fire protection planning report

BUILDING CONSTRUCTION INFORMATION FROM THE CONCRETE AND MASONRY INDUSTRIES

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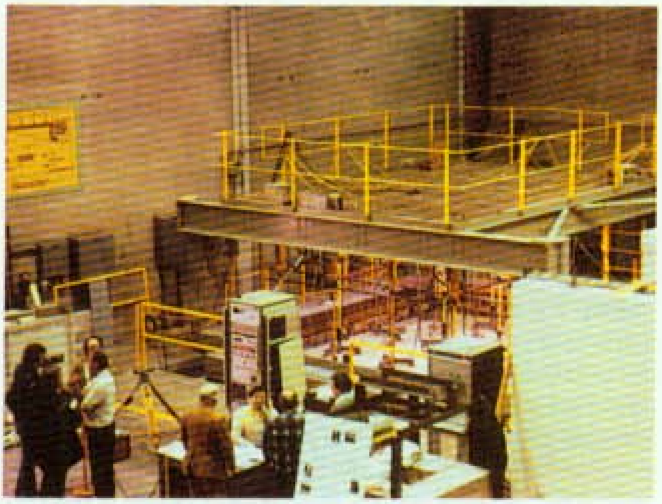
THE IMPACT OF POSITIVE FURNACE PRESSURE ON ASTM E119 TESTED ASSEMBLIES

A wall specimen is loaded into a multipurpose test furnace in preparation of an ASTM E119 fire test.



A horizontal test furnace for conducting E119 floor/ceiling tests.

BACKGROUND

ASTM E119, "Standard Test Methods for Fire Tests of Building Construction and Materials",[1] the nationally recognized standard for fire testing of construction assemblies in the United States, does not provide any guidance in specifying furnace pressure during testing. As a result, furnaces have been traditionally designed to operate under negative pressure in order to prevent products of combustion (smoke) from entering laboratory facilities.[2]

In Europe and other parts of the world, standardized testing under positive furnace pressure has received greater recognition. ISO Document 834, the international equivalent of E119, specifies a positive pressure of 0.04 $\pm$ 0.02 in. of water (10 $\pm$ 5 Pa) in the furnace during the entire heating period of the test, excluding the first 10 minutes.[3] Although laboratory tests are not intended to duplicate all of the conditions of real-world fires, testing conducted under positive pressure represents a more accurate portrayal of the compartment fire environment.

The issue of positive versus negative pressure has generated much discussion and debate in the ongoing effort to update and rewrite the ASTM E119 standard test method. Recent addition of provisions in the Uniform Building Code (1992 Supplement)[4] on positive pressure testing of fire doors has heightened the awareness of this issue even more. In an attempt to come to a resolution, ASTM has formed a task group charged with studying the issue and making a recommendation to the E119 rewrite subcommittee.

PURPOSE

The purpose of this report is to explain why E119 fire tests should be conducted under positive furnace pressure. Evidence is offered that certain types of assemblies tested under negative furnace pressure may not be able to withstand the E119 fire condition for the same duration when tested under positive pressure. This can lead to unconservative conclusions when E119 tests are used as a tool for assessing the adequacy of some fire-rated assemblies in building construction.

Table 1. Calculated Pressures at the Furnace Ceiling During an E119 Test of a Wall Specimen

Time	ΔP reading at 6 ft level[1]	E119 furnace temperature	Calculated ΔP at ceiling[2]
(Minutes)	(Pascals)	(Degrees Celsius)	(Pascals)
5	-12.5	538	-5.54
10	-12.5	704	-4.87
15	-12.5	760	-4.69
20	-12.5	795	-4.59
25	-12.5	821	-4.52
30	-12.5	843	-4.46
35	-12.5	862	-4.41
40	-12.5	878	-4.37
45	-12.5	892	-4.34
50	-12.5	905	-4.31
55	-12.5	916	-4.29
60	-12.5	927	-4.26

[1]The measured P corresponds to the furnace pressure taken at an elevation of 2/3 the height of the furnace ceiling. Typical pressures range from 0.03 to 0.05 in. of water column (7.5-12.5 Pascals) less than atmospheric.

[2]The calculated P is the difference of the inside and outside furnace pressure at an elevation equal to the furnace ceiling height.

THE EFFECT OF POSITIVE AND NEGATIVE FURNACE PRESSURES ON CONSTRUCTION ASSEMBLIES

Furnace pressure distributions during testing will vary from one furnace to another based on the furnace design and the rate at which combustion gases are vented. Table 1 shows a pressure-temperature profile that is experienced by an E119 wall specimen at the ceiling level of the furnace. The ceiling is chosen because this is the location in real-world fires where temperature and pressure conditions are the highest. Pressure calculations in Table 1 are based on running the furnace at a negative pressure of 0.05 in. of water column (12.5 Pa), measured at a level approximately 2/3 the height of the furnace from its base (6 ft). The negative pressure represents the difference between the pressure within the furnace and the atmospheric pressure outside the furnace at the measurement evaluation.

Furnace design and the smoke development potential of a test specimen dictate the amount of negative pressure that is needed to prevent combustion gases from entering the laboratory environment. In testing floor/ceiling or roof/ceiling assemblies under negative pressure, ambient air enters the furnace through gaps between the specimen and the furnace's restraining frame. For concrete slabs and planks, this "cool" air entering the furnace will have little effect on fire endurance of these assemblies. For lighter weight floor/ceiling or roof/ceiling assemblies with plenums created by suspended ceilings, and where cool air is drawn through the plenum into the furnace, the impact of negative furnace pressure is considerably more pronounced. The following figures from Seigel's article compare the impact of positive and negative furnace pressure on one such assembly.[5]

Fig. 1(a) indicates the temperature and heat flow conditions present for the given assembly, after being subjected to an E119 fire test under negative furnace pressure for a period of approximately one hour. Fig. 1(b) shows the same parameters for an identical assembly tested under positive furnace pressure. From these figures, it is clear that the fire's damage potential is reduced by the current practice of testing under negative furnace pressure. Seigel's computations are based on an air leakage rate of 835 cu ft/min through a 1/4 in. crack between the furnace frame and specimen at a pressure difference of 0.05 in. of water column (12.5 Pa). Leakage was also assumed to be of uniform distribution over the internal surfaces of the specimen.

Although the above examples are specific to a floor/ceiling assembly, the same concept applies to walls employing structural members protected by a membrane (e.g. gypsum wallboard on studs). For walls, the cooling effect of entrant air under negative pressure may not be as prominent as in the above case. Of greater significance, however, is the effect that furnace pressure has on restricting or aiding the flow of hot gases into cracks that develop in the specimen during testing. Cracking in gypsum wallboard at elevated temperatures is largely due to the material's shrinkage. This typically results in the opening of joints between adjacent panels.

Under positive pressure, hot gases are forced into cracks and ultimately into the wall (and ceiling) cavity behind the panels. This phenomenon increases the rate of heat transmission through the specimen to the unexposed surface. In wood-framed assemblies it is likely to cause an earlier ignition of the wood studs and thus decrease the assembly's structural fire endurance. Steel studs are similarly affected. Their structural strength is depleted sooner, which can lead to an earlier failure of the wall. From both a structural and heat transmission perspective, hot gases driven into cracks by positive pressure will have the effect of reducing fire resistance of specimens whose ratings have been established by tests conducted under negative furnace pressures.

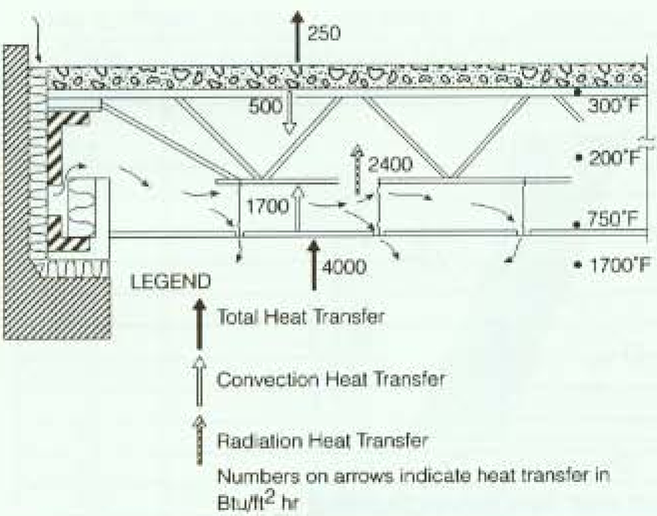


Fig. 1a. Estimated effect of furnace pressure on fire test results—negative furnace pressure and leakage into furnace

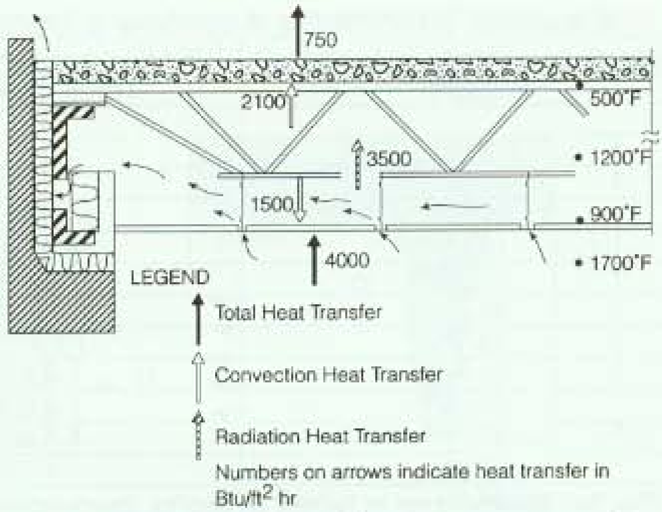


Fig. 1b. Estimated effect of furnace pressure on fire test results—positive furnace pressure and leakage out of furnace.

In contrast, if the above specimens are tested under negative furnace pressure, a dampening effect is experienced. As surface cracks widen and deepen, inevitably reaching the wall cavity, hot gases and localized "cool" air are drawn from the cavity toward the fire-exposed surface and are exhausted through the furnace vent. This occurs because the gaseous mixture is moved from the zone of higher pressure at the crack (atmospheric) to the lower negative pressure zone within the furnace. The result is a less severe fire exposure to construction components that are shielded by the surface layer, and an unconservative fire endurance rating of the specimen. Fire testing conducted under negative furnace pressure negates one of the most fundamental and important phenomena of real-world fire behavior.

PRESSURES DEVELOPED IN REAL-WORLD FIRES

A full discussion of compartment fire behavior is beyond the scope of this report. Some observations, however, need to be made with respect to pressures that are developed in real fires, and their potential impact on construction.

During the early stages of a fire, air expansion and the movement of products of combustion in the fire plume cause pressures to build up in the vicinity of the plume. If the fire takes place in a compartment that is not excessively large, the pressures within the room or compartment will continue to increase with fire growth until a venting condition occurs. This will typically be an open door or a window that breaks generally within the first 3 to 10 minutes of the fire, depending on a number of conditions.

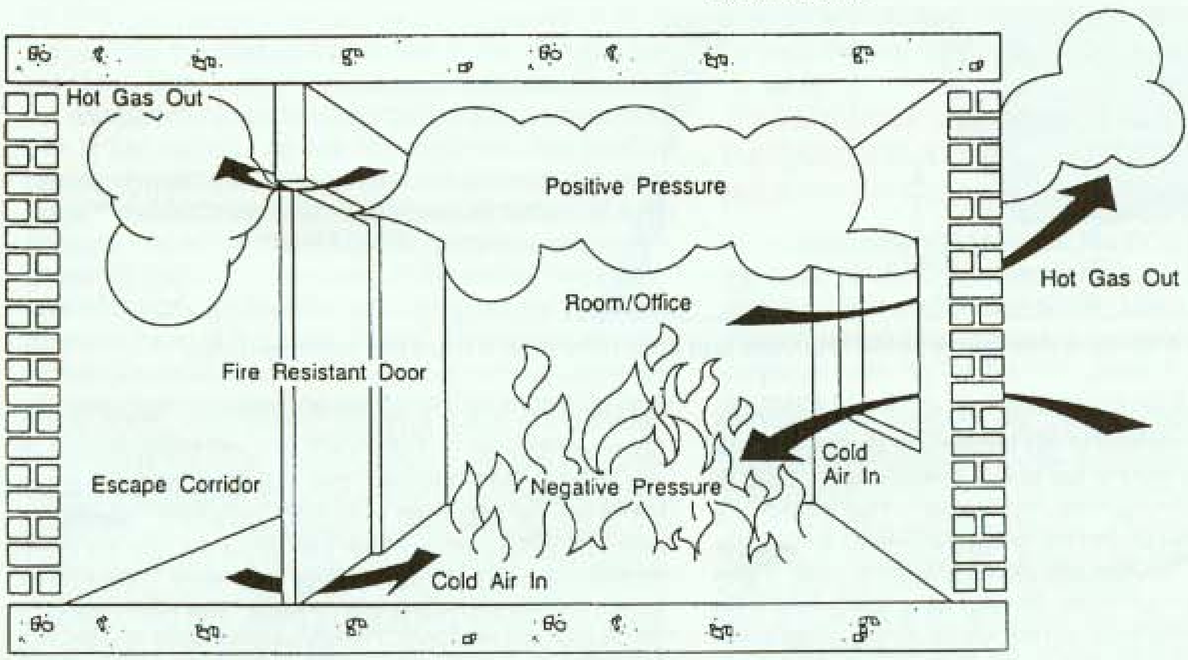


Fig. 2. Typical air and combustion gas movement in compartment fires

PRESSURE PROFILES ACROSS A VENT

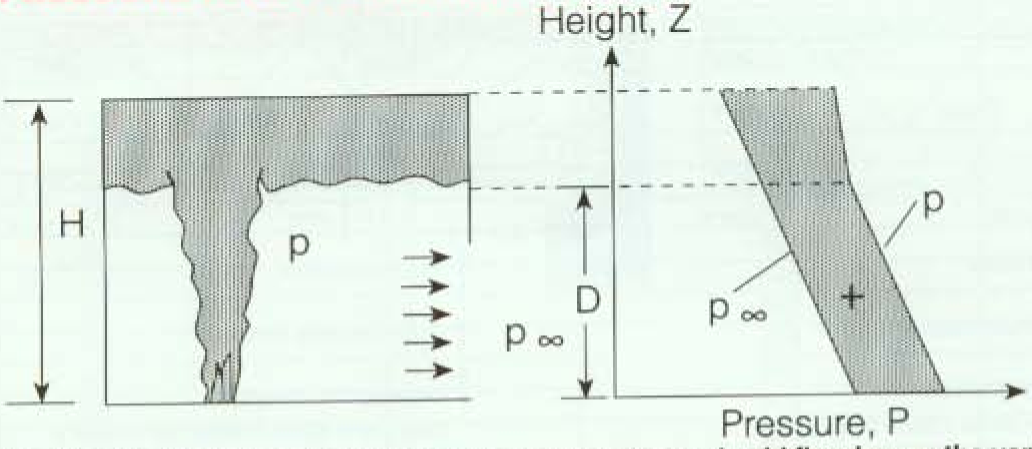


Fig. 3a. Smoke layer at height D, begins descending and cold flow leaves the vent

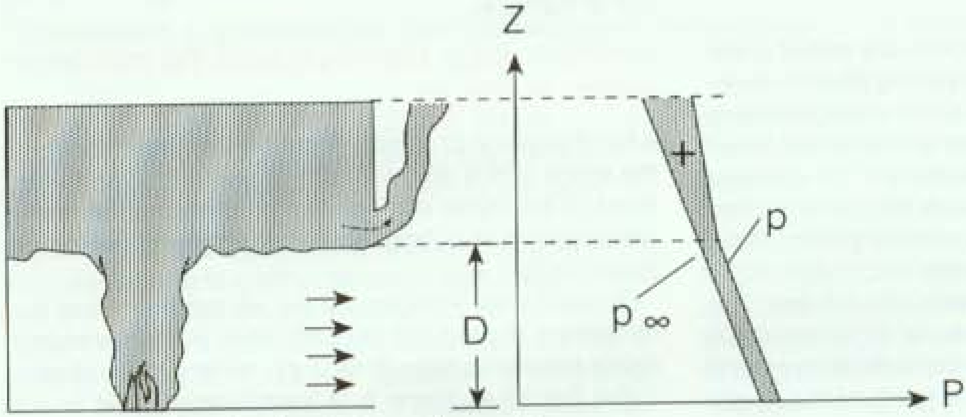


Fig. 3b. Hot flow begins to leave the vent

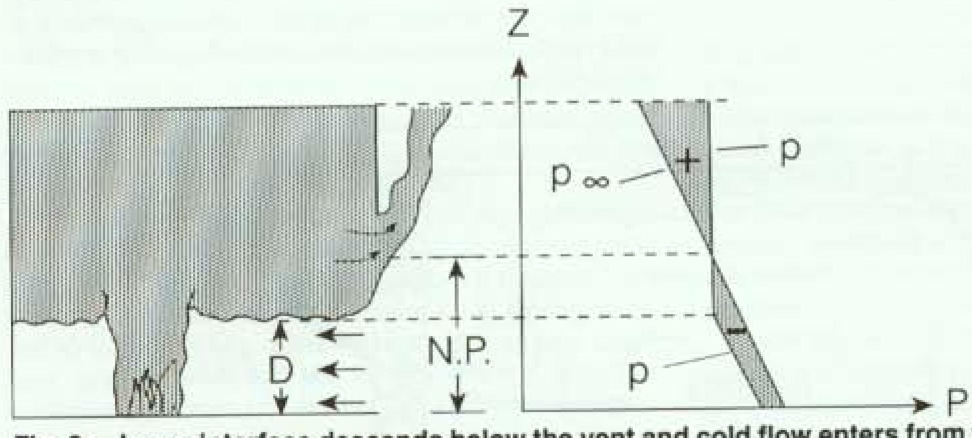


Fig. 3c. Layer interface descends below the vent and cold flow enters from the surroundings

As fire propagation continues, buoyant flow becomes the driving mechanism of gas movement and causes the pressure at the floor to fall below atmospheric. This, in turn, draws fresh air into the room. The in-and-out movement of gases and the pressure profiles across the vent as the fire progresses are illustrated in Figs. 2 and 3, respectively. At some vertical level within the vent there will be no net flow and the pressure inside the room will equal that outside. This level is referred to as the neutral plane (n.p.). In reality, the elevation of the neutral plane will change during a fire's growth. For purposes of this discussion, however, the elevation of the neutral plane will be assumed to remain constant. Maximum pressure differentials within test furnaces and fire compartments occur at the ceiling and floor. Pressures above the neutral plane are positive, and those below it are negative with respect to the environment outside the furnace or compartment.

Table 2. Pressure and Temperature Development Inside a Compartment in a Real-World Fire Scenario

Time (Minutes)	ΔP at floor from HAZARD[1] (Pascals)	Upper layer temp. from HAZARD[1] (Degrees Celsius)	Calculated ΔP at ceiling inside room[2] (Pascals)
1	4.714	72.4	9.17
2	29.06	172.9	39.15
3	97.44	479	115.42
4	-1.411	883.3	20.61
5	-5.326	994.3	17.35
6	-5.375	1029.5	17.48
7	-5.438	1074.1	17.64
8	-4.650	726.3	16.19
9	-4.107	638.5	15.90
10	-3.815	600.5	15.78
15	-3.113	467.4	14.70
20	-2.782	437.4	14.54
25	-2.591	422.5	14.47
30	-2.471	414.3	14.44
40	-2.341	406.6	14.43
50	-2.281	403.4	14.43
60	-2.252	402	14.43

[1]Reference 7.

[2]The calculated P is the difference between the pressure inside the fire compartment and atmospheric pressure at a ceiling height of 8 ft.

Through experimental work, pressures of 0.4 -0.5 psf (approx. 0.08-0.10 in. of water column or 19.2-23.9 Pa) have been observed in fully developed fires. More recently, computer software such as FPETOOL[6] has been developed to estimate these pressures and has shown that these values are not unreasonable. More sophisticated software for modeling compartment fire behavior (HAZARD)[7] has shown that compartment pressures can reach nearly 2 psf (0.38 in. of water column or 95.8 Pa) prior to venting—a level that is almost 10 times higher than the pressure specified in the ISO 834 test standard. Upon opening of the vent, the pressure within the compartment declines sharply but still remains positive at the ceiling. As the fire continues, the positive pressure within the compartment continues to decrease but at a much slower rate. The pressure history of a fire scenario based on the HAZARD computer program is shown in Table 2. Pressures at the ceiling have been adjusted from HAZARD's output values by the static pressure head due to room height. Notice that after the vent is fully established at 3 minutes, the pressure values at the compartment ceiling are within the range of furnace pressure requirements specified in ISO 834.

As mentioned previously, the influence of the environmental pressure on cracks can significantly effect the fire performance of an assembly. Joints between panels of gypsum wallboard are especially susceptible to cracking. The joint tape quickly burns off and shrinkage of the heated panels widens the natural crevaces. Hot gases penetrating joints and impinging against combustible structural members, resulting in their early ignition, increases the risk of an extended fire. Once the fire has spread to combustibles in concealed spaces, the fire's damage potential also increases.

In tall buildings, additional factors such as wind and stack effects can have a substantial impact on pressures developed from fire. In fact, their influence on pressures during a fire is far greater than that which can be produced by the fire alone. These are considerations that cannot even be approached, much less, adequately addressed, by tests that are conducted under negative pressure.

ASSEMBLIES CURRENTLY REQUIRED TO BE TESTED UNDER POSITIVE FURNACE PRESSURE

All three model building codes, the *BOCA National Building Code (BNBC)*,[8] the *Standard Building Code (SBC)*,[9] and the *Uniform Building Code (UBC)* [10], require that through-penetration protection systems be tested in accordance with ASTM E814[11] under a positive furnace pressure of 0.01 in. of water column (2.5 Pa). Therefore, it is logical to conclude that the walls and floor/ceiling assemblies in which the penetrating systems are installed should also be tested under positive furnace pressures. Without testing the components of an entire construction assembly under equal terms, one cannot identify the weakest point. In view of typical pressures that are developed inside rooms during real-world fire conditions, it can be argued that the codes should require higher pressures. Revising the code provisions to require test pressures within the range of 0.04 to 0.06 in. of water column (10-15 Pa) would make test conditions more representative of those that can develop in actual building fires.

For the same reasons, the aforementioned code provisions should also apply to door assemblies. The need to test door assemblies under positive pressure was recognized at the 1991 ICBO Hearings and resulted in a code change published in the *1992 Supplement* to the UBC[4]. The change was to UBC Standard No. 43-2, "Fire Tests of Door Assemblies," which is the UBC equivalent of ASTM E152. It specifies that the neutral plane be established no more than 40 inches above the door sill after the first five minutes of the test, and be maintained throughout the duration of the test. Example 1 shows that this requirement has the same effect as maintaining a positive pressure differential of approximately 0.04 in. of water column (10 Pa) at the top of the door during a one-hour E119 fire exposure.

EXAMPLE 1

Given: a 7-ft door (2.154 m) exposed to a one-hour E119 fire condition. Venting is such that the neutral plane (n.p.) is established at 40 in. (1.0256 m) above the door sill.

Determine: the maximum positive pressure that occurs on the door.

The maximum pressure occurs at the top of the door when the temperature reaches its peak (at the one-hour period). Temperature, T, at one hour is 1700°F (927°C = 1200°K) = T_{fire}.

Assumptions: temperature is considered uniform throughout the furnace; ambient pressure outside of the furnace at the floor level, P_{floor}, is 1 atmosphere (101,325 Pa); ambient temperature, $T_{ambient}$, is 68°F (20°C = 293°K).

From Drysdale,[12] the density of air under ambient conditions, $\rho_{ambient}$, is 1.20 kg/m³. The density of air at 1100°K is 0.32 kg/m³, and will be used as the density of the air inside the furnace, ρ_{fire}.

Using Eq. 1, where "g", the gravitational constant is 9.81 m/sec², and "h_1", the distance from the floor to the neutral plane is 40 in. (1.0256 m), the pressure at the n.p. can be determined.

$$P_{np} = P_{floor} - (\rho_{ambient}\, g h_1) \quad \text{Eq. 1}$$

By substitution, P_{np} = 101,312.9 Pa.

Since the neutral plane represents the elevation at which the pressure both inside and outside of the furnace or fire compartment is equal, the pressure inside the furnace at the top of the door can be determined from Eq. 2. The distance from the n.p. to the top of the door, "h_2", is 44 in. (1.1282 m).

$$P_{top\ inside} = P_{np} - (\rho_{fire}\, g h_2) \quad \text{Eq. 2}$$

Substituting, $P_{top\ inside}$ = 101,309.4 Pa. By replacing ρ_{fire} with $\rho_{ambient}$ in Eq. 2, the pressure at the top of the door outside of the furnace is computed at 101,299.6 Pa. The difference between these two pressures indicates that the pressure inside the furnace is 9.78 Pa or 0.039 in. of water column higher (more positive) than that outside.

The 43-2 Standard fire condition is identical to that of the E119 time-temperature relationship. In a real-world fire, similar temperatures and pressures to those shown above are likely to occur at the top of the door, with higher pressures and temperatures occurring at the ceiling. Tests of greater than one-hour durations would produce even higher pressures, since pressure varies directly with temperature. Example 1 has shown that doors tested in accordance with UBC Standard 43-2 are being done so under positive pressure. Again, it is only logical that this should be applied to building assemblies as well.

CLOSING STATEMENTS

It is understood that ASTM E119 tests are not intended to simulate all possible real fires. However, the standard specifically states the following, *"... results of this test may be used as elements of a fire risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard of a particular end use. ...The results of these tests are one factor in assessing fire performance of building construction and assemblies."* Based on the following two items: (1) the apparent dampening effect in potential fire severity that is experienced by specimens tested under the current system of negative pressure; and (2) the fact that installed assemblies are exposed to positive pressures in real-world fire conditions; unconservative conclusions are likely to be reached when using the test standard for making such fire safety assessments.

One reservation expressed about the implementation of conducting tests under positive pressure has been the question of its effect on previously tested assemblies. Computer modeling combined with validation procedures, and comparisons of existing assemblies tested under both positive and negative pressures, seems to be the logical solution. The technology to accomplish the first task is available.[13] Acquiring data on similar assemblies tested under both pressure regimes for comparison purposes has proven more difficult.

Positive pressure development in real-world compartment fires is a known fact of fire science. Computer fire models and Table 2 results have shown that sustained pressures due to fire are in the range of those prescribed in the ISO 834 test method. In view of the combination of factors presented, it is recommended that positive pressure testing requirements consistent with ISO 834 should be incorporated into the next rewrite of E119 or be adopted by model building codes. Since the current version of E119 does not specify furnace pressures, negative pressures are likely to continue to be used in U.S. test furnaces. Under these circumstances, unconservative assessments can be expected when such test results are used to evaluate the fire endurance of specific types of wall and floor/ceiling assemblies in actual building construction. This report has shown that panelized construction assemblies that are susceptible to cracking, such as those utilizing gypsum wallboard, belong in this category. Lightweight assemblies containing plenums or suspended ceilings are also included.

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