NUREG/CR-0468
SAND78-1990
RP

Nuclear Power Plant Fire Protection-Fire Barriers (Subsystems Study Task 3)

Earl E. Minor
Dennis L. Berry

Manuscript Submitted: January 1979
Date Published: September 1979

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for the
U. S. Department of Energy

Prepared for
Engineering Methodology Standards Branch
Office of Standards Development
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

UNITED STATES NUCLEAR REGULATORY COMMISSION

GPO Printed copy price: $5.50

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Under Interagency Agreement DOE 40-550-75
NRC FIN No. A-1080

ABSTRACT

Standards currently used in the fire protection field are analyzed in relation to their applicability to nuclear power stations and recommendations concerning their improvement are made. Results of mathematical analyses of typical fire barriers are given. Based on the temperature gradient established in the mathematical analyses, a stress analysis of poured concrete walls is described. Recommendations are made for follow-up studies and experiments.

ACKNOWLEDGMENT

The authors thank D. W. Larson and C. E. Sisson of Sandia Laboratories' Fluid and Thermal Sciences Department for their assistance in defining and modeling the ASTM E 119 standard fire, and J. D. McClure of Sandia's Engineering Analysis Department for stress analyses of the concrete fire barrier.

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NUCLEAR POWER PLANT FIRE PROTECTION -
FIRE BARRIERS (SUBSYSTEMS STUDY TASK 3)

1. Introduction

1.1 Task Description

Based on the need to support near-term regulatory and licensing objectives for nuclear power plant fire protection, the Nuclear Regulatory Commission (NRC) Office of Standards Development requested Sandia Laboratories to develop the underlying logic and technical bases associated with four specific fire protection topics.[1] The topics selected by the NRC were fire ventilation, fire detection, fire barriers, and fire hazards analysis. The third topic, fire barriers, is the subject of this report; separate reports cover the other topics.

It was the objective of this study to assess the adequacy of current standards which govern the design and testing of fire barriers. Specific areas of investigation included the severity of test conditions, the ability of test procedures to represent actual fire conditions, the repeatability of test results, the amount of safety margin afforded by current tests, and the sensitivity of barrier performance to specific design details. It was not an objective of this study to predict the actual conditions to which a barrier will be exposed during a fire or to predict the response of a barrier under these actual conditions. These problems are discussed as part of the fire hazards analysis topic.[2]

1.2 General Procedure

To accomplish the study objective, it was necessary to become familiar with the way in which fire barriers are presently tested and, where possible, to mathematically model the response of barriers under test conditions. Where a clear definition of certain test conditions was lacking or, because of physical complications, the conditions could not be accurately modeled, a qualitative assessment of the test requirements was made. The study procedure can be generally described as follows:

- Study and evaluate the standards currently in force or proposed to determine if the needs of fire safety in nuclear power stations are satisfied by these standards.

- Evaluate thermal characteristics of typical 3-hr barriers and calculate their thermal response when exposed to the standard ASTM E 119 furnace test, using a computerized mathematical model.

- Determine and recommend necessary follow-up action.

1.3 Technical Approach

The NRC has established the requirement that safety-related areas shall be separated by 3-hr-rated barriers.[3] Existing guidelines and standards applicable to the testing of fire barriers (ASTM E 119, ASTM E 152, and IEEE 634)[4-6] were reviewed to determine whether their test methods and criteria satisfy the needs of nuclear power stations.

Using the test conditions defined in these standards, a mathematical model was developed to investigate the thermal response of typical fire barriers when exposed to standard test conditions. To establish limiting barrier performance characteristics, thermal properties of the selected barriers were then varied to determine those property limits for which each barrier would just fail the thermal response criteria of the standard tests.

A study of current available literature was conducted, especially in the area of penetration fire stops. Reports of tests were evaluated against the needs of nuclear power stations.

As a result of the above investigations, recommendations are made for follow-up studies and experiments. (See Section 5.)

2. Evaluation of Existing and Proposed Standards

2.1 General

Standards evaluated in this study were limited to those specifying fire tests of barriers, doors, and penetration seals.

The following standards were evaluated:

- ASTM E 119-76, "Standard Methods of Fire Tests of Building Construction and Materials." This standard is similar to NFPA 251 and UL 263 standards on the same subject.

- ASTM E 152, "Standard Methods of Fire Tests of Door Assemblies." This standard is similar to NFPA 252 and UL 10B.

- IEEE 634-78, "Standard Methods of Fire Tests of Cable Penetration Fire Stops."

These standards were reviewed only for areas which present technical difficulties or which are poorly defined in relation to the requirements of nuclear power stations. No attempt was made to do a comprehensive critique of the standards.

2.2 Evaluation of ASTM E 119

Standard ASTM E 119, "Standard Methods of Fire Tests of Building Construction and Materials," prescribes test methods and acceptance criteria for the elements of construction such as walls, ceilings, floors, beams, and columns. This standard had its origin in recommendations of the International Fire Prevention Congress in London, 1903. The recommendations were based on experience from actual fires and results from fire tests conducted before 1903. Tests had been performed in England using small brick huts and wood as a fuel. The fire was built until it reached the desired temperature and maintained around that temperature as an average for the duration of the test (commonly 4 hours). The temperature most commonly selected was 1700°F (926°C).

In the United States the first attempt at establishing a national standard was begun by the American Society for Testing and Materials (ASTM) in 1907. This effort produced a national standard closely resembling the requirements of the New York building code of 1899 for testing floor elements in a fire hut with a wood-fueled fire. As prescribed in the test procedure, an average temperature of 1700°F (926°C) was to be maintained for 4 hours. In 1909 the ASTM added a separate test for walls, to be performed in a manner similar to floor tests except that the test duration was limited to 2 hours. Both the floor and wall tests made use of a furnace to produce the high-temperature test conditions.

Although the ASTM efforts in 1907 and 1909 are recognized as the first genuine attempts to establish a national standard for fire barrier testing in the United States, it was not until 1917 that ASTM E 119 as it exists today was adopted. In 1917 the ASTM standard was changed from an average-temperature test (at 1700°F or 926°C) to a better defined test using a prescribed time-varying temperature test curve. Today this test curve is often referred to as the standard time-temperature curve.

<u>Origin of Standard Time-Temperature Curve</u> -- Before the establishment of the standard time-temperature curve, exposure in most fire tests had been specified as a temperature, on the average, greater than some value. In 1916 and 1917, two meetings were held to establish fire standards for the United States. These conferences were attended by representatives from American Society for Testing and Materials, National Fire Protection Association, Underwriters Laboratories, National Bureau of Standards, National Bureau of Fire Underwriters, Factory Mutual, American Institute of Architects, American Society of Mechanical Engineers, American Society of Civil Engineers, Canadian Society of Civil Engineers, and American Concrete Institute. The new Standard, ASTM C 19 (later renumbered E 119), was issued at the February 24, 1917, meeting.

The major accomplishment of the new standard was its prescribed time-temperature curve. First published in a 1916 description of proposed UL column tests, this curve has remained unchanged since.

It is important to realize that the standard curve was defined in 1917 without the knowledge of what actual temperature profiles in building fires might be. Although burnout experiments had been conducted in Europe, none had been conducted in the United States at that time and building fire parameters were essentially unknown. Following the adoption in this country of the standard curve, however, the National Bureau of Standards conducted tests which showed that, while the temperature rise during the initial stages of a test fire was more rapid than the ASTM curve indicated, results as measured by the endurance of walls indicated that the ASTM curve approximated the maximum fire severity of the Bureau of Standards tests.

However, the conditions under which these tests were performed differ from conditions to be found in nuclear power plants. For example, the first burnout building (constructed in 1922) was accoutered with furniture and papers to resemble an office and it contained windows which supplied ventilation for the fire. Such test fires, representative of offices and residences, continued into the 1940s and, although no detailed test results of this work were published, it appears that none of the tests were conducted using the conditions of limited ventilation, heavy construction, and synthetic combustibles found in nuclear power plants.

<u>"Standard" Exposure</u> -- It must be understood at the outset that, even though a given barrier has received a 3-hr rating, this does not imply that it will last 3 hrs in every fire situation. Nor does it imply that it will last twice as long as a barrier which has a 1-1/2-hr rating. It means only that a representative barrier has been subjected to a specified time-varying temperature test in a furnace under specified conditions of restraint and has not failed the criteria in ASTM E 119. Many variables enter into the endurance of a barrier, such as construction and loading differences, fuel loading and ventilation (which primarily control the burning rate and the removal of hot gases), fuel distribution and exposed urface of the fuel, and even the volume into which hot gases are vented

from the fire chamber. Also, it is not clear that a comparative quality rating is achieved between the "standard" exposure and endurance in a real fire. Babrauskas[7] presents the argument as follows:

> It is sometimes asserted that, even though under many conditions the standard curve exposure will not be at all similar to the expected realistic exposure, it is still justified to use the curve. The argument usually runs, "we know the test results will not be the same as endurance time in a fire, but so long as the test exposure is fully standardized, all materials will be tested fairly and adequate ranking established." It should be adequately clear that such a viewpoint is untenable. Compare, for instance, an assembly using materials which are good insulators and have low T_C*, with one using poorly insulating, high T_C materials. When tested under appropriately low temperatures, the first assembly will be superior, but at higher temperatures the second will be better. In general, there is no way of assuring that even relative rank will be preserved; in consequence testing under conditions greatly differing from those of the expected fire is not a suitable design philosophy.

On the other hand, Kanury and Holve concluded that ". . . there is no reason to discard the standard time-temperature curve as a specified exposure source for fire performance evaluation of materials, even though superficially it fails to be a realistic duplicate of any one particular full-scale enclosure fire exposure history."[8]

Walls most commonly used in nuclear power plants are of poured concrete. Other walls which could be used are concrete block or gypsum board with appropriate structural support. The exposure provided by the ASTM E 119 standard fire-exposure test is a reasonable method of assessing these fire barriers when it is combined with a knowledge of expected fire conditions to which a particular barrier may be exposed.

Restraint -- Standard ASTM E 119 provides for bearing walls and partitions to be tested with a load superimposed "in a manner calculated to develop theoretically, as nearly as practicable, the working stresses

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*T_C is the critical temperature of the material. As an example, for structural steel the critical temperature is usually considered to be 1000°F (538°C).

contemplated by the design." For bearing walls, the standard specifically states that the test specimen shall not be restrained on its vertical edges. Test specimens of nonbearing walls and partitions, on the other hand, are specifically required by the standard to be restrained on all four edges.

Restraint of walls during test has been debated for years with no consensus reached. In view of the difficulty in determining a reasonable restraint specification and in view of the fact that the furnace test is a poor simulation of actual building fires, no change is recommended in this study. Of considerably more importance is the need to protect steel beams and columns so that critical temperatures are not exceeded, thereby causing structural failure.

Critical Temperature of Steel -- Steel structural elements must be protected so that their critical temperature is not exceeded.

Columns and beams must be tested in a configuration simulating their actual construction and loaded "in a manner calculated to develop theoretically, as nearly as practicable, the working stresses contemplated by the design."[4] The component is considered as passing the fire endurance test successfully if it sustains the applied load for a period equal to that for which the classification is desired.

An alternate method for testing the protection of structural steel columns does not require that a load be applied. Instead, the column is instrumented with at least three thermocouples located at each of four levels to measure temperatures of the steel. The test is considered successful if "the transmission of heat through the protection during the period of fire exposure for which classification is desired does not raise the average (arithmetical) temperature of the steel at any one of the four levels above 1000°F (538°C) or does not raise the temperature above 1200°F (649°C) at any one of the measured points."

In actual situations, the failure temperature of steel is a function of the stresses present in the steel,[9] which are not really determinable in a complex situation because the load-bearing contributions of the associated structures (decking, etc.) are uncertain and may in fact change as a fire progresses. The commonly accepted critical temperature for steel of 1000°F (538°C) is a satisfactorily conservative figure. The point must be stressed, however, that protection of steel beams and columns must be provided so that barrier integrity is maintained.

<u>Hose-Stream Test</u> -- Section 9 of ASTM E 119 describes the hose-stream test required of walls which have a rating of 1 hr or more. A duplicate of the sample wall exposed to the fire endurance test shall be exposed to a fire exposure test for a period equal to one-half of that indicated as the resistance period in the fire endurance test, but not for more than 1 hr. Immediately thereafter it shall be subjected to the impact, erosion, and cooling effects of a hose stream directed first at the middle and then at all parts of the exposed face ~~with changes in direction being~~ made slowly. As an alternate, the specimen exposed to the fire endurance test may immediately thereafter be exposed to the hose-stream test.

While it is apparent that the hose-stream test might eliminate excessively flimsy structures by applying a horizontal load, the force delivered by the hose stream and the application of that force to the wall are not readily calculable or precisely controllable.

Under E 119 conditions, S. H. Ingberg determined that with 30 psi water pressure the measured force against a test panel was 257 N (about 58 lb).[10] The area on which the stream impinges is about 56.7 cm^2 (about 9 $in.^2$), giving an average static stress of 4.53×10^4 Pa (6.6 psi). In case of failure, an average stress value is meaningful only if a large segment of the wall buckles. However, failure usually is caused by a more puncture-like penetration of the hose stream.

Harmathy and Lie[9] have stated:

> The results of the hose stream test and cotton waste test* are very difficult to interpret in strict scientific terms. If unbiased scrutiny were to indicate that there is need for tests of this kind in the standard specification, they would have to be respecified to yield well-defined, quantitatively expressible results.

Babrauskas[7] has suggested that orthogonal loading be applied to walls only and that the hose-stream test be eliminated in favor of "either a pendulum impact test after the specimen is removed from the furnace (as is done in Germany)[11], or a constant orthogonal loading applied throughout the test."

The German specification (DIN 4102) to which Babrauskas refers provides for a spherical impact in three equally-spaced locations on the outside (unexposed) surface of the test specimen 3 min before the expiration of the rating period. The impacts are to be imparted by a pendulum with a spherical mass of 15 to 25 kg displaced so that an impact of 20 Nm (i.e., 20 J or 14.75 ft-lb) occurs at the point of impact.[11] The obvious advantages of such a system are the capability of calibrating the equipment and the ability to compute the impact force.

This report does not advocate any specific replacement for the hose-stream test but does point out that it is neither repeatable nor capable of rigorous analysis.

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*ASTM E 119 requires that the wall or partition being tested "shall have withstood the fire endurance test without passage of flame or gases hot enough to ignite cotton waste, for a period equal to that for which classification is desired."

Furnace Differences -- As explained earlier, ASTM E 119 tests are conducted using furnaces which are controlled to produce a specified time-varying temperature environment for each test wall. In practice, temperature control is accomplished by regulating fuel flow into a furnace in response to a fuel-demand signal generated by thermocouples installed 6 inches from the test specimens. Because furnace configurations and construction materials can vary from one test facility to another, some investigators have questioned the validity of controlling furnace temperatures from thermocouple response signals without first calibrating the thermocouples in conjunction with the particular furnace environments to ensure consistency among all test furnaces. This concern may be unfounded.

Based on the analysis described in the Appendix, it appears that the present use of thermocouples actually minimizes the effects of different furnace configurations on test results. The analysis shows that, for thermocouples in two different furnaces to follow the same temperature history, the severity of the test conditions must be equal for the two furnaces. This result is supported by a set of measurements taken in the University of California (Berkeley) wall test furnace and reported by Babrauskas.[7] These measurements demonstrate that the effect of the thermal properties of a furnace on the heat flux to the test specimen is slight and, indeed, may not be any more significant than the variation between tests in the same furnace. In addition to the insensitivity of test results to furnace properties, Babrauskas has found that, over a wide range of thermocouple sizes and shapes, all thermocouples respond comparably after a lag period ranging from several seconds to about 10 minutes, depending on the thermocouple mass. For a 3-hr test, this lag is negligible.

2.3 Evaluation of ASTM E 152

Standard ASTM E 152, "Standard Methods of Fire Tests of Door Assemblies," provides for both a fire endurance test and a hose-stream test. The discussion of the standard time-temperature curve given in Section 2.2, Evaluation of ASTM E 119, is applicable to ASTM E 152 as well.

Criteria which must be met by a door assembly during the fire endurance test are:

- No flaming is allowed on the unexposed surface during the first 30 min of fire exposure.

- Light (approximately 6-in.) flames are allowed along the edges of the door on the unexposed side after 30 min for periods not exceeding 5 min.

- Light flaming, as defined above, may occur on the unexposed surface during the last 15 min if the flames are within 1-1/2 in. of a vertical edge or within 3 in. of the top edge.

- A hose-stream test shall be performed after the fire exposure without openings developing during the impact.

When hardware is to be evaluated for use on fire doors, it shall hold the door closed in accordance with the conditions of acceptance throughout the exposure period and, in addition, the latch bolt shall remain projected and shall be intact after the test. The hardware need not be operable after test.

Hose-Stream Test -- Perhaps the hose-stream test applied to door assemblies is more defensible than the application of the hose-stream test to walls (see discussion in Section 2.2) because of the elimination of excessively flimsy door assemblies from consideration as rated doors. However, the criticism mentioned in the earlier section is still valid, insofar as inability to calculate the resulting forces or control the application of those forces to the door.

The authors' view is that, although the hose-stream test is of value in eliminating flimsy structures, an improved method which is more readily controlled and capable of analysis would be desirable.

Furnace Pressure -- ASTM E 152 directs, "Maintain the pressure in the furnace chamber as nearly equal to the atmospheric pressure as possible." (The pressure of a natural-draft furnace may be controlled by dampers in the exhaust flues, while a forced-draft furnace may be controlled by controlling the blowers.)

In a compartment fire, a positive pressure difference between the room and the surrounding environment is generated by the expansion of gases within the room, and the pressure will vary according to the available ventilation to the room and the density (and temperature) of the combustion gases. Unfortunately, furnace tests of doors, as well as other building components, are consistently performed with a slightly negative furnace pressure, apparently to minimize the escape of toxic smoke and gases from the furnace to adjacent areas. Because of this, the effectiveness of a door in limiting the spread of flame and smoke is not fully tested. Heating of the door cracks, especially along both the top and the door jam, will be significantly affected by the furnace pressure. If the furnace pressure is positive, the cracks will be heated; conversely, if the furnace pressure is negative, the cracks will be cooled by the inflow of air. Obviously, a considerable advantage accrues to doors being tested under negative pressure conditions.

Section 6.2.5, Part 2, of the German standard, DIN 4102, requires that, "when testing building components whose function includes sealing a room, a positive overpressure of 10 $\pm$ 2 Pa must be maintained throughout the test, beginning 5 min after ignition."[11] Ten pascals is equivalent to 0.00145 psi or 0.04 in. of water, a slight positive pressure. A positive pressure of at least that magnitude should be incorporated into Standard ASTM E 152 to improve the evaluation of doors.

2.4 Evaluation of IEEE 634

Until very recently there was no standard to specify tests or criteria for penetration seals. IEEE 634, "IEEE Standard Cable Penetration Fire Stop Qualification Test,"[6] is the first attempt to fill this need.

Before this standard appeared, tests had been performed using ASTM E 119 criteria. The new standard is also based on ASTM E 119, with the only apparent difference being that the temperature rise on the unexposed surface is limited by the self-ignition temperature of the outer cable covering, the fire stop materials, or material in contact with the fire stop. For power generating stations, the standard specifies a maximum temperature (not temperature rise) of 700°F on the unexposed surface.

The discussion of the standard time-temperature curve given in Section 2.2, Evaluation of ASTM E 119, is applicable to IEEE 634.

Criteria which must be met by penetration seals are quoted below:

> 6.1.1 The cable penetration fire stop shall have withstood the fire endurance test as specified without passage of flame or gases hot enough to ignite the cable or other fire stop material on the unexposed side for a period equal to the required fire rating.
>
> 6.1.2 Transmission of heat through the cable penetration fire stop shall not raise the temperature on its unexposed surface above the self-ignition temperature as determined in ANSI K65.111-1971 of the outer cable covering, the cable penetration fire stop material, or material in contact with the cable penetration fire stop. For power generating stations, the maximum temperature is 700°F.
>
> 6.1.3 The fire stop shall have withstood the hose-stream test without the hose stream causing an opening through the test specimen.

Hose-Stream Test -- As in the case of door tests, the hose-stream test may have some validity as a method for eliminating inadequate materials or poor installations. However, the criticism given in Section 2.2 of this report remains applicable to hose-stream tests of penetration seals. The unevenness of forces resulting from the hose stream and the lack of repeatability of the test complicate the performance of an engineering analysis of test results. Therefore, the test represents only a factor upon which a subjective judgment may be based.

Furnace Pressure -- See Section 2.3 for a discussion of furnace pressure as it applies to tests of doors. The points mentioned there are applicable to penetration seals as well. The fact that furnace tests are commonly run with a slightly negative furnace pressure instead of a positive pressure simulating an actual fire is probably a more serious error for penetration seals than for any other construction component.

Penetration seals are commonly made of a foamed-in-place silicone rubber compound which has the characteristic of burning slowly so as to provide protection a prescribed length of time.

In contrast to the negative pressure of the furnace test, the positive pressure of an actual fire will cause the following:

- Increased burning rate of the fire-stop material because of a better supply of oxygen to the burning surface.

- Increased erosion of the char which normally forms on the surface of fire-stop material exposed to the test fire. Increased erosion--or less char--will allow easier access of oxygen to the burning surface and also provide less insulation against heat penetration.

- Increased likelihood of hot gases or flame being emitted from cracks or openings in the penetration seal.

Thus, it is apparent that a negative furnace pressure during the fire exposure test of a penetration seal could result in an undertest and consequent over-rating of a particular seal.

It is, therefore, the strong recommendation of this study that a positive pressure be defined and incorporated into the standard for fire exposure testing of penetration seals.

3. Thermal Modeling of Walls

3.1 Description of Walls Modeled

Three types of wall construction were chosen for analysis. Predominant in the nuclear power industry is the concrete wall with steel reinforcement. For this first case the analysis concentrated on a thickness of 8 in. as representing the minimum thickness which might be used as a 3-hr barrier.[12]

For the second wall type, a concrete block wall was selected as being representative of a typical add-on (or backfitted) 3-hr configuration (see Figure 1). Again, an 8-in. thickness (minimum 7-5/8-in. thickness) was chosen to represent the minimum for a 3-hr barrier.[12]

To complete the analysis, a wall consisting of steel and gypsum board was modeled. There are cases in older nuclear power plants where space limitations dictate the use of this type of wall construction. Details of the wall configuration were taken from design No. U603 in the UL Fire Resistance Index, 1976.[12] The "back face" was a duplicate of the "front" or fire-exposed face so that a 3-hr rating from either side was obtained. See Figure 2 for construction.

Though not necessarily defining all possible 3-hr barriers, these walls are typical of those which might be used as 3-hr fire barriers in nuclear power plants. Conversations with representatives from a cross section of nuclear power plants indicate that the steel-reinforced cast concrete wall is the most commonly used.

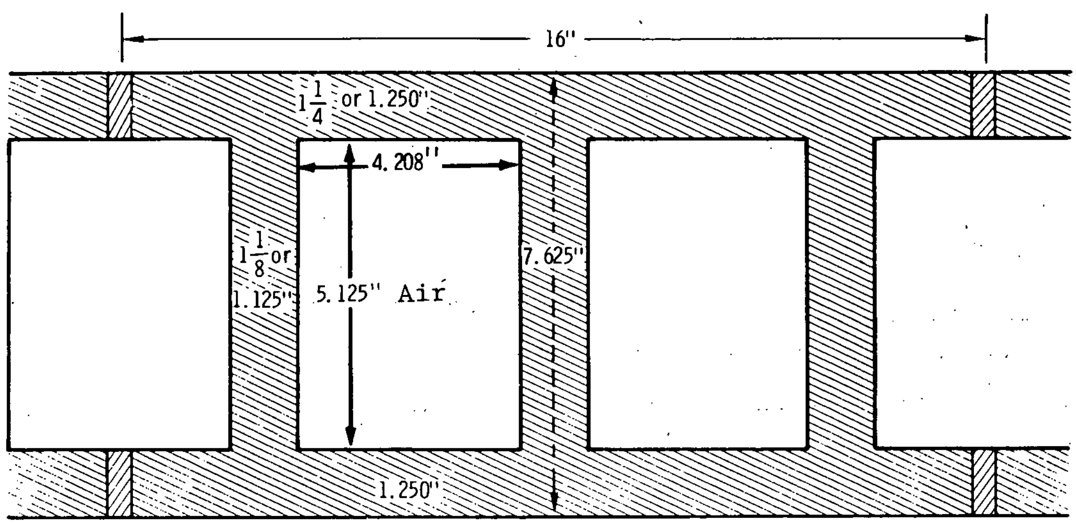


Figure 1. Typical Block Construction

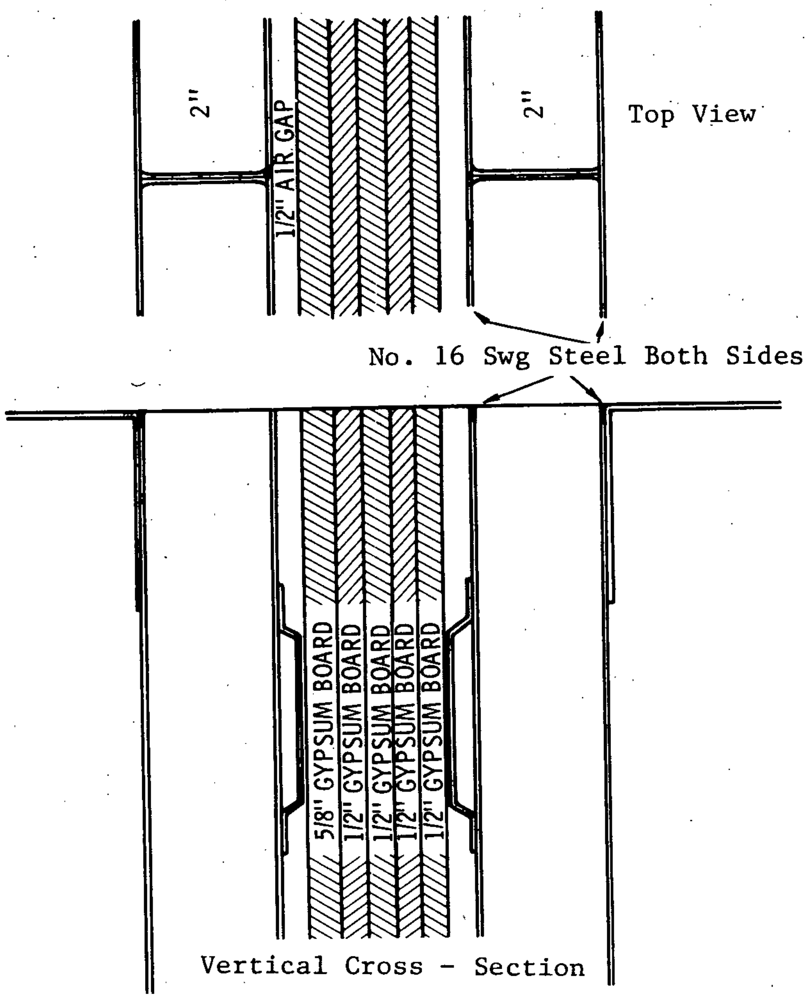


Figure 2. Diagram of Composite Wall

3.2 Thermal Analysis

Description of Method -- Basic equations for radiative, conductive, and convective heat transfer were solved to determine the temperature profile through the typical walls described in Section 3.1. These equations take the form

$$q_R = \sigma\epsilon\left(T_1^{\;4} - T_2^{\;4}\right) \qquad \text{for radiation,}$$

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \qquad \text{for conduction, and}$$

$$-k \frac{\partial T}{\partial x} = h\,(T_1 - T_2) \qquad \text{for convection,}$$

where

σ = the Stefan-Boltzmann constant
ε = emissivity
ρ = density of the material
C_p = specific heat of the material at constant pressure
k = thermal conductivity of the material
h = convection coefficient
T = temperature (K).

In general, these equations were solved by using a computer program which mathematically divided each of the three wall types being analyzed into segments. By using small wall segments and small time steps, the differential terms in the heat transfer equations could be treated as finite differences. Once the heat transfer mechanism for the walls was modeled in this way, the thermal response of the walls was calculated using the controlled temperature conditions which exist in a test furnace as defined by ASTM E 119. Then, by mathematically varying the thermal properties of the walls (e.g., density, thermal conductivity, and heat capacity) over a realistic range of values until the thermal response of each wall "just failed" the criteria in ASTM E 119, limiting values for each thermal property were calculated. The Appendix presents the details of this approach.

Proceeding in this manner, it is possible to assess the relative importance of each thermal parameter and to judge whether a reasonable variation of the parameters from one installation to another could result in an unexpected barrier failure. This knowledge, when combined with a knowledge of the anticipated severity of a fire in particular power plant areas, can be used to predict barrier response under installed conditions.[2]

Cast-Concrete Wall -- Temperature gradients through an 8-in. concrete wall were calculated by using the approach outlined above. The results of this effort are shown in Figures 3 and 4. Figure 3 includes the temperature rise vs time for the test furnace flame, the furnace thermocouples, and the wall's front face and back face. The curves in Figure 4 depict temperature gradients through the wall at 30 min and at each 30-min increment of time through 3 hrs. The thermal responses shown correspond to those expected to occur in a wall which "just passes" an ASTM E 119 furnace test for 3 hrs (i.e., the back-face temperature increases 250°F during the test). To arrive at this condition, the wall emissivity (ε_W), thermal conductivity (k), and heat capacity (ρC_p) were adjusted as explained earlier. The adjusted values are shown in Table I.

Based on a comparison of the limiting values shown in Table I with typical literature values for concrete,[13-16] it is concluded for this study that the thermal performance characteristics of cast concrete barriers are insignificantly affected by practical variations of wall thermal properties.

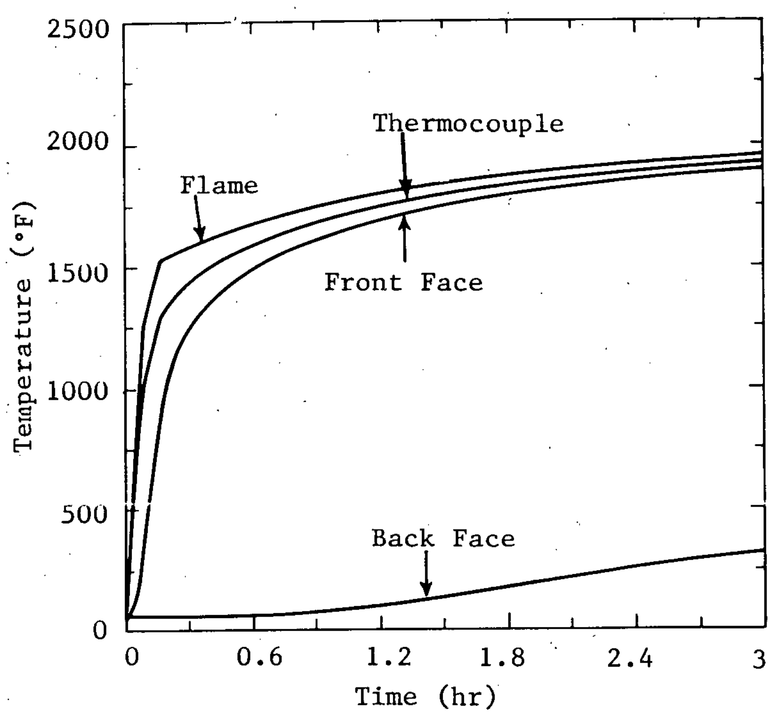


Figure 3. Thermal Model Results for Fire Test of Concrete Wall (8 in.)

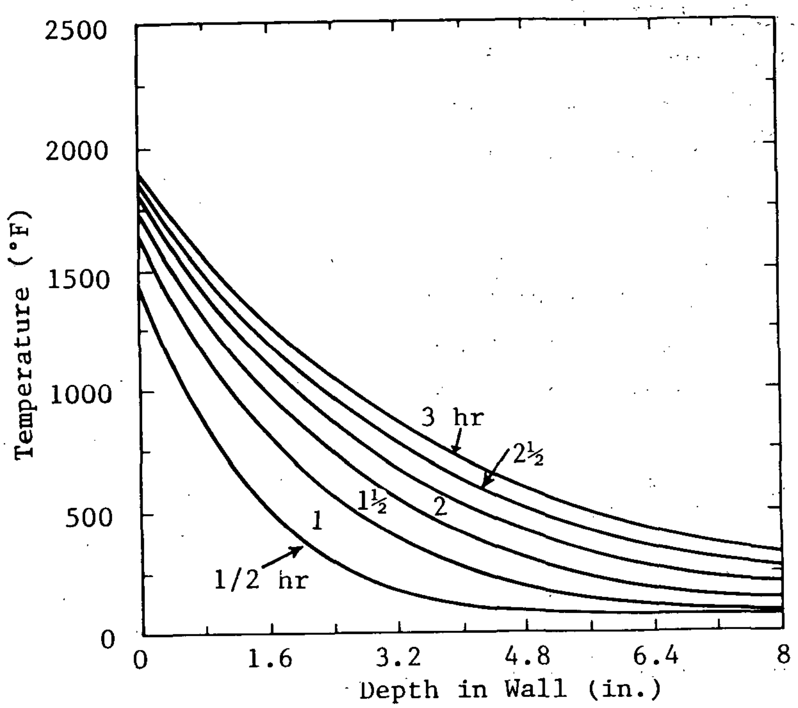


Figure 4. Thermal Model Results for Fire Test of Concrete Wall (8 in.) - Profile Through Wall

TABLE I

Thermal Characteristics of Cast-Concrete Wall

Thermal Property (footnote)	Value
ε_W (a)	0.65
k (b)	2.043-0.001096T W/m-°C
ρC_p (c)	2.02×10^6 J/m^3-K

[a]Calculations using 0.4 and 0.8 for emissivity (representing practical lower and upper limits) for the 8-in. concrete wall resulted in a back-face temperature difference of only 8.7°F (4.8°C) at the end of 3 hrs. On this basis, the use of an approximate midrange value of 0.65 was considered justified.

[b]This value is based on work described in Reference 13. The multiplying constant was adjusted to obtain a "just-passing" temperature rise on the back face of an 8-in. concrete wall. T in this formula is in degrees centigrade.

[c]Adapted from measurements by Harmathy and Allen.[14] This value represents an effective heat capacity of the wall over the temperature range calculated. The value includes latent heat effects.

Concrete-Block Wall -- As done for the cast-concrete wall, the thermal properties of a concrete-block wall were varied to yield a "just passing" thermal response. The thermal property values used are presented in Table II, and Figures 5 and 6 are graphs of the thermal response results.

Except for the thermal conductivity (k), the values in Table II for a block wall are the same as those in Table I for a cast-concrete wall. It was found that an extremely high value of thermal conductivity (0.382 W/m-K) was needed to cause "just passing" conditions in the concrete-block wall. In fact, this value is 73% higher than expected for block wall material,[15] and therefore represents a very conservative limiting case.

Based on this result, it is concluded for this study that the thermal performance characteristics of concrete-block barriers are insignificantly affected by practical variations of wall thermal properties.

TABLE II

Thermal Characteristics of Concrete-Block Wall

Thermal Property	Value
ε_W	0.65
k	0.382 W/m-K
ρC_p	2.02 x 10^6 J/m^3-K

Steel-and-Gypsum-Board Wall -- To complete the thermal analysis of 3-hr barriers exposed to the ASTM E 119 standard time-temperature curve, a steel-and-gypsum-board wall was analyzed. In addition to the analysis previously described, the latent heat of vaporization (which was included in the value of ρC_p for concrete) was modeled separately for gypsum. This was necessary because gypsum typically consists of 20% water by volume.

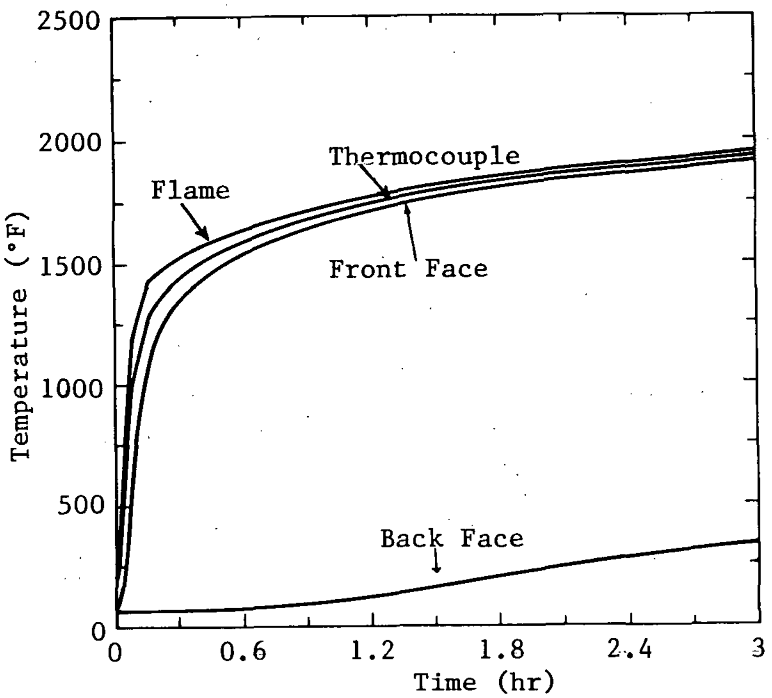


Figure 5. Thermal Model Results for Fire Test of Concrete Block Wall (8 in.)

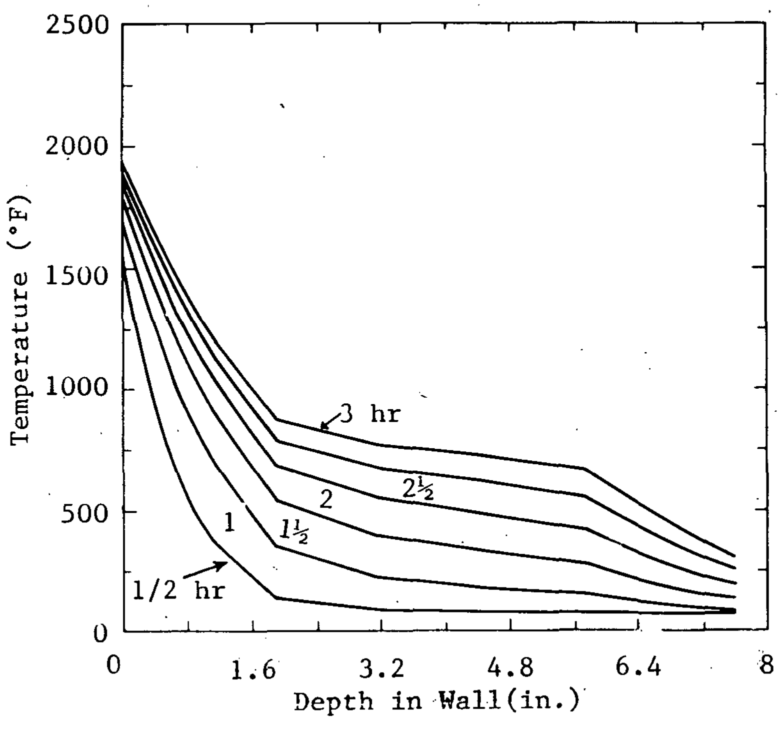


Figure 6. Thermal Model Results for Fire Test of Concrete Block Wall (8 in.) - Profile Through Wall at Web

The thermal properties of steel and gypsum which were used (from Reference 16) are listed in Tables III and IV.

TABLE III

Thermal Properties of Steel[16]

Temp (°C)	k(W/m-K)	ρC_p (J/m^3-K)	ε
0	43.26	3.688×10^6	0.8
100	43.26		
200	43.26		
300	41.54		
400	39.80		
600	31.15		
800	29.42		
1000	29.42		
1200	31.15		

TABLE IV

Thermal Properties of Gypsum[16]

k(W/m-K)	ρC_p (J/m^3-K)	ε
0.457	6.027×10^5	0.8

Latent heat of vaporization was taken into account at each node of the computer model as the node reached 212°F (100°C). According to Kanury and Holve, vaporization occurs abruptly at the boiling point of water.[8] Figure 7 shows the temperature-vs-time history of each element of the wall. Temperature gradients at 30-min intervals are shown in Figure 8. The "steps" occur because of the loss of heat to the water vapor as the nodes reach vaporization temperature. Density of the water was taken as 62.4283 lb/ft^3 (1 g/cm^3 or 1000 kg/m^3) and the specific heat, C_p, as 4.184 J/g-°C.

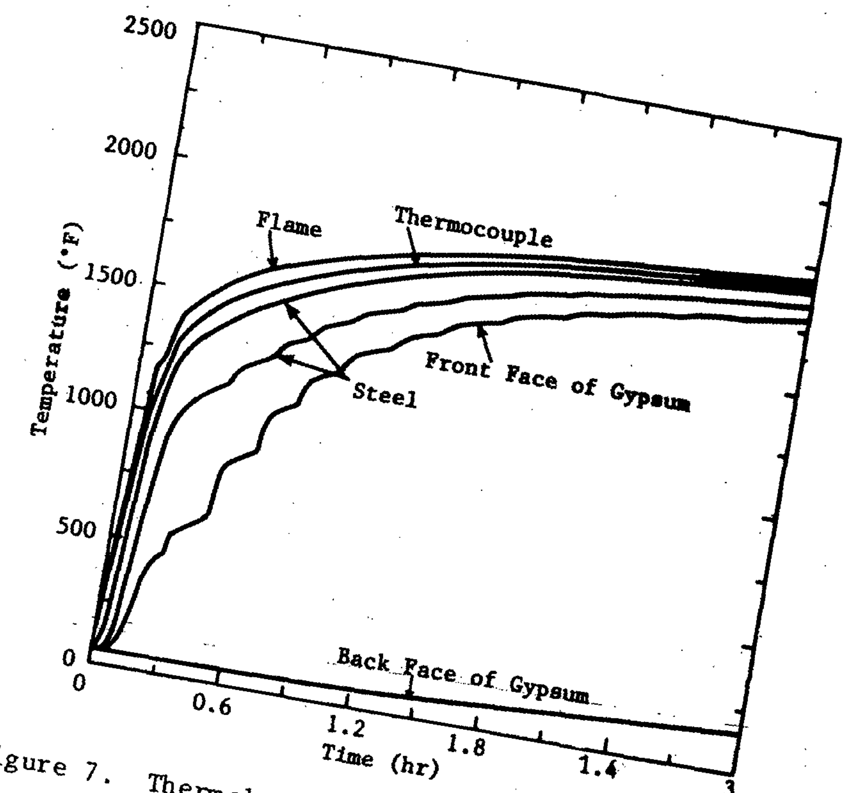


Figure 7. Thermal Model Results for Fire Test of Composite Wall (8 in.)

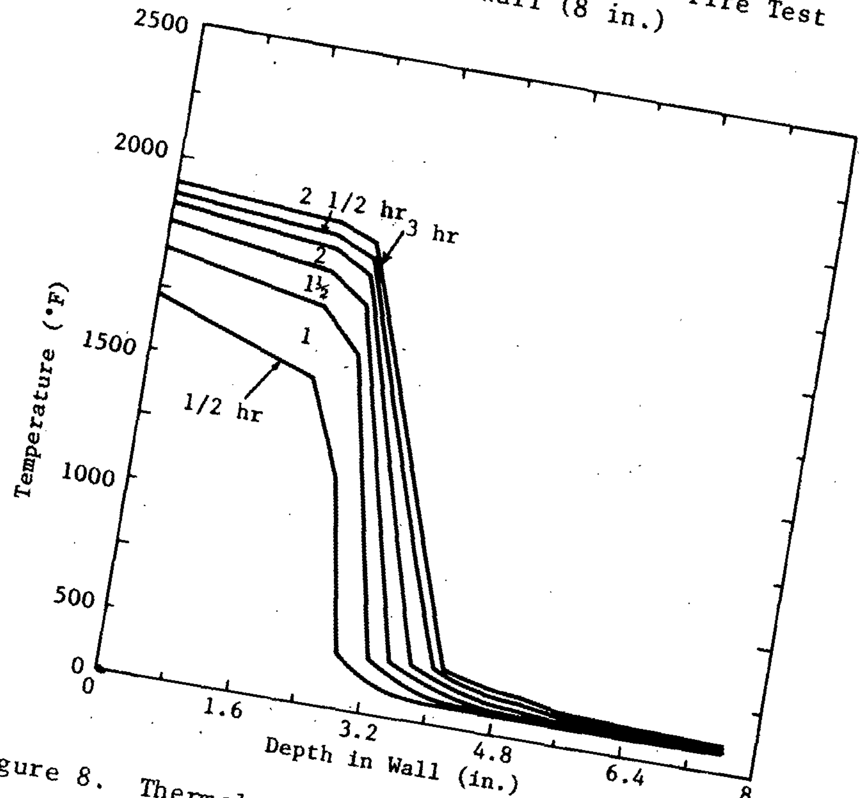


Figure 8. Thermal Model Results for Fire Test of Composite Wall (8 in.) - Profile Through Wall

From Figures 7 and 8 it can be seen that, unlike the cast-concrete and concrete-block walls discussed earlier, an 8-in. composite wall will pass a 3-hr test with considerable thermal margin for the back-face temperature. This is because moisture vaporization from the gypsum board affords considerable fire protection; to "just pass" the 8-in. composite wall, an unrealistically low (<20%) moisture content would have to be assumed.

Kanury and Holve has shown that increasing the moisture content to 50% would afford the greatest protection;[8] however, the 20% value used in this study is typical of commercially available materials. On this basis it is concluded for this study that the thermal performance characteristics of a composite gypsum board/steel fire barrier are insignificantly affected by practical variations of barrier thermal properties.

3.3 Stresses Caused by Thermal Gradient

In addition to studying the thermal degradation of fire barriers under test conditions involving prolonged, high-temperature exposures, it was recognized that an evaluation of the material stresses within the barriers also should be made. Unfortunately, a rigorous mathematical assessment of the thermally induced stresses occurring within a fire barrier presents a formidable problem whose solution lies beyond the scope of this study. In particular, the following difficulties complicate the stress analysis:

- The constraining loads which bound fire barriers during testing and during an actual fire in a power plant are not readily quantified.

- The degree of stress relief afforded by localized cracking and spalling of the barrier surface is a complicated function of the barrier age, induced stress gradients, amount of reinforcement, and constraining loads.

The significance of these factors was evaluated by performing a finite-element stress analysis of an 8-in.-thick, reinforced concrete wall when exposed to the temperature gradients predicted by the thermal analysis described above. It was found that, without allowing some degree of stress-relief cracking within the concrete wall, the barrier would be expected to fail within 30 min. Since such test failures are not observed for 8-in. concrete walls, it is clear that a simple stress analysis model which ignores localized spalling or cracking is inadequate.

Despite these analytical shortcomings, however, several qualitative conclusions can be reached. First, problems associated with calculating the effects of various constraining loads can in part be avoided by following standard ASTM E 119 requirements (to load test walls) ". . . in a manner calculated to develop theoretically, as nearly as practicable, the working stresses contemplated by the design." Second, as stated earlier (page 26) and discussed further in Section 5.1, adequate barrier performance can best be demonstrated by ensuring that the actual fire conditions do not exceed the temperature or duration limits to which a barrier originally is tested. Third, as will be discussed in the next section, a survey of numerous test reports reveals that barrier penetration seals, and not the barriers themselves, are probably the weakest element of nuclear power plant fire barriers.

On the basis of these observations and the limited scope of this study, it appears that further evaluation of the stresses induced in barriers during testing is not warranted at this time.*

*Work to refine the wall stress model discussed above to include the effects of localized stress relief is proceeding at Sandia Laboratories in conjunction with a nuclear power plant fire protection program being funded by the U. S. Department of Energy.

4. Literature Study of Penetration Seals

A study of the available reports on fire tests of cable penetration fire stops reveals a lack of sufficient data upon which to base an adequate conclusion. Of nineteen reports evaluated, four were of 1-hr tests,[17-20] fourteen reported 3-hr tests,[21-34] and one was of a test extended to 5 hr.[35] Two tests of 3-hr duration were performed with a positive furnace pressure;[21 26] other tests--where furnace pressures were reported--were performed with a negative furnace pressure of 0.08 in. of water.[24 29 32-34] Tests for which furnace pressures were not reported are assumed to have been conducted with negative furnace pressures because they are conventionally done in that way. One of the tests conducted with a positive pressure is considered a severe overtest as the pressure was controlled at 9 in. of water inside the furnace.[21] Predictably, the fire stop failed. Back pressure in the furnace for the test reported in Reference 26 ranged from 0.25 to 0.5 in. of water, a reasonable value for an actual fire. Although most of the penetration seals tested were of the foamed silicone type, the seal in the test just mentioned was constructed with fireproof hardboard dams at both ends of the penetration, the cables sprayed with a hard-setting fireproof material, and the cavities and seams packed with an insulating wool. No failure was observed.

The actual performance of commercial penetration seals in a realistic fire environment has not been well demonstrated by most of the fire tests reviewed.[17-35] These tests have not been conducted in a consistent enough manner to allow significant conclusions to be reached.

5. Conclusions and Recommendations

5.1 Walls

Capability of Walls Modeled -- The reinforced concrete, concrete block, and gypsum walls modeled in this study represented configurations with conservatively realistic thermal properties. On this basis, walls of these types used in nuclear power plants would serve as adequate barriers, if exposed to actual fire conditions which do not exceed the temperature and duration limits to which the walls were originally tested.[2]

Standard Time-Temperature Curve -- Because the standard fire cannot be considered as representative of compartment fires, the fact that a given barrier has received a standard rating does not mean that it will last for the rated duration in every fire situation or that a comparative quality rating is achieved. Nevertheless, it is recommended that no change be made to the standard time-temperature exposure because

- A large amount of experience has been gained using the standard exposure,
- No "standard" exposure can be defined which will eliminate all such objections, and
- Utilities are expected to assess the types of fires to which a given barrier may be exposed and evaluate the barrier in the light of such knowledge.

In addition to this, it can be concluded that the present use of thermocouples to control barrier exposure temperatures during testing minimizes the effects of different test furnace configurations and, therefore, represents an acceptable practice for ensuring standard temperature test conditions.

Critical Temperature of Steel -- Of considerable importance is the need to protect steel beams and columns so that critical temperatures are not exceeded.

Hose-Stream Test -- It is recommended that the hose-stream testing of walls be eliminated. If it is felt that an orthogonal load should be applied to the wall, a more repeatable method which is amenable to either analysis or measurement of forces should be developed.

5.2 Doors

Hose-Stream Test -- Because of an inability to accurately calculate or control the forces applied to a test specimen during the hose-stream test, an improved method should be defined to replace that test. Such a method should be suitable for analysis or direct measurement of the applied forces.

Furnace Pressure -- To ensure that the test realistically represents compartment fires and the response of doors to these fires, it is recommended that fire exposure tests be performed with a slight positive furnace pressure. The German standard DIN 4102 requires a positive furnace pressure of 10 ± 2 Pa (0.00145 psi or 0.04 in water).[11] A positive furnace pressure of at least that magnitude should be required for the testing of door assemblies.

5.3 Penetration Seals

Hose-Stream Test -- The criticism of the hose-stream test in Section 5.2, Doors, is applicable to penetration seals also. It is recommended that a repeatable method of loading the seals which is amenable to analysis or direct measurement of forces be developed.

Furnace Pressure -- As discussed at length in Section 2.4 of this report, the practice of testing with a negative furnace pressure is especially inadequate for penetration seals. Therefore, it is recommended that a requirement be added to Standard IEEE 634 for a reasonable positive pressure in the furnace during fire exposure tests.

Definition of Test Specimens -- The ANSI/IEEE 634 standard should specify that the configuration tested be representative of the assembly as it is installed in the power plant, not only duplicating the penetration seal itself, but also providing the same layout among cable trays with the same suspension and restraints as will be incorporated into the power plant barrier. While it is presumed that the NRC has consistently required that this be done as a condition of licensing, the practice does not appear to be documented as a requirement.

Recommendation for Further Investigation -- A series of controlled fire tests are needed to gain sufficient information to evaluate commercially available seals. The following steps are recommended:

1. Determine the magnitude of the steady-state pressure to be expected in a burning area of a nuclear power plant.

2. Determine the magnitude and duration of any pressure pulses which may result from a sudden introduction of air into a burning room deficient in oxygen (as when a door is opened).

3. Expose representative, commercially available penetration seals to a standard ASTM E 119 furnace test, in the steady-state pressure defined by item 1 and the pressure pulse defined in item 2.

4. Expose representative, commercially available penetration seals to the worst-case temperature and pressure conditions expected in nuclear power station fires.

During the tests outlined above, the effects of both steady-state and impulse pressure differentials across the seals and the effects of thermal expansion of penetration components such as pipes, conduits, and cable trays would be investigated.

APPENDIX

Thermal Model of ASTM E 119 Fire Exposure Test

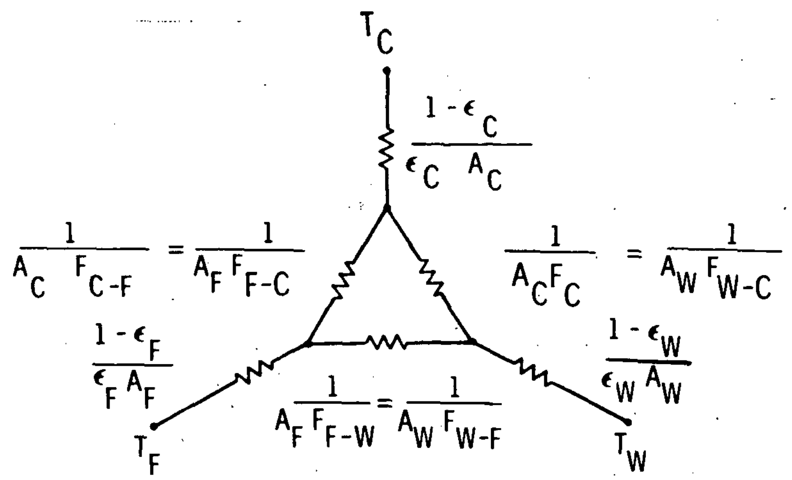
ASTM E 119 requirements for the furnace test of building construction and materials were used as the basis for modeling the responses of the three types of walls to the standard fire. The following basic assumptions were made:

- Blackbody radiation from furnace walls was assumed.
- Thermocouples 6 in. from the test wall are required to follow the standard time-temperature curve. Thus, the fire temperature and the wall temperature were computed based on the view factors between the wall and the thermocouple and the flame.
- Emissivity of the thermocouple was assumed to be 0.8. This assumption was tested by holding other parameters constant and calculating the thermal response of the 8-in. concrete test wall with a thermocouple emissivity of 0.2. A back face temperature difference of about 3% resulted. Therefore the more conservative (and probably more realistic) value of 0.8 was chosen.
- Thermocouples were idealized to massless spheres to simplify calculations.
- Flames were assumed not to touch the test wall with a significant velocity.

- Radiation was considered the means of transmitting heat to the test wall. Convection was ignored as contributing 10% or less of the energy reaching the wall. Other investigators agree with this conclusion.[7,8] Kanury and Holve agree, even though convection was considered in their analysis. (Notice that this assumption and the first one listed tend to be compensating.)

- In the cavities of the block wall and the composite wall, radiation was considered the means of transmitting heat and convection was ignored.

An electrical analog of the energy "circuit" is given in Figure A-1.



T_F = ABSOLUTE TEMPERATURE OF FIRE
T_C = ABSOLUTE TEMPERATURE OF THERMOCOUPLE
T_W = ABSOLUTE TEMPERATURE OF WALL
F = VIEW FACTOR
A = AREA
ϵ = EMISSIVITY
SUBSCRIPTS:
C = THERMOCOUPLE
F = FLAME
W = WALL

Figure A-1. Electrical Analog of Energy Circuit

Energy exchange between the fire and the thermocouple is given by

$$q_{F-C} = \sigma \left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C A_C} + \frac{1}{A_C F_{C-F}} + \frac{1-\varepsilon_F}{\varepsilon_F A_F}} \right] \left(T_F^4 - T_C^4 \right) . \qquad (1)$$

Similarly, energy exchange between the wall and the thermocouple is given by

$$q_{C-W} = \sigma \left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C A_C} + \frac{1}{A_C F_{C-W}} + \frac{1-\varepsilon_W}{\varepsilon_W A_W}} \right] \left(T_C^4 - T_W^4 \right) , \qquad (2)$$

and between the fire and the wall by

$$q_{F-W} = \sigma \left[\frac{1}{\frac{1-\varepsilon_F}{\varepsilon_F A_F} + \frac{1}{A_F F_{C-W}} + \frac{1-\varepsilon_W}{\varepsilon_W A_W}} \right] \left(T_F^4 - T_W^4 \right) . \qquad (3)$$

For a zero-mass thermocouple, Eqs. (1) and (2) must be equal, since the thermocouple cannot store energy. Therefore,

$$\left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C A_C} + \frac{1}{A_C F_{C-F}} + \frac{1-\varepsilon_F}{\varepsilon_F A_F}} \right] \left(T_F^4 - T_C^4 \right) =$$

$$\left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C A_C} + \frac{1}{A_C F_{C-W}} + \frac{1-\varepsilon_W}{\varepsilon_W A_W}} \right] \left(T_C^4 - T_W^4 \right) \qquad (4)$$

or

$$\left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C}+\frac{1}{F_{C-F}}+\left(\frac{A_C}{A_F}\right)\frac{1-\varepsilon_F}{\varepsilon_F}}\right]\left(T_C^4 - T_C^4\right) =$$

$$\left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C}+\frac{1}{F_{C-W}}+\left(\frac{A_C}{A_W}\right)\frac{1-\varepsilon_W}{\varepsilon_W}}\right]\left(T_C^4 - T_W^4\right) \tag{5}$$

Since the area of the thermocouple is very small,

$$\frac{A_C}{A_W} = \frac{A_C}{A_F} \approx 0$$

Therefore,

$$\left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C}+\frac{1}{F_{C-F}}}\right]\left(T_F^4 - T_C^4\right) = \left[\frac{1}{\frac{1-\varepsilon_C}{\varepsilon_C}+\frac{1}{F_{C-W}}}\right]\left(T_C^4 - T_W^4\right), \tag{6}$$

or

$$\left[\frac{F_{C-F}\varepsilon_C}{F_{C-F}(1-\varepsilon_C)+\varepsilon_C}\right]\left(T_F^4 - T_C^4\right) =$$

$$\left[\frac{F_{C-W}\varepsilon_C}{F_{C-W}(1-\varepsilon_C)+\varepsilon_C}\right]\left(T_C^4 - T_W^4\right), \tag{7}$$

where

$$T_C^4 - T_W^4 = \frac{F_{C-F}\left[F_{C-W}(1-\varepsilon_C)+\varepsilon_C\right]}{F_{C-W}\left[F_{C-F}(1-\varepsilon_C)+\varepsilon_C\right]}\left(T_F^4 - T_C^4\right) , \tag{8}$$

and

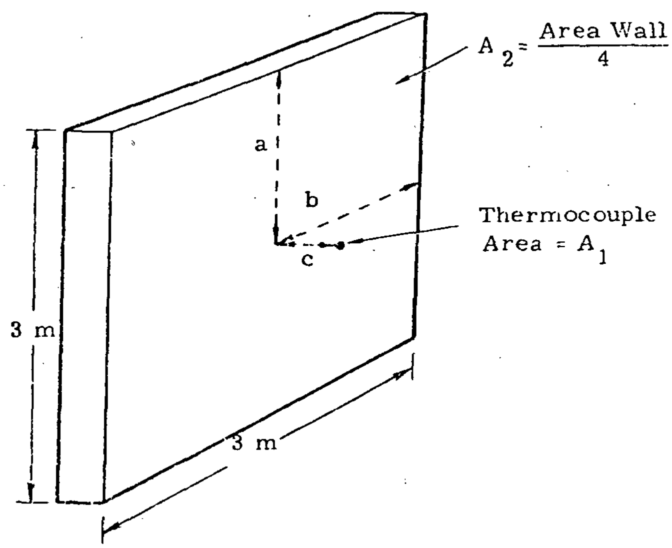
$$T_F^4 = T_C^4 + \left(T_C^4 - T_W^4\right)\left\{\frac{F_{C-W}\left[F_{C-F}(1-\varepsilon_C)+\varepsilon_C\right]}{F_{C-F}\left[F_{C-W}(1-\varepsilon_C)+\varepsilon_C\right]}\right\} , \tag{9}$$

or

$$T_F = \left[T_C^4 + \left(T_C^4 - T_W^4\right)\left\{\frac{F_{C-W}\left[F_{C-F}(1-\varepsilon_C)+\varepsilon_C\right]}{F_{C-F}\left[F_{C-W}(1-\varepsilon_C)+\varepsilon_C\right]}\right\}\right]^{1/4} . \tag{10}$$

In the computations, T_F lags T_W by one time increment. However, the error resulting from this calculation is insignificant when the time increment is small. The thermocouple temperature, T_C, is defined by the standard time-temperature curve. There remains, then, the calculation of view factors F_{C-W} and F_{C-F} to complete the information necessary to calculate the energy impinging on the test wall.

View factor calculation was accomplished as follows.[25]



Thermal modeling of the fire test represents a test wall which is three metres square (i.e., 3 m on each side). The flame temperature is controlled by a single thermocouple near the geometric center of the test wall responding to the standard time-temperature curve.

The area designated A_2 in the figure is the area of 1/4 of the test wall, while the thermocouple area is designated by A_1. The thermocouple is placed 6 in. (0.1524 m) from the wall. Thus,

$$c = 0.1524 \text{ m} \quad .$$

Dimensions a and b are the sides of 1/4 of the test wall area; therefore,

$$a = b = 3/2 \text{ m, and}$$

$$a/c = b/c = 9.8425 \quad .$$

Letting $x = a/c$ and $y = b/c$, the following formula, taken from Reference 36, gives us

$$F_{dA_1 - A_2} = \frac{1}{2\pi} \left[\frac{x}{(1 + x^2)^{1/2}} \tan^{-1} \left(\frac{y}{(1 + x^2)^{1/2}} \right) + \frac{y}{(1 + y^2)^{1/2}} \tan^{-1} \left(\frac{x}{(1 + y^2)^{1/2}} \right) \right] \quad . \tag{11}$$

Since in our case $a/c = b/c = x = y$, Eq. (11) may be simplified to

$$F_{dA_1 - A_2} = \frac{y}{\pi(1 + y^2)^{1/2}} \tan^{-1} \left(\frac{y}{(1 + y^2)^{1/2}} \right) \quad . \tag{12}$$

Substitution of numerical values for the arguments gives us

$$F_{dA_1-A_2} = 0.2479 \text{ (for each of four such areas)},$$

$$F_{dA_1-A_2} = 0.9916 \text{ for the active side.}$$

Since the thermocouple is considered as sphere instead of a point (thus only 1/2 of its area is viewing the test wall),

$$F_{C-W} = 0.9916/2 = 0.496, \text{ and}$$

$$F_{C-F} = 1.000 - 0.496 = 0.504$$

With a knowledge of the test furnace flame temperature given by Eq. (10), it is possible to determine temperature profiles through the test wall as a function of time by using the following equation for heat conduction.

$$\rho C_p \frac{\partial T_W}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T_W}{\partial x}\right), \tag{13}$$

where $T_W = T_W(x, t)$ = wall temperature
$k = k(T)$ = thermal conductivity
ρ = density of wall
$C_p = C_p(T)$ = specific heat of wall.

Note: It is assumed that there is no heat generated in the types of walls under consideration.

The governing initial condition is

$$T_W(x, o) = T_{AMB} \quad , \tag{14}$$

and the boundary conditions are

$$-k \frac{\partial T_W}{\partial x} = \sigma \left[\frac{1}{\frac{1-\varepsilon_F}{\varepsilon_F A_F} + \frac{1}{A_F F_{C-W}} + \frac{1-\varepsilon_W}{\varepsilon_W A_W}} \right] \left(T_F^4 - T_W^4 \right) \tag{15}$$

at $x = 0$ (fire side)

$$-k \frac{\partial T_W}{\partial x} = h \left[T_W(L) - T_{AMB} \right] + \varepsilon\sigma \left[T_W^4(L) - T_{AMB}^4 \right] \tag{16}$$

at the back face ($x = L$)

h = convection coefficient

ε = emissivity of back face

σ = Stefan Boltzmann constant

The convection coefficient, h, was computed using the quation,

$$h = 0.29(\Delta T/L)^{1/4} \quad , \tag{17}$$

which describes free convection over a vertical plate with laminar flow. L is the vertical dimension in feet, ΔT is in degrees F, and h is in Btu/hr-ft^2-°F.

By simultaneously solving Eqs. (10) and (13) and all governing boundary conditions, it is possible to calculate the wall temperature profile as a function of time and position, given the test thermocouple temperature as a function of time.

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NRC FORM 335 (7-77) U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET**	1. REPORT NUMBER (Assigned by DDC) NUREG/CR-0468 SAND 88-1990
4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Nuclear Power Plant Fire Protection - Fire Barriers (Subsystems Study Task 3)	2. (Leave blank)
	3. RECIPIENT'S ACCESSION NO.
7. AUTHOR(S) Earl E. Minor, Dennis L. Berry	5. DATE REPORT COMPLETED MONTH September YEAR 1979
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Sandia Laboratories Albuquerque, New Mexico 87185	DATE REPORT ISSUED MONTH September YEAR 1979
	6. (Leave blank)
	8. (Leave blank)
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Engineering Methodology Standards Branch Office of Standards Development U. S. Nuclear Regulatory Commission Washington, D. C. 20555	10. PROJECT/TASK/WORK UNIT NO.
	11. CONTRACT NO. FIN No. A-1080
13. TYPE OF REPORT Final Technical	PERIOD COVERED (Inclusive dates)
15. SUPPLEMENTARY NOTES	14. (Leave blank)

16. ABSTRACT (200 words or less)

Standards currently used in the fire protection field are analyzed in relation to their applicability to nuclear power stations and recommendations concerning their improvement are made. Results of mathematical analyses of typical fire barriers are given. Based on the temperature gradient established in the mathematical analyses, a stress analysis of poured concrete walls is described. Recommendations are made for follow-up studies and experiments.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Fire

Fire Barriers

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT	19. SECURITY CLASS (This report)	21. NO. OF PAGES
Unlimited	Unclassified	
	20. SECURITY CLASS (This page) Unclassified	22. PRICE S