Computer studies utilizing a finite-element model that includes cracking simulation were conducted to (A) determine the capacity of a 6-metre (19.7 ft) coke-oven-battery wall to resist a given unbalanced normal pressure and (B) establish the relationship between the greatest unbalanced pressure exerted against the battery coke-oven wall and the peak oven-wall pressure measured for the given coal blend in a movable-wall test. For a 33-inch-thick (838 mm) wall, the ultimate unbalanced pressure corresponding to nearly complete crack penetration at the top and bottom is about 1.75 psi (12.1 kPa), but the recommended peak-service oven-wall pressure, corresponding to about a 0.02-inch (0.5 mm) maximum joint opening, is 1.0 psi (6.9 kPa). In estimating the pressure on the battery wall for a given coal blend to compare with these values, the oven-wall pressure measured in a movable-wall test should be considered a lower bound and the peak gas pressure measured in the movable-wall test should be considered an upper bound.

INTRODUCTION

During recent years, there has been increasing concern regarding the serviceability of the between-oven walls of tall coke-oven batteries. This has tended to become more critical in 6-metre (19.7 ft) batteries compared with lesser height batteries because the ratio of the wall-strength requirement to the wall-strength capacity has been greater for 6-metre batteries. The wall-strength requirement is governed largely by the peak unbalanced lateral coking pressures that are exerted on the walls during the coking process. These unbalanced pressures cause wall bending in the vertical direction, which must be stabilized by the vertical gravity loading, including the weight of the roof and the wall, because the joints in the wall have no consistent tensile strength.

There are two separate evaluations that must be made for a given coal blend to determine the safety and serviceability of a given coke-oven wall in resisting the unbalanced lateral wall pressures occurring during the coking process. First, the capacity of a wall to resist unbalanced pressure must be determined, both with regard to (A) ultimate loading before collapse, and (B) serviceability, as related to wall cracking. Second, the relationship must be established between the unbalanced pressure, presumed to be uniform in the vertical direction, exerted against the battery coke-oven wall during normal operations and the peak oven-wall pressure measured for the given coal blend in a movable-wall test, Figure 1. These two evaluations will now be discussed separately for 6-metre coke ovens. Throughout this paper, the unbalanced lateral pressure on a wall will be considered to be the pressure applied on one face of the wall, because at some time the peak coking pressure may occur when an adjacent oven is empty, in spite of all precautions to adhere to a pushing sequence aimed at avoiding such an unbalance.

WALL CAPACITY TO RESIST GIVEN UNBALANCED PRESSURE

Mathematical Model

To evaluate the structural behavior of a 6-metre coke-oven wall over a wide range of unbalanced pressures, a mathematical model of a 33-inch-thick, 19.8-foot-high (6 m) wall, extending over the clear space from the coke-oven floor to the roof, was subjected to lateral pressures increasing from 0.5 psi (3.4 kPa) to 1.75 psi in 0.25-psi (1.7 kPa) increments. A pressure of 1.8 psi (12.4 kPa) was also considered. The analyses were made by using the finite-element computer program, ANSYS.(1)*

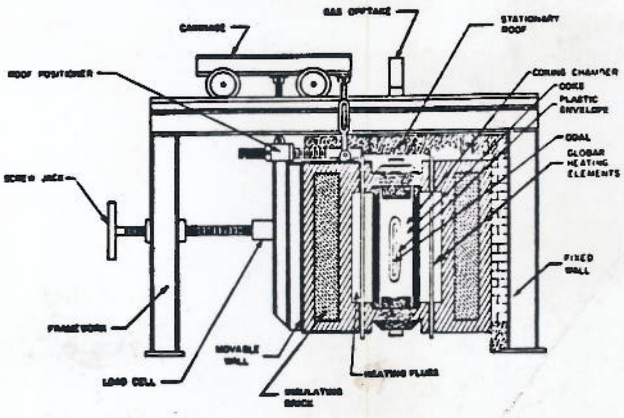

Fig. 1 Movable-wall-test-oven set up at U. S. Steel Research Laboratory.

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* See References.

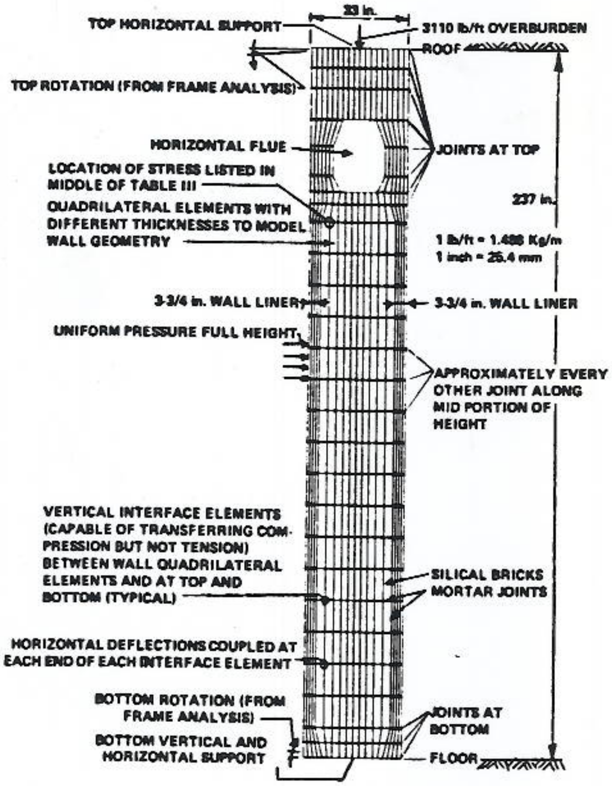


Fig. 2 Mathematical model of wall (elevation).

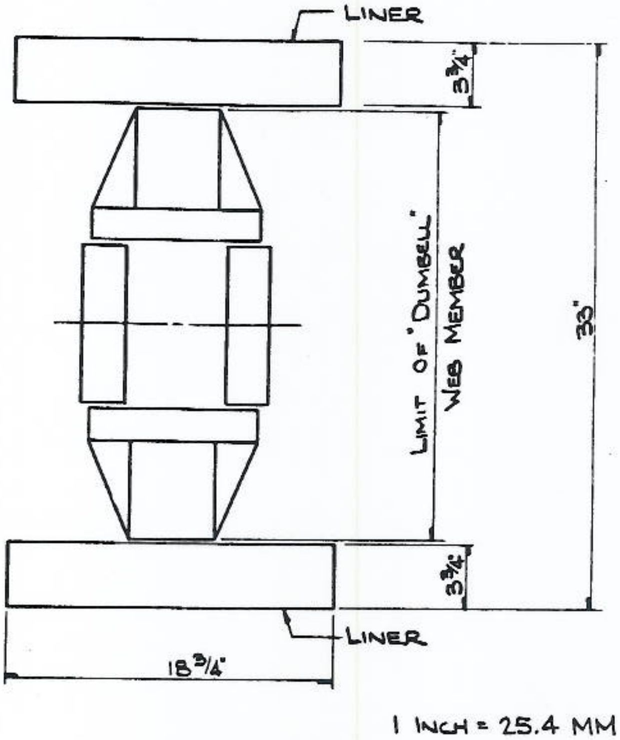


Fig. 3 Plan section of repeating module of coke-oven wall.

Iterative solutions were required because of the horizontal-crack modeling to be discussed.

The mathematical model, Figure 2, consisted of a continuum of two-dimensional solid isoparametric quadrilateral elements separated by horizontal joints. Different thicknesses, extending in the length direction of the wall, were input to represent (for an 18-3/4-inch or 476 mm repeating module of the wall, Figure 3) the refractory in the liners (continuous exterior bricks) and the dumbell-shaped web members (noncontinuous interior bricks). The model assumes homogeneous material properties throughout the wall except for cracks at joints, as will be discussed. No time-dependent creep response or alteration of the material properties as a result of the coking environment is considered.

The refractory is presumed to be silica brick. From tests at the U. S. Steel Research Laboratory, the unit weight of silica brick ranges from about 108 to 120 pcf (1730 to 1922 Kg/m^3); 112 pcf (1794 Kg/m^3) was used in the present study. Widely varying values for modulus of elasticity have been measured in the U. S. Steel tests for silica brick within the above range of unit weight; that is, from about 3000 ksi to nearly 10,000 ksi (20,700 to nearly 68,900 MPa) at 1600°F (871°C); from about 1000 to about 1700 ksi (6890 to about 11,700 MPa) at 2000°F (1093°C); and from about 700 to about 1600 ksi (4800 to about 11,000 MPa) at 2400°F (1316°C). Because a reasonably precise variation of modulus with temperature could not be established, the modulus of elasticity was assumed to be 2000 ksi (13,800 MPa) throughout the wall. The refractory was assumed to have a coefficient of thermal expansion above 1100°F (593°C) equal to 0.0000013 in./in./°F (0.00000234 mm/mm/°C).

The horizontal joints in the wall, Figure 2, were assumed to exhibit no fracture toughness and to have no tensile capacity. Thus, vertical tension at any location in the wall causes, at the corresponding joint, a crack that ends at the beginning of the vertical compression stress. Consequently, horizontal joints in the wall are modeled by vertical interface elements, which are springs (representing the stiffness of the joint mortar) that are capable of transferring compression, but not tension. Within the midportion of the height, only approximately every other joint is thus modeled because of computer-program size limitations. At every horizontal joint that was modeled, each pair of vertically aligned node points are coupled for identical horizontal movement.

Appropriate boundary or restraint conditions are applied at the bottom and top of the mathematical model, Figure 2, to simulate the restraints and rotations imposed by the floor and roof. Vertical support is provided at the bottom, and the roof weight, 3110 lb per running foot of wall (4630 Kg/m), is applied at the top. Horizontal movement is prevented at only the top and bottom of the center plane of the wall. Rotations at the top and bottom are the corresponding joint rotations obtained from an ANSYS(1) analysis of an uncracked frame representing the refractory of a series of ovens, including the regenerative areas beneath, Figure 4. In that analysis, the given unbalanced pressure is against the subject wall, and 0.5-psi unbalanced pressure is against the other walls in directions tending to add to the rotations of the subject wall, Figure 4.

The wall temperatures are assumed to vary linearly in the horizontal direction from a conservatively high value, 2550°F (1399°C), at the flue surface to either 1950°F (1066°C) at the pressure face (upon which the applied pressure is assumed to act) or 1850°F (1010°C) at the leeward face (the other exterior surface of the wall), Figure 5. However, to simplify the solution, the temperatures were assumed to be uniform in the vertical direction, although it is known that, from the bottom to the top of the wall, there is generally about a 50°F (28°C) drop at the outside surface and about a 100°F (56°C) drop at the flue surface.

Results of Computer Analyses

All the solutions for lateral pressure up to and including 1.75 psi converged; that is, interface-element gaps that were open/closed during the second-to-last iteration remained open/closed during the last iteration. However, the solution for 1.8-psi lateral pressure did not converge, even after 28 iterations. Therefore, the analyses indicate that the unbalanced lateral pressure that could cause the wall to become unstable and collapse, regardless of the strength of the bricks, is between 1.75 and 1.80 psi.

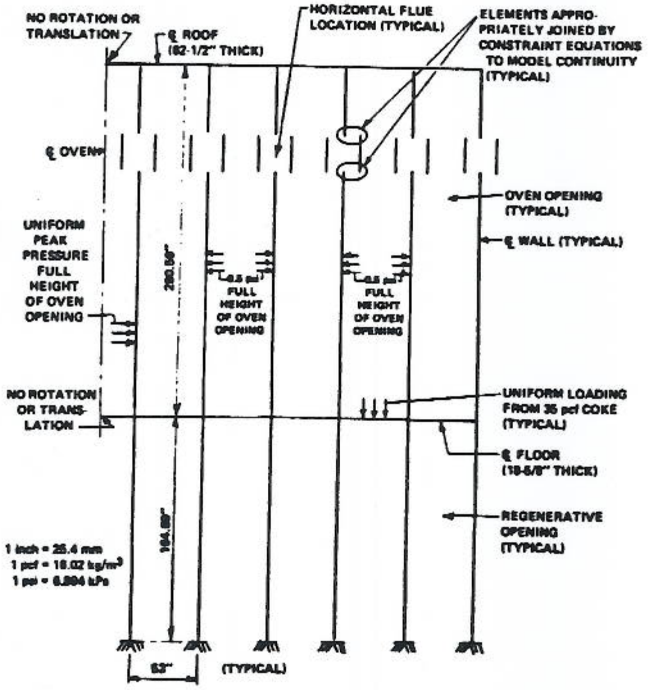
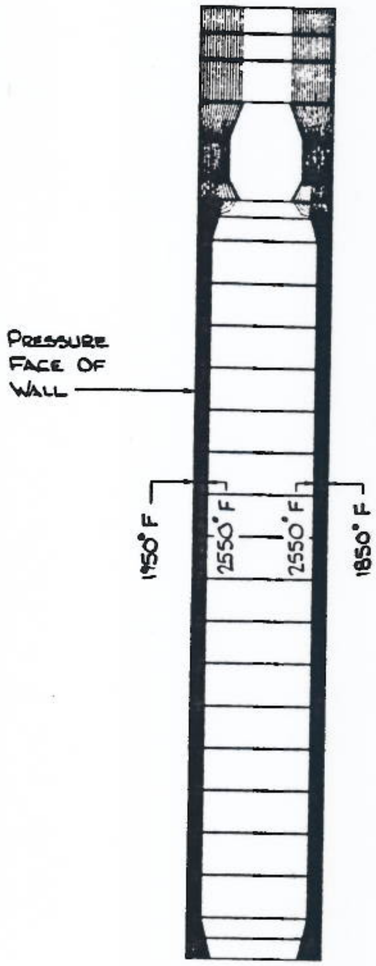


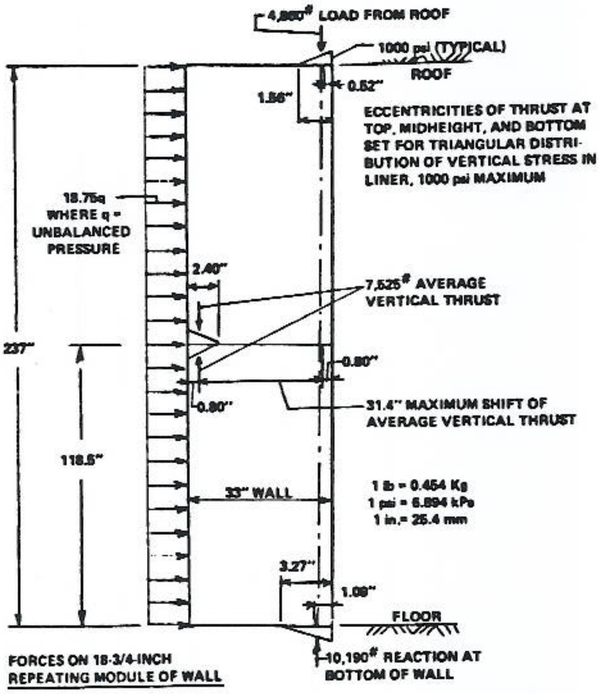
Fig. 4 Mathematical model and loading for uncracked frame analysis.



°C = (°F-32)/1.8

Fig. 5 Assumed temperatures.

This can be predicted by an approximate limit analysis, Figure 6, that assumes horizontal cracks at the top, midheight, and bottom of the wall. The cracks extend through most of the wall thickness so that the maximum vertical compression stress in the wall liner at each location is 1000 psi (6.89 MPa), based on a triangular distribution of stress. For this calculation, the top and bottom cracks begin at the pressure face, and the midheight crack initiates at the leeward face. The simple-beam bending moment from the unbalanced pressure is equal to the average vertical thrust in the wall times its maximum horizontal shift measured at the midheight. (This is about equivalent to assuming nearly equal values of plastic-hinge bending moments at the top, midheight, and bottom of the wall, as is considered in the



(MAXIMUM SIMPLE-BEAM BENDING MOMENT FROM UNBALANCED PRESSURE) = (AVERAGE VERTICAL THRUST) x (MAXIMUM SHIFT OF AVERAGE VERTICAL THRUST)

$(1/8)(18.75\,q)(237)^2 = (7{,}525)(31.4) \rightarrow \underline{q = 1.79 \text{ psi}}$

Fig. 6 Approximate calculation of ultimate unbalanced pressure on wall.

plastic analysis of a vertical beam.) The result is an applied unbalanced pressure of 1.79 psi (12.3 kPa). This calculation is independent of the temperature distribution and the geometry of the dumbell-shaped web members and is not very sensitive to the value assumed for the maximum vertical compression stress. However, it is assumed that the pressure triangle is within the limits of the liner, as in the present example (Figure 6 compared with Figure 2).

There is presently no definition of what the load factor against collapse should be for a coke-oven wall. For building structures, the American Concrete Institute specifies(2) a live-load factor of 1.7, relating ultimate loading to design or service loading. Applying this to the greatest pressure (1.75 psi) that gave a converged solution would limit the design unbalanced pressure to about 1.0 psi.

For each converged solution, the penetrations of the horizontal cracks and crack openings are as indicated in Figures 7 through 12. The variations with unbalanced pressure of the maximum penetrations at the top and bottom and in the midportion are listed in Table I and plotted in Figure 13. At only 0.5-psi lateral pressure, the bottom crack penetrated to the flue, and the midportion cracks penetrated almost through the 3-3/4-inch (95 mm) liner thickness. This reflects the effect of the temperature distribution more than the

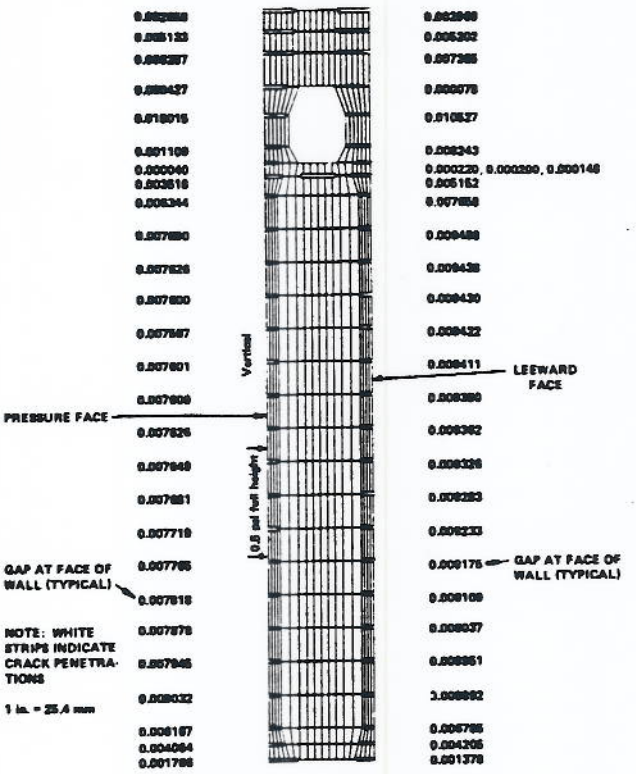


Fig. 7 Crack openings for 0.5 psi pressure.

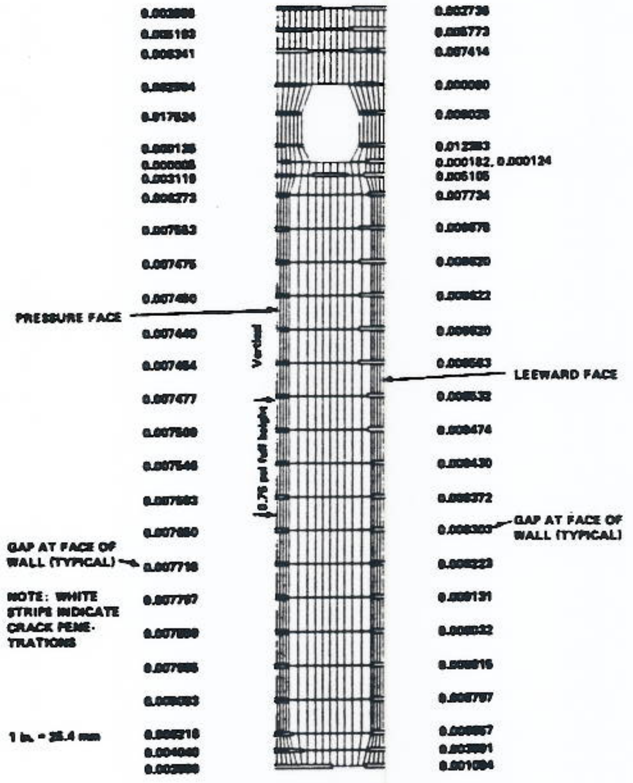


Fig. 8 Crack openings for 0.75 psi pressure.

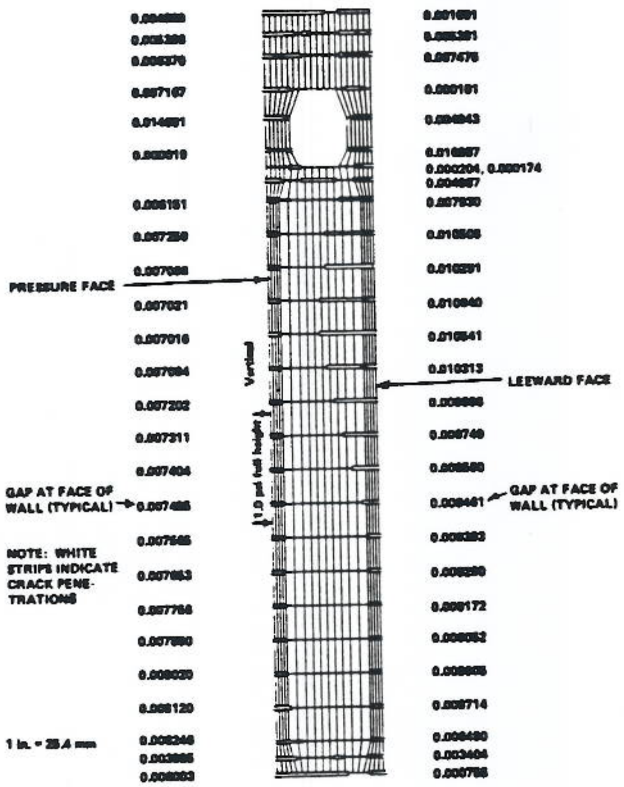


Fig. 9 Crack openings for 1.0 psi pressure.

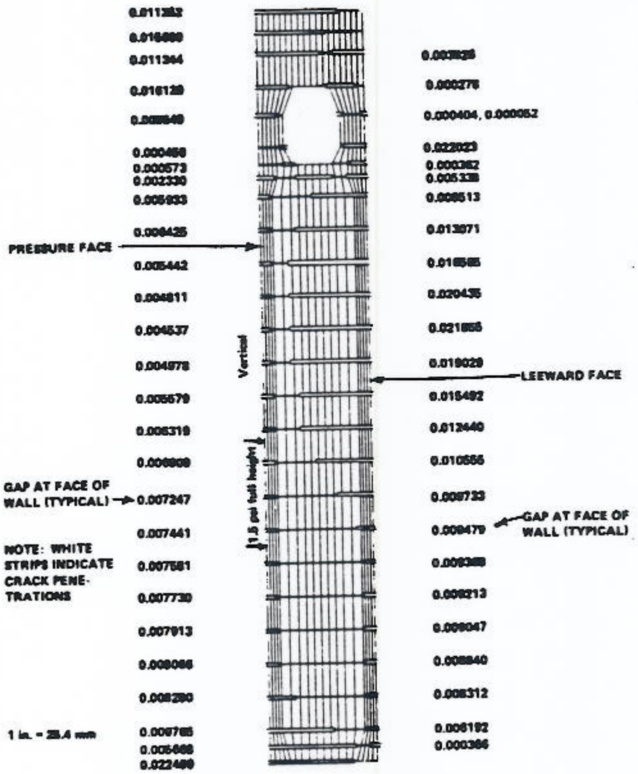


Fig. 11 Crack openings for 1.5 psi pressure.

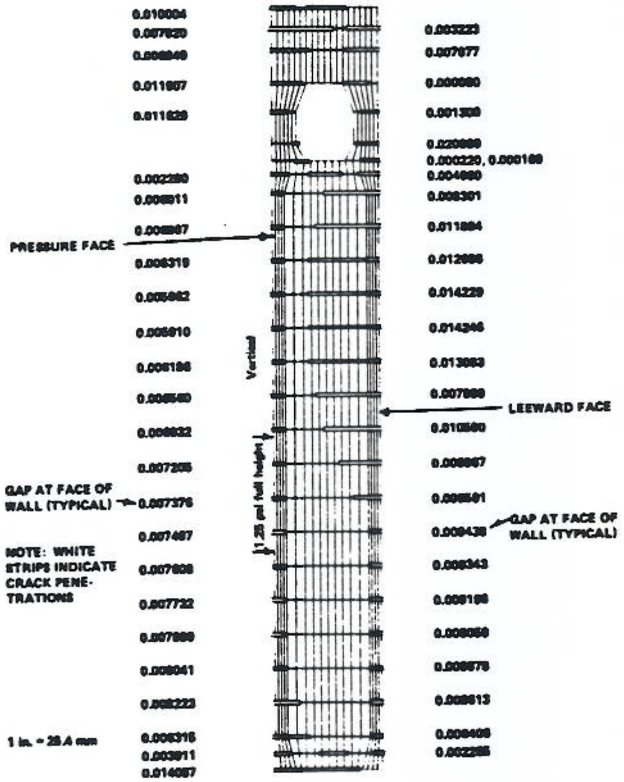


Fig. 10 Crack openings for 1.25 psi pressure.

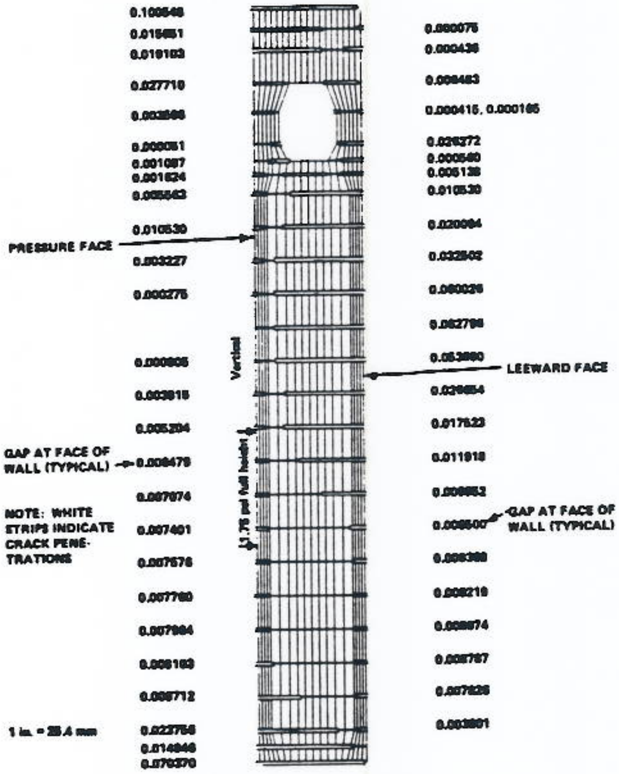


Fig. 12 Crack openings for 1.75 psi pressure.

Table I

Maximum Penetrations of Horizontal Cracks

Elevation	Reference Face of Wall	Penetration of Crack from Reference Face, inches*					
		0.5-psi Pressure	0.75-psi Pressure	1.0-psi Pressure	1.25-psi Pressure	1.5-psi Pressure	1.75-psi Pressure
Top of Wall	Pressure	10.68	14.05	19.88	22.32	25.83	32.81
Between Midheight and Horizontal Flue	Leeward	3.74	9.00	17.21	22.36	25.37	28.44
Bottom of Wall	Pressure	8.61	16.50	21.87	25.57	26.11	32.23

* From extrapolation to zero gap by using the two node-point gaps nearest the crack tip, just beyond the compression zone.

Conversion Factors:
1 inch = 25.4 mm
1 psi = 6.895 kPa

Table II

Vertical Gaps at Locations Tending Toward Maximum Openings

Location		Outside Face of Wall*	Vertical Gap, inch					
Elevation			0.5-psi Pressure	0.75-psi Pressure	1.0-psi Pressure	1.25-psi Pressure	1.5-psi Pressure	1.75-psi Pressure
Top of Wall		Pressure	0.0027	0.0029	0.0050	0.0100	0.0113	0.1005
Horizontal Flue	Top	Pressure	0.0004	0.0029	0.0072	0.0119	0.0161	0.0277
	Upper Bend	Pressure	0.0180	0.0175	0.0147	0.0116	0.0095	0.0036
		Leeward	0.0105	0.0090	0.0048	0.0013	0.0001	0.0002
	Lower Bend	Leeward	0.0082	0.0124	0.0169	0.0210	0.0220	0.0263
Between Midheight and Horizontal Flue (Maximum Value)		Leeward	0.0095	0.0097	0.0106	0.0142	0.0219	0.0628
Bottom of Wall		Pressure	0.0018	0.0029	0.0060	0.0141	0.0225	0.0704

* Maximum values of horizontal crack openings occur at either the pressure face of wall (against which the indicated pressure is bearing) or the leeward face of wall (the other face)

Conversion Factors:
1 in. = 25.4 mm
1 psi = 6.895 kPa

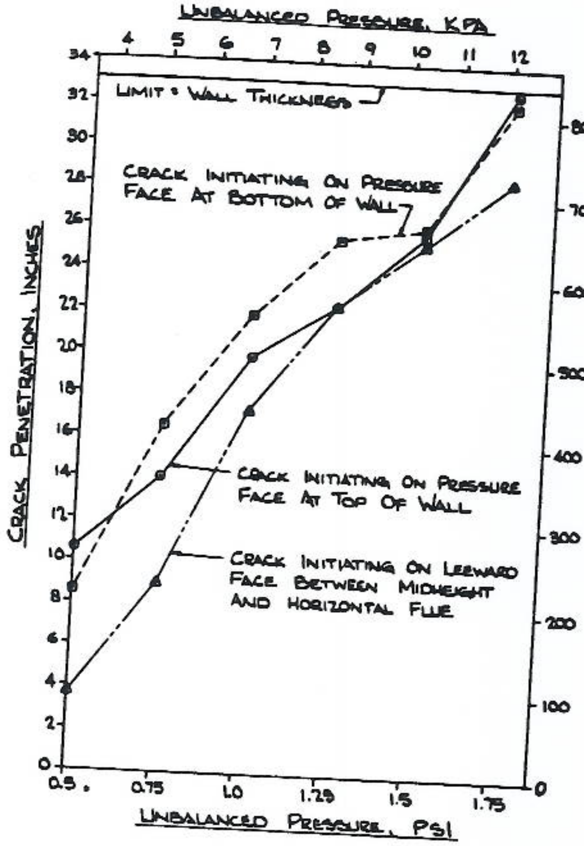


Fig. 13 Crack penetrations.

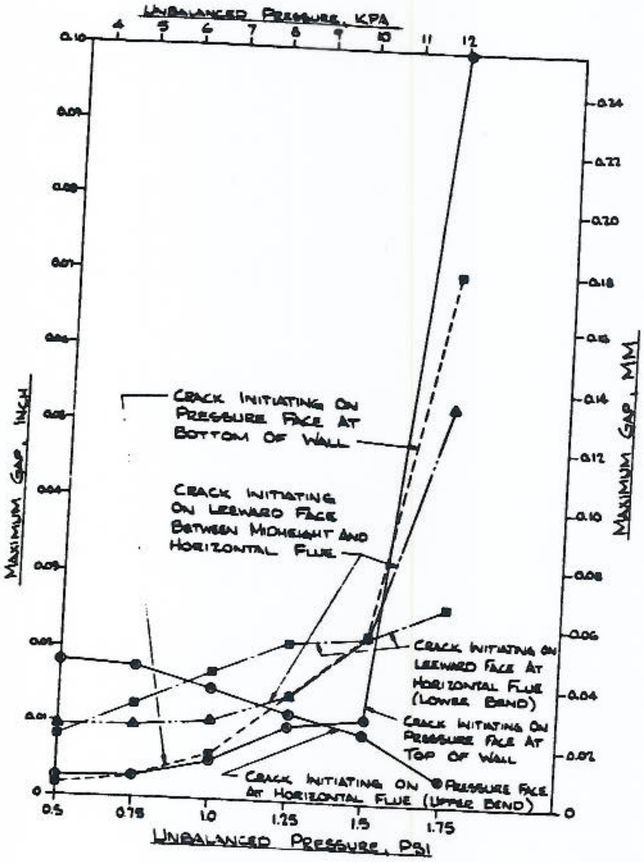


Fig. 14 Crack openings.

effect of pressure loading. As expected, the cracks penetrate further as the lateral pressure increases until, at 1.75-psi pressure, the top and bottom cracks extend over almost the entire wall thickness.

The maximum vertical gaps occurring in the horizontal cracks, that is, the joint openings, are indicated in Figures 7 through 12. Depending on whether the overall bending from the pressure tends to open or close the cracks, the gaps increase or decrease with increase in lateral pressure. For the joints that tend to have the greatest openings, the joint openings for the range of pressures are listed in Table II and plotted in Figure 14. The computed gaps are less than 0.02 inch for lateral pressures not exceeding 1.0 psi or 0.025 inch (0.64 mm) for pressures not exceeding 1.5 psi (10.3 kPa). However, the maximum gap jumps to over 0.1 inch (2.5 mm) for a lateral pressure of 1.75 psi. This indicates the onset of large joint openings, which lead to instability at a slightly greater unbalanced pressure.

There is presently no definition of how large the gaps can be in the horizontal cracks before serviceability of a coke-oven wall is affected. It is noted that crack openings greater than 0.02 inch are not tolerable in reinforced-concrete construction(2) because of the inability of cracks with such openings to seal against egress of moisture. Although sealing against egress of gases and tars rather than moisture is more pertinent to coke-oven walls, it would , because other criteria are lacking, appear to be practical to require that joint openings greater than 0.02 inch not be permitted in coke-oven walls under anticipated conditions of unbalanced pressure. For the present walls, such a crack-control serviceability requirement would limit the design unbalanced pressure to about 1.0 psi. This is the same limiting design pressure previously suggested for safety against wall collapse.

Vertical compression stresses computed at critical locations in the wall are listed in Table III and are plotted in Figure 15. Contours of vertical compression stress for the different pressures are shown in Figure 16. At the lower lateral pressures, stresses tend to be zero or small at the wall exterior faces because of the initial tensile cracking caused by the temperature distribution. As the lateral pressure increases, some of the cracks close at the wall exterior faces, and compression starts to build at those locations while decreasing at interior locations, as evidenced by the bumps in the curves in Figure 15. The computed vertical

Table III

Vertical Stresses at Locations Tending Toward Maximum Stress

Location		Vertical Compression Stress, psi					
Elevation	Hor. Dist. from Leeward Face, in.	0.5-psi Pressure	0.75-psi Pressure	1.0-psi Pressure	1.25-psi Pressure	1.5-psi Pressure	1.75-psi Pressure
Top of Wall*	0.0	0.0	0.0	0.0	1.4	62.7	2728.**
	1.79	0.0	0.0	0.0	3.6	44.1	0.0
	3.58	0.0	0.0	0.0	7.0	32.6	0.0
	5.38	0.0	0.0	0.0	17.5	24.8	0.0
	7.17	0.0	0.0	0.0	37.5	11.8	0.0
	8.96	0.0	0.0	0.0	78.3	0.0	0.0
	10.75	28.9	45.3	115.9	0.0	0.0	0.0
	12.67	27.9	40.8	23.1	0.0	0.0	0.0
10.2 in. below Horizontal Flue***	26.37	59.2	69.7	81.8	88.9	89.7	96.5
Bottom of Wall*	0.0	0.0	0.0	0.0	1.5	99.8	1412.**
	1.56	0.0	0.0	0.0	7.2	87.1	0.0
	3.13	0.0	0.0	0.0	55.5	111.4	0.0
	4.69	0.0	0.0	79.2	193.7	96.5	0.0
	6.25	132.3	189.0	210.6	130.1	4.4	0.0
	7.88	138.1	185.8	192.2	0.0	0.0	0.0

* Except where noted, stress at top or bottom of wall = force in interface-element spring ÷ area of interface-element spring.

** $$\text{Stress} = \left[\frac{\text{(2)(force in interface-element spring)}}{\text{(wall width)} - \text{(crack penetration)}}\right] \cdot \left[\frac{1}{\text{18.75 in. element depth}}\right]$$
assuming a triangular-pressure distribution.

*** Computer printout stress.

Conversion Factors:
1 inch = 25.4 mm
1 psi = 6.895 kPa

compression stress does not exceed 211 psi (1.45 MPa) for lateral pressures of 1.5 psi or less. However, for 1.75-psi lateral pressure, the maximum vertical compression stress, which occurs at the leeward wall face at 1850°F, spikes to about 1400 psi (9.7 MPa) at the bottom and about 2700 psi (18.6 MPa) at the top of the wall, corresponding to the deep crack penetrations there, Figure 12. Because the crushing strength of silica brick at 1850°F is estimated to be about 3000 psi* (20.7 kPa), it appears likely that a silica-brick wall could withstand up to, but not more than, about 1.75-psi unbalanced lateral pressure without crushing or surface-spalling failures that would lead to collapse. Thus, the strength of silica brick should prove just barely sufficient to permit the wall to achieve the collapse strength discussed previously, which was determined on the basis of stability rather than strength.

The assumption of a constant modulus of elasticity (2,000 ksi) throughout the wall means that the portions of the wall adjoining the flue are assumed to be stiffer than they will actually be under the hot service conditions. A more refined analysis, with the modulus decreasing from the outside surface to the flue surface, would generally result in somewhat smaller crack gaps at the outer surface and less abrupt stress variations, Figure 15, for a lateral pressure of 1.5 psi or less, but would have no anticipated effect on the top and bottom spikes in vertical compression stress for a 1.75-psi pressure. Thus, compared with a more refined analysis, the present assumption of a constant modulus of elasticity could lead to somewhat conservative judgments on cracking but should not significantly affect the collapse loading.

CORRELATION OF MOVABLE-WALL-TEST PRESSURE WITH UNBALANCED PRESSURE AGAINST BATTERY WALL

Definitions

To ensure that terms will not be misunder-

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* Based on extrapolations from the room-temperature compression strengths determined in the tests at the U. S. Steel Research Laboratory.

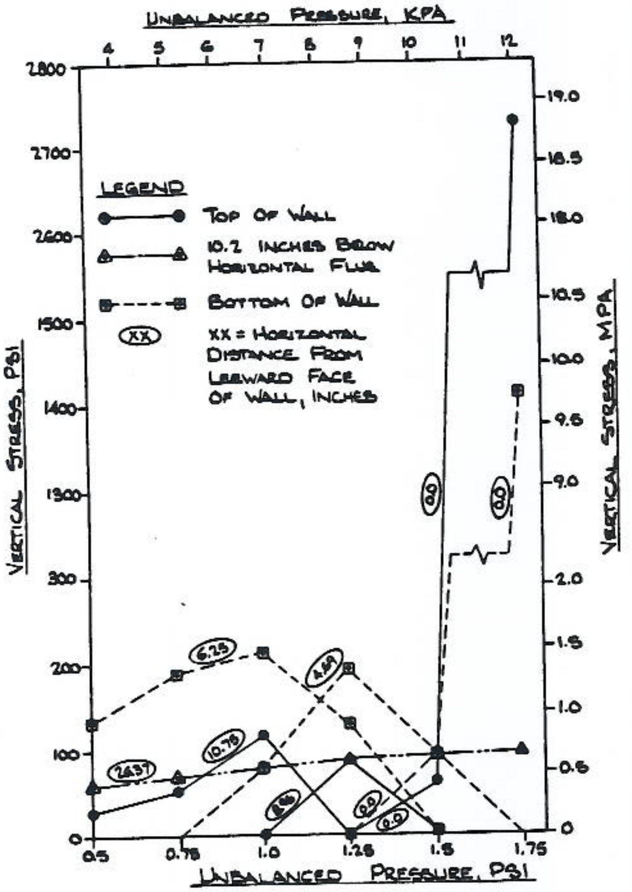

Fig. 15 Vertical compression stresses.

stood, the following definitions will be adhered to in discussing the correlations of coke-oven-wall and gas pressures in movable-wall-test and battery ovens:

1) For either a battery wall or a movable-wall-test oven, oven-wall pressure is the total force exerted by the coke against the pressure face of the oven wall divided by the area of the oven wall contacted by the coke.

2) The plastic zone is a thin layer of plastic coal that develops when coal temperatures are 400 to 500°C (752 to 932°F); the plastic zone starts at the face of each wall and proceeds toward the vertical center plane of the oven.

3) The plastic envelope is the continuous envelope of the plastic zone that may form around the uncoked coal and which generally occurs when the two separate plastic zones meet at the center plane of the oven.

4) The gas pressure is the pressure of the gas within the boundary of the plastic zone.

5) For either the battery oven or the movable-wall-test oven, the pressure ratio is the ratio of the peak gas pressure during the coking cycle, occurring within the plastic zone or the plastic envelope if it forms, to the corresponding oven-wall pressure.

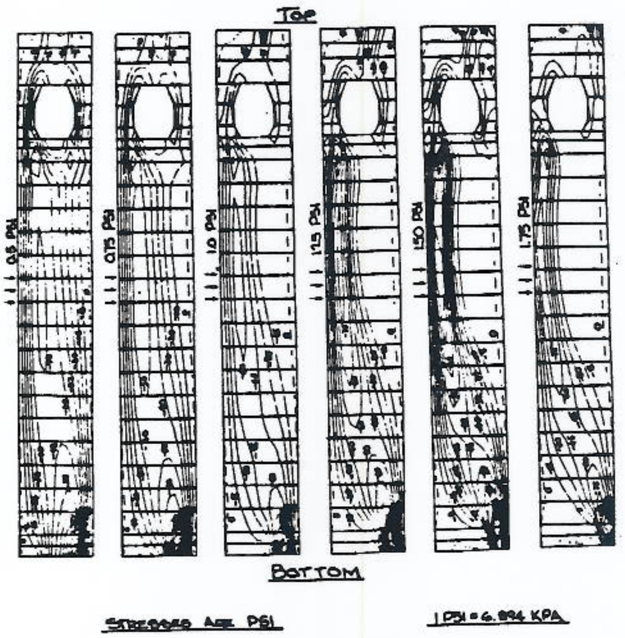

Fig. 16 Contours of vertical compression stresses.

6) For either the battery oven or the movable-wall-test oven, the area ratio is the ratio of the projected area of the plastic envelope, measured on a longitudinal plane parallel to the wall, to the projected oven-wall area in contact with the coke.

7) The use of the same coal blend for the battery coke oven and the movable-wall test implies that the coking rate and dry-oven bulk density are the same in the movable-wall-test oven and the battery coke oven.

Problem Statement

The evaluation discussed in this section requires relating the measured movable-wall-test oven-wall pressure to the battery oven-wall pressure for a given coal blend. These pressures are not necessarily identical, but it may be possible to correlate them by considering the pressure ratios. The peak gas pressure can be assumed to be the same in the movable-wall test and the battery for the previous definition of coal blend given. Also, it is possible to determine the pressure ratio in the movable-wall test by measuring the gas pressure as well as the oven-wall pressure. The only remaining problem is determining the pressure ratio for the battery oven. As will be discussed, structural analyses were directed at evaluating the battery-oven pressure ratio following a literature review of this subject.

Literature Review

No data apparently exist in the literature to define the relationship between movable-wall-test and actual oven lateral wall pressures. The reason these data are absent is that it would be extremely difficult to measure oven-wall pressures in an actual oven. An article(3) by Lambert, et al., compares (A) peak gas pressures in an actual oven with those for the same coal blend in movable-wall tests, (B) peak gas pressures with wall pressures in movable-wall tests only, and (C) wall lateral deflections in both cases.

Other field measurements of internal gas pressure have been made for comparison with the results of movable-wall tests, but the actual oven-wall pressures have not been determined. No general relationship has been firmly established between the peak gas pressures in the actual oven and the peak oven-wall pressures in the movable-wall tests(3). In other references, pressure ratios have been obtained for movable-wall tests(4). In general, the peak gas pressures are greater than the peak oven-wall pressures in the movable-wall tests, Figure 17. The literature generally assumes that the wall pressure occurring at the time of the peak internal gas pressure is uniform because gas pressures measured within the plastic zone at various heights of the oven charge do not vary substantially despite great differences in the bulk density of the charge(4).

It has been observed(4) that the pressure ratio in a movable-wall test can be about 2. This has generally been attributed(4) to (A) the area-ratio effect whereby the plastic-envelope area is less than the wall area, and (B) a bridging or coke-barrier-wall effect whereby the coke that extends between the plastic envelope and the wall does not transmit all the pressure to the wall.

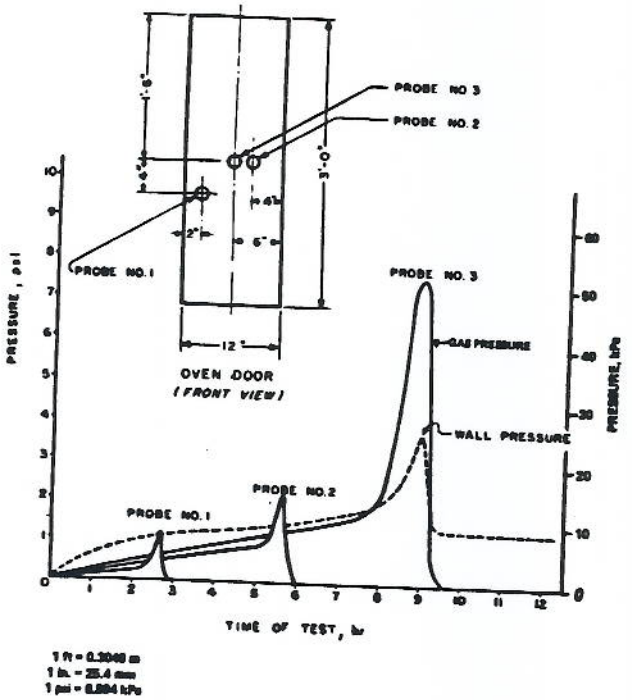

Fig. 17 Measurement of pressures in a U. S. Steel movable-wall test.

Area-Ratio Effect. Some investigators have indicated that the area ratio is nearly 1 in a battery oven throughout the coking cycle but in a movable-wall test is only about 0.5 at the time of peak gas pressure(5,6). In the latter, the area ratio decreases from nearly 1 when each plastic zone first forms near a wall to about 0.5 when the plastic zones meet to form the plastic envelope at the center plane of the oven. This effect alone would explain a pressure ratio of about 2 in a movable-wall test, whereas a pressure ratio of about 1 is implied for the battery oven. In that case, the same coal blend would cause a maximum oven-wall pressure in the battery that is two times the maximum oven-wall pressure measured during the movable-wall test. This would imply that the movable-wall test can significantly underpredict battery oven-wall pressures.

Coke-Barrier-Wall Effect. A bridging effect of the coke could conceivably reduce the pressure ratio in the battery oven. However, the bridging effect is questionable because the coke would have to act as a barrier wall between the peak gas pressure and the refractory wall to be effective. Data from tests at the U. S. Steel Research Laboratory in which the plastic zone crossed different pressure-measuring tubes exhibited a gas pressure exceeding the wall pressure only when the plastic zone was moving by the tube, Figure 17. This suggests that only within the plastic zone or plastic envelope is there a reduction from the peak gas pressure to an intergranular pressure about equal to the wall pressure. In that case, the plastic envelope would act as the barrier, and the coke would merely act as a medium to transmit a constant pressure to the wall, and its behavior as a barrier wall would be quite minimal. It has been noted that the action of the coke in transmitting the pressure is complicated by the swelling of the coke, the contraction of the semicoke, and the settling of the uncoked coal(5,6).

Structural Analyses

To evaluate the possibility of a barrier effect, structural analyses of the battery wall were made with the use of ANSYS(1) assuming (A) the area ratio is 1; (B) the mathematical model is extended, Figure 18, to include quadrilateral elements representing a 9-inch-thick (19.1 mm) coke mass between the plastic envelope and the wall as well as horizontal interface elements between the coke mass and the wall; (C) a uniform lateral pressure is exerted against the coke mass at the plastic-envelope face of that coke mass, (D) boundary and restraint conditions on the model include those used for 1-psi pressure on the original model discussed previously; and (E) the coke mass acts

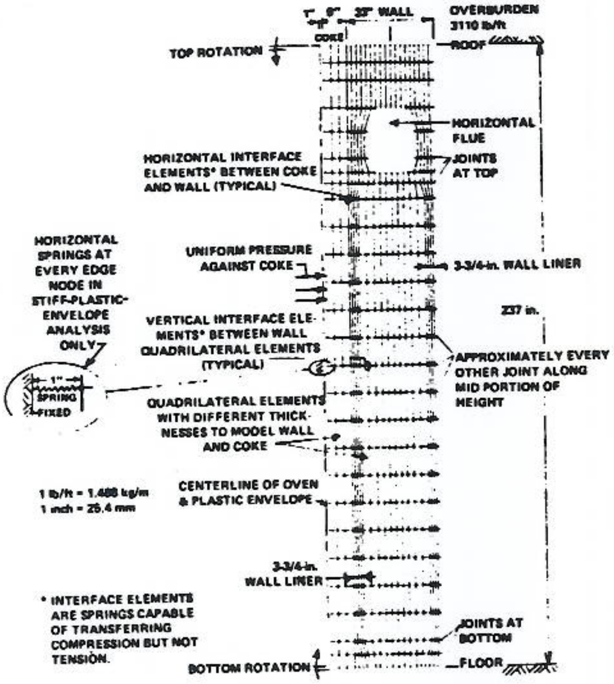

Fig. 18 Extended mathematical model.

as an unfailed elastic medium with a modulus of elasticity of 100 ksi (689 MPa) rather than a somewhat cohesive granular material.

This extended model also served to represent conditions in the movable-wall test when an additional restriction was imposed upon the battery-wall model. This restriction is that horizontal deflection of the refractory is prevented. The reason this restriction represents conditions in the movable-wall test is that the actual horizontal movement of the wall in the movable-wall test is quite small because the compression of the load cell, Figure 1, is quite small, whereas significantly larger horizontal deflections of the wall have been measured in battery ovens loaded with comparable pressures(3).

An additional variation in the model was made to investigate the possible barrier effect of the plastic envelope. For a "flexible" plastic envelope, no special barrier effect was presumed; the model terminated at the coke mass, and a 1-psi pressure was exerted against the coke mass. For a "stiff" plastic envelope, the possible barrier effect of the plastic envelope was modeled by a series of horizontal springs extending from the edge of the coke mass, Figure 18, to a fixed vertical plane at the

Table IV

Results of Computer Analyses to Investigate Coke-Barrier Bridging Effect

Barrier-Effect Assumption for Plastic Envelope	Horizontal Deflection of Wall Permitted?	Coke-to-Horizontal Continuity* Assumed for Coke Above and Below Plastic Envelope?	Pressure Applied to Plastic-Envelope Face of Coke Mass, psi	Wall Contact Pressure over Middle Half of Wall Height, psi
Flexible (No Horizontal Springs in Model)	No (Movable-Wall-Test Simulation)	No	1.0	1.0
	Yes (Battery Wall)	No	1.0	0.998
		Yes	1.0	0.998
Stiff (With Horizontal Springs in Model)	No (Movable-Wall-Test Simulation)	No	2.0	1.0
	Yes (Battery Wall)	No	2.0	Varies, Significantly Less than
			1.0	

* Horizontal continuity consisted of restraining against horizontal movement the top 13-1/2 inches (343 mm) and the bottom 10-3/8 inches (264 mm) of the coke depth at the center of the oven.

Conversion Factor:
1 psi = 6.895 kPa

center of the plastic envelope, and a 2-psi (13.8 kPa) pressure was exerted against the coke mass. The stiffnesses of the added horizontal springs were determined such that the average pressure delivered to the wall at the coke interface when horizontal movement of the wall was precluded, that is, when the movable-wall-test condition was being simulated, was 1 psi. When there is horizontal movement of the wall, as in the battery oven, the greater extension of the horizontal springs would cause more horizontal force to be resisted by the springs and less to be resisted by the wall.

Computer runs were obtained for the various combinations of assumptions as indicated in Table IV. With the assumption of a flexible plastic envelope, there is very little difference between the coke-to-wall contact pressures of the movable-wall-test simulation (1.00 psi or 6.89 kPa) and the battery-wall calculation (0.998 psi or 6.88 kPa). (The latter resulted whether or not the horizontal continuity of the coke above and below the plastic envelope was considered in the model.) This indicated that the combined effect of (A) the lateral deflection of the refractory wall and (B) the bridging of the coke, which could tend to act as a barrier wall, appears not to affect significantly the pressure transmitted to the face of the refractory wall.

The modeling of a stiff plastic envelope by horizontal springs that cause the coke-to-wall contact pressure to be half the applied pressure in the movable-wall-test simulation is apparently not valid. The reason is that application of this modeling to the battery-wall analysis (see the last item in Table IV) resulted in not only considerably less pressure delivered to the wall, but also stresses and wall deflections much less than reasonable. Thus, there is no reason to anticipate a bridging effect offered by the plastic envelope.

CONCLUSIONS

The results of the calculations and the literature review suggest that (A) the coke does not effectively act as a barrier wall in transmitting peak gas pressures to the refractory wall, and the plastic envelope offers no specific barrier effect; (B) the deflection of the refractory wall does not affect the pressure transmission; (C) the peak gas pressures probably do not extend beyond the plastic zones or the plastic envelope; and (D) the experimental comparisons indicate no consistent overprediction of internal gas pressures by movable-wall tests. Thus, in movable-wall tests, the fact that the peak oven-wall pressure frequently is only about half the peak gas pressure is more likely explained by the ratio of the plastic-envelope area being only about half the wall area rather than by a coke-barrier-wall effect. In contrast, in a battery oven, the peak oven-wall pressure should be nearly equal to the peak gas pressure because the ratio of the plastic-envelope area to the wall area is closer to 1. Thus, for the same coal blend, coking rate, and dry-oven bulk density, the oven-wall pressure measured in a movable-wall test may underpredict pressures on battery walls.

Therefore, it is recommended that, for a given coal blend, the oven-wall pressure measured in the movable-wall test be used as a lower bound and the peak gas pressure measured in the movable-wall test be used as an upper bound in estimating the pressure on the battery wall. This estimated battery-wall pressure should be compared with an allowable unbalanced pressure for the wall that is based on satisfactory serviceability, as defined by acceptable limits on cracking, and safety against collapse, as determined by applying a suitable load factor to the ultimate lateral loading the wall can withstand. The evaluations of cracking and ultimate loading can be determined by finite-element computer analyses in which the crack penetrations and thermal effects can be adequately simulated in the mathematical model. An approximate evaluation of ultimate loading can be obtained from a simple analysis that equates the simple-beam bending moment from the lateral loading to the average vertical thrust in the wall times a dimension that represents, over the wall height, the range of the horizontal shift of the vertical thrust.

For the wall analyzed in the present study, the unbalanced lateral pressure that could cause collapse was calculated to be just above 1.75 psi (12.1 kPa). However, when a 1.7 load factor as well as serviceability relative to cracking are taken into consideration, the allowable unbalanced lateral pressure should not exceed about 1.0 psi (6.9 kPa).

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