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Fire Resistance Testing for Performance-based Fire Design of Buildings. Final Report

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Prepared for
U.S. Department of Commerce
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Notice

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FIRE PROTECTION
RESEARCH FOUNDATION

FIRE RESEARCH

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FOREWORD

The ASTM E119 test procedure (or equivalent) is used to determine whether a construction assembly or structural element meets the fire resistance rating requirements specified in prescriptive building codes. Fire statistics indicate that these requirements appear to be adequate in meeting the intended fire safety objectives of the prescriptive codes. In recent years it has become more common to design buildings for fire safety on a performance basis. The standard fire resistance test in its present form is not designed to provide discrete information that can be used in support of performance-based structural fire design. The technology of the test standard could be improved to make the measurements and results more useful for performance-based fire design.

This report presents the results of a study undertaken by the Foundation to develop the technical basis for changes and additions to ASTM E119 so that measurements and results can be used in performance-based design, without compromising the traditional use of the test standard for prescriptive building code compliance.

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The content, opinions and conclusions contained in this report are solely those of the authors.

Fire Resistance Testing
For Performance-based Fire Design of Buildings

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FIRE RESISTANCE TESTING
FOR PERFORMANCE-BASED FIRE DESIGN OF BUILDINGS

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1.0 INTRODUCTION

There is an ongoing trend in Fire Protection Engineering toward Performance-Based Design (PBD) and toward rational engineering of fire protection in lieu of prescriptive requirements. This approach requires engineering data that existing test methods, like ASTM E 119 (American Society for Testing and Materials), are not currently configured to provide (Grosshandler, 2002). The lack of engineering data from standard fire resistance test methods requires that performance-based design utilize data obtained from ad hoc test methods performed outside of the scope of standard test methodologies. This process is lacking in both standardization and efficiency.

In addition to other limitations with respect to test procedures, measurements, and reporting, reproducibility of standard furnace testing has always been a serious issue. Fire resistance tests are unique within the fire test world in that the apparatus is only generally specified in the test standard. Fuels, burners, furnace linings, furnace dimensions, loading levels, and loading mechanisms are either unspecified or only generally specified. This has led to the situation that test results cannot be reproduced from laboratory to laboratory. This situation causes significant problems in a performance-based design environment.

The goal of this project is to identify the needed capabilities of a standard fire resistance test to support Performance-Based Structural Fire Engineering (PBSFE). A test plan outline to develop and validate the proposed capabilities, procedures, and instrumentation has been developed and is included in this report. The test plan outline provides an approach to evaluate the ability of the recommendations to be implemented, and to evaluate the value added by the recommendations. The recommendations developed in this report are intended to apply to the entire range of fire resistive assemblies. However, the accompanying test plan outline utilizes two common building elements; composite concrete slab/steel beam floor assemblies and gypsum-protected load bearing steel-stud walls as test beds for the evaluation of the recommendations. It is intended that such testing will provide a partial basis for the inclusion of the recommendations into a test standard. It is envisioned that the work will support the ongoing development of fire resistance test methods in ASTM E 5.

While there is emerging interest in Performance-Based Structural Fire Engineering, it is understood that the existing test methods that support prescriptive requirements will be needed for the foreseeable future. It is recognized that some of the recommendations in this report may be applicable to existing test methods that support current prescriptive design approaches. Recommendations that may be applicable to existing test methods are summarized in Section 6.4.

The existing test methods and the listings that have resulted from application of these test methods are a significant legacy that has served the fire community since the 1920s. The combination of the test methods, the listings, and prescriptive fire resistance requirements of the building codes have resulted in very satisfactory overall fire performance of buildings. The goal of this work is not to alter this prescriptive-based system. Rather, the goal of this work is to provide a partial basis for a complementary performance-based system for the provision of structural fire protection. Given the long history of the prescriptive-based system, discussions of the provisions of a new performance-based system will inevitably include a juxtaposition of the properties of the new performance-based system relative to the existing prescriptive-based system. These juxtapositions inevitably focus on the shortcomings of the prescriptive system with respect to performance-based design. The simple fact is that the design approaches are different and have different requirements. It is appropriate for the development of performance-based methods to grow out of our extensive experience with the prescriptive system. When elements of the prescriptive system are highlighted as not appropriate for performance-based design, these are simply expressions of the differences in the requirements of the two systems and are not appropriately regarded as failures of the prescriptive system. The prescriptive approach has provided very satisfactory results in application. It is simply hoped that the performance-based system can provide similarly satisfactory or better results in a more cost-effective manner.

1.1 Ongoing Developments in Structural Fire Protection Design Methods

In the area of engineered structural fire protection, there are many ongoing organizational efforts to develop the required design method infrastructure. The Society of Fire Protection Engineers (SFPE) has a committee working on a standard for determination of the design fire exposure. SFPE is also in the process of constituting a committee to develop a standard on the thermal/heat-transfer portion of the design process. The National Fire Protection Association (NFPA), meanwhile, is developing a standard for fire loads for structural fire protection design. These committees are coordinating their efforts to produce a suite of documents that collectively support PBSFE.

While the American Society of Civil Engineers (ASCE) had announced some time ago its intention to produce a document in the structural portion of the design process, it seems that this process has not yet materialized (ASCE Committee for Structural Design for Fire Conditions is charged with development of a Performance-Based Fire Design Standard). There is no doubt that the SFPE efforts on the heat-transfer portion and ASCE's efforts on the structural portion will require data that cannot be obtained using current test methods.

In that vein, there is a task group working within ASTM E 05.11 (Fire Resistance) that is developing a guidance document for conducting nonstandard furnace tests. All these activities have European counterparts generally encompassed by the Eurocode suite of documents. Based upon the various ongoing related activities, there is a genuine need to develop means for integrating standardized fire resistance test results into the performance-based structural fire engineering process.

1.2 Outline of the Analysis Approach

The approach to analyzing the recommendations for fire resistance testing in support of PBSFE begins by reviewing the PBSFE design process. Based upon the needs of PBSFE and the research literature, recommendations are developed in the areas of heat-transfer/thermal response, structural performance, and test documentation. The recommendations are first stated, and then the basis for the recommendation is developed from the research literature. Appendix A includes a bibliography of research in structural fire engineering.

2.0 PERFORMANCE-BASED STRUCTURAL FIRE ENGINEERING (PBSFE)

While the field of Performance-Based Structural Fire Engineering is in the developmental stage, the overall structure of the process has been well defined for some time. Grosshandler (2002) outlined the process in summarizing a recent fire resistance workshop. The process includes both design and analysis components. The analysis components involve the definition of the design fire exposure, the thermal/mechanical response of the structural assembly (including any fireproofing materials), and structural response of the structural system. The broader design processes are shown in Figure 1, including inputs from building code requirements and inputs from assembly listings. Here we take a broad view of assembly listings to include any engineering data that can be deduced from the testing involved in the development of the listing (despite the fact that such test data is not made public by the listing organization or test sponsors at the current time) or fire resistance testing not associated directly with the listing process. The recommendations developed in this report are intended to provide additional engineering information and data from the activity noted in Figure 1 as “Assembly Listing and Data.” These infrastructure components are shown above the dashed line, while the actual design portion of the process is shown below the dashed line. The design components include the architectural and structural designs of the building, which form the basis for the fire engineering design.

The fire engineering begins with the development of a design fire exposure to the structure. This normally takes the form of a time-temperature curve based upon the fire load, ventilation, and thermal properties of the bounding surfaces (walls, floor, and ceiling). Design fire loads are dependent upon the occupancy and other fire protection features of the building. Significantly, with respect to furnace testing, the performance of the boundaries to limit fire spread is the primary component of defining the design fire area. Often the exposed fire area is defined by boundaries with sufficient fire resistance to prevent fire spread under the design fire load density. It is significant to note that the time-temperature curves developed in compartment fires most often exceed the time-temperature curves used in the test methods like ASTM E 119. As noted by Drysdale (1999), this has been recognized but tacitly accepted since the 1920s in the setting of prescriptive fire resistance requirements for buildings.

Based upon the architectural and structural designs, the design fire is used to develop the passive fire protection design. This involves the selection of fire resistive assembly constructions for use as walls, columns, and floor/ceiling assemblies. The assemblies are selected to survive the design fire exposure, to be consistent with the architectural/structural design, and to provide cost-effective protection. It would be normal to develop more than one set of conceptual designs for further evaluation.

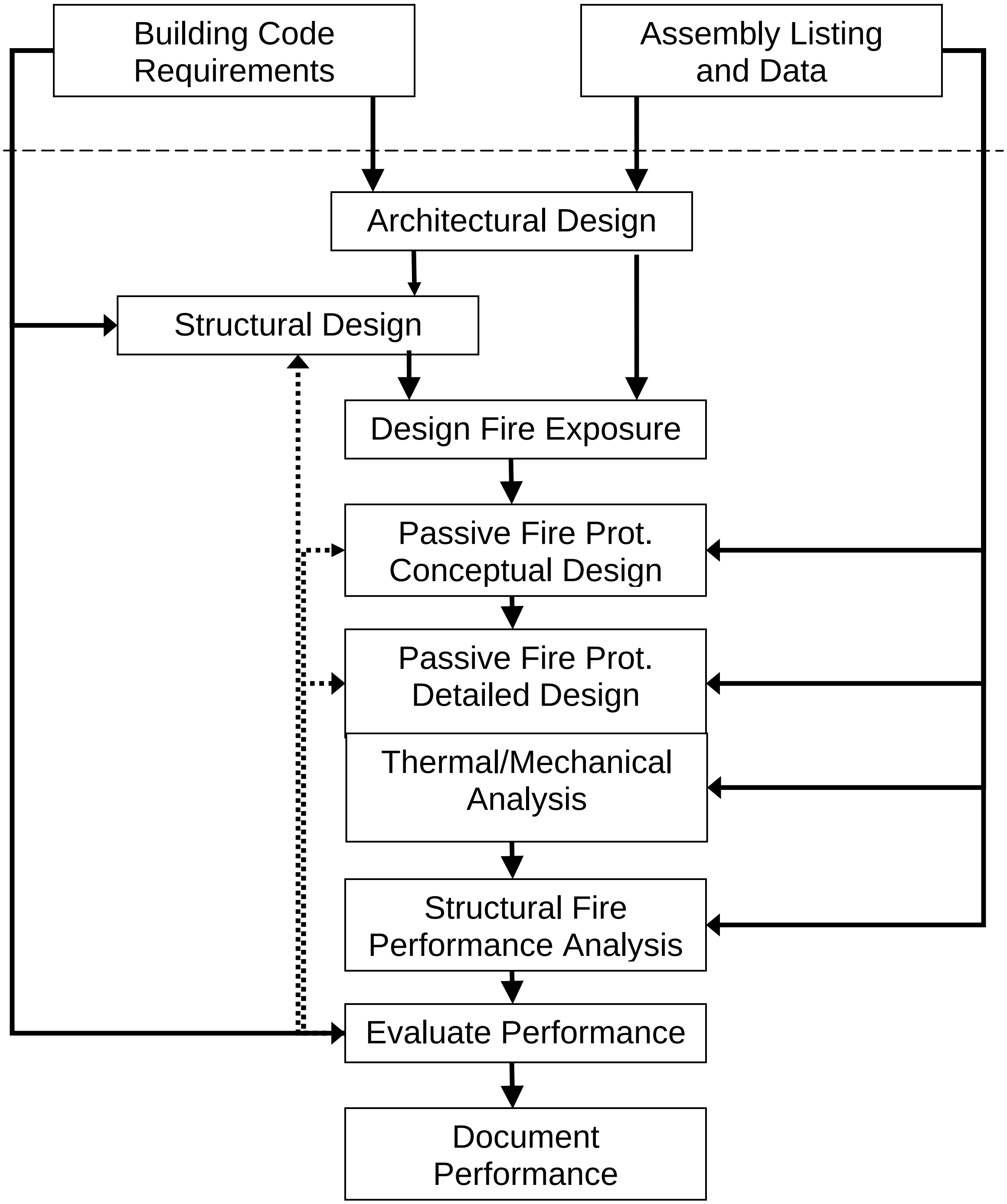


Figure 1. Performance-based structural fire engineering (PBSFE) design process.

Detailed design involves the use of thermal/mechanical models to assess the performance of each conceptual design, resulting in trial protection thicknesses based upon tentative thermal failure criteria. It is typical to perform two-dimensional heat-transfer analyses, but three-dimensional analyses are sometimes required. It is significant that existing models cannot deal with the mechanical performance of the assembly in any substantive manner. Loss of physical integrity of a material or the assembly cannot be modeled at this time. The designer relies entirely upon the results of testing to assure that physical integrity is maintained over the design exposure period. In most cases, the engineer will seek to use materials and assemblies that can be relied upon to maintain integrity, or alternatively simple, and somewhat ad hoc, assumptions about material loss are made in the design calculations.

The final analysis process is the prediction of structural performance of the structure under design loads with the structural elements heated according to the heat-transfer analysis. This analysis can be performed for individual elements, for the substructure in the fire area, or for the complete structural system. Typically, multiple analyses are performed with more detailed analysis at the element level and more basic analysis at the structural system level.

Based upon the performance of the system, redesign may be indicated. This could include changes to the structural design (especially if changes here could allow removal of fireproofing altogether), changes in the passive design concept (e.g., change insulating material), or alterations in the detailed design of the passive fire protection (modify the thicknesses of the insulation). Other redesign aspects are possible, but these are the most common.

As indicated in Figure 1, the assembly listing and data that is, or could be, included in the listing documentation can contribute to the passive fire protection design, the thermal/mechanical analysis, and the structural fire performance analysis. It is important to note that the listing documentation (e.g., the test report) is not a public document under the current system so that these can only be used with the assistance of the owner of the listing. In addition, the current listing may not be directly supported by reported tests. Testing may have been performed with an old version of the protective material and the current material may be accepted under the listing based upon the listing agency's engineering judgment. While this may be satisfactory for prescriptive use of the product, it has serious limitations with respect to PBSFE.

Other data sources, not shown in Figure 1, also contribute to these design and analysis processes. These include other published data concerning temperature dependent structural properties of materials and thermal properties of insulating materials. While some of this data is produced using standard methods, other data is obtained via ad hoc testing methods.

The analysis methods employed in the design process may vary from special purpose software to general heat-transfer or structural analysis software. Some software is developed by the designer, some is developed by government laboratories, and some is commercial software. There is a specific need to address applicability, validation, and verification of these methods for use in specific Performance-Based Structural Fire Engineering (PBSFE) designs.

It is the vision of this report that a fire resistance test in support of PBSFE should be a part of the validation and verification (V&V) basis for the application of analysis tools to specific fire resistance designs. All needed data to support the analysis should be developed through tests designed for that purpose (e.g., thermal properties and structural properties). The furnace test should be conducted and instrumented to provide high quality data and boundary conditions to form a data set that can be predicted using the analysis tools. The successful prediction of the test would form a partial basis for demonstrating the applicability of the models to the particular fire resistance design. The test would further identify any mechanical behaviors such as erosion, cracking, spalling, shrinkage, fastener failures, warpage, and other behaviors that need to be mitigated in the design or accommodated in the design calculations.

There is a wide range of testing and reporting aspects of standard fire test methods that are required to support PBSFE. These include simple characterization of the test article and the properties of the component materials, as well as substantive measurements made and the conduct of the test itself. It has been recognized for many decades that realistic fire exposures can exceed the exposure in ASTM E 119 and that the exposure conditions to the assembly vary among furnaces operated in a manner consistent with existing test methods. There is also a need to develop and validate thermal properties of insulating materials and the methods and instrumentation of standard test methods to support PBSFE. There are definite unresolved issues concerning the structural conduct of the test to assure that the results are applicable to longer spans and connections found in actual construction. This brings to the fore issues of structural scaling laws, and the use of structural rather than thermal endpoints for the test. Issues also exist with the conduct of the test with respect to failure criteria. Valuable failure mode data can be provided by the practice of "testing to failure." These and other issues have received varying levels of attention in the testing and research literature. There is no doubt that a new fire resistance test method can become a valuable tool in PBSFE design. The recommendations included in the following sections are in support of this objective.

3.0 TEST METHOD RECOMMENDATIONS – THERMAL/HEAT-TRANSFER

The test requirements with respect to the thermal aspects of the test method involve measurements/instrumentation, furnace-operating conditions, and test documentation. These requirements relate to the representation of realistic fire exposures and production of data that can directly support PBSFE. The recommendations are followed by a discussion of the issue and the basis for the recommendation.

Heat-transfer analysis through an assembly exposed to fire conditions must be conducted using models that have been verified and validated (V&V) with data that is representative of the expected fire conditions. Guidance is provided in this section of the report to develop a furnace test that generates thermal response data that can be used to V&V heat-transfer models. Data collected will provide a means for engineers to V&V models for predicting the variables of potential concern in a fire resistance simulation including temperature profiles through the assembly, temperature rise of an item placed against the unexposed side of the assembly, and total heat flux off the unexposed side and/or through transparent portions of the assembly.

Furnace construction and control are detailed to provide a consistent, repeatable exposure that minimizes the effects of test article construction on the exposure conditions. A furnace calibration test is recommended to quantify the thermal exposure onto a test article. This should be done through the measurement of total heat fluxes from the furnace onto the test article as well as the thermal response of noncombustible boards with known thermal properties. With this data, heat-transfer models can be used to predict temperature profiles through the noncombustible boards, demonstrating the capability of the model to predict heat transmission due to a furnace exposure. These procedures minimize furnace-to-furnace differences and provide a basis for validating the model performance with the furnace to be used to test the assembly to be used in PBFPE. This procedure will directly support round-robin comparisons of furnaces to insure the consistent application of the test method among laboratories.

The recommended furnace exposure conditions are based on an upper bound of conditions that have been measured in compartment fire testing, including temperature, pressure, and oxygen levels. By conducting tests at the upper bound of possible conditions, the performance of the assembly has been evaluated over the range of potential fire exposures. The use of an upper-bound exposure condition to evaluate materials or assemblies will provide some assurance that for most materials, performance under a less severe exposure will not result in a degradation of performance. When extrapolating performance from one fire exposure to a more severe fire exposure, there are no assurances that the performance of materials or assemblies will be predictable. Some materials may perform well at elevated temperatures, while other materials may expand, contract, warp, spall, change phase, debond, or crack, and fasteners may fail. Materials may lose integrity and fall off from the surface. Many of these phenomena and failure modes cannot be predicted using the current state-of-the-art models. Therefore, testing products at the upper bound of temperature level expected is currently the only way to demonstrate the overall performance of a material.

A model that is validated against this upper-bound exposure data will also be demonstrated to be appropriate for predicting the thermal response of the assembly over the range of exposures. Temperature data can be used to demonstrate that the thermal properties being used in the heat-transfer analysis are appropriate. In cases where material failures occur (i.e., fall off the exposed side), the through-thickness temperature data can be used to understand when such failures may occur and data could be used to assist in developing/validating constitutive models to predict these failures. Through model validation with the calibration test, as well as the test on the actual assembly, the heat-transfer model could be used with confidence to predict thermal response of the assembly during compartment fire exposures.

3.1 Instrumentation

3.1.1 Furnace Temperature Control

Recommendation T-1: Plate thermometers should be used to measure furnace temperature and control the furnace exposure. There should be nine plate thermometers equally distributed across the test specimen surface. Plate thermometers are typically placed 0.10 m (4 in.) away from the sample; however, a larger spacing is desired to prevent them from potentially being damaged by failing test articles. Testing needs to be performed to demonstrate that a larger spacing does not affect the thermometer measurement.

Engineers need a repeatable furnace exposure that is as independent as possible from the test article construction and the furnace details. This will allow modelers to use the thermal exposure calibration test described in Section 3.2 as a basis for the thermal exposure in all tests. In order to provide a repeatable furnace exposure, the furnace temperature measurement used to control the furnace should not be sensitive to test article construction and furnace details.

Plate thermometers have been documented to provide a more repeatable exposure furnace-to-furnace and within the same furnace with different types of test articles. Based on analysis by Babrauskas and Williamson (1978), Wickstrom (1989, 1997) developed the plate thermometer to provide a temperature measurement that had no radiative view of the test article, to remove the variation due to thermocouple design and bead size, to reduce the effects of variations in furnace construction, and to result in a heat-transfer coefficient similar to a test specimen.

Plate thermometers have been shown to minimize the variation in exposure measured within different furnaces. Testing with different furnaces has demonstrated that using plate thermometers to control furnace temperature reduces the effects of different furnace linings (van der Luer and Twilt, 1999, Harada et al., 1997, Davies and Dewhurst, 1996, Cooke, 1994), furnace depths (Harada et al., 1997, Fromy and Curtat, 1999, Cooke, 1994), and furnace gas emissivity through burning different fuels (Cooke, 1994, Harada et al., 1997, Fromy and Curtat, 1999). Testing has also demonstrated that plate thermometers provide a more consistent thermal exposure, independent of the thermal properties of the test specimen (van de Leur and Twilt, 1999).

The thermal exposure produced when the furnace exposure is controlled using plate thermometers has been shown to be less severe than furnaces controlled using shielded thermocouples in the early portions of the test (up to about 10 minutes), but more severe than furnaces controlled with bare thermocouples throughout the test. Compared with shielded thermocouples, Sultan (2006) determined that controlling the furnace with plate thermometers produced a less severe exposure during the initial 10 minutes of the test, but thereafter the exposures were similar. Compared with furnaces controlled with bare thermocouples, van der Leur and Twilt (1999) measured that furnaces controlled by plate thermometers resulted in higher temperatures (as measured using 1-mm diameter sheathed thermocouples) during the entire test, compared with temperatures measured when the furnace was controlled with 1-mm sheathed thermocouples.

Plate thermometers are typically placed 0.10 m (4 in.) from the specimen surface. This is done to keep the thermometer as close as possible to the test article so that the thermometer is measuring the exposure seen by the test article. In performing tests to failure, test articles may deflect more than 0.10 m (4 in.) into the furnace, which could potentially damage plate thermometers. As a result, plate thermometers need to be located as much as 0.30 m (12 in.) from the test article to allow room for it to deflect and fail. Wickstrom (1998) states that the location of the plate thermometer away from the test article is not expected to influence the plate thermometer furnace temperature measurement. Testing is recommended to verify that the plate thermometer measurement is not significantly influenced by the increased offset from the test article.

<u>Furnace Differential Pressure</u>

Recommendation T-2: Tests should be performed with a positive furnace pressure (relative to laboratory conditions) across the entire test article. All furnace pressures *should be measured using the tube sensor provided in ISO 834 and EN1363-1. In a vertical furnace, pressure should be measured at the bottom and top of the test specimen. The neutral plane in the furnace should be maintained at the bottom of the test specimen with no limit on the pressure at the top of the specimen. In a horizontal furnace, the furnace pressure should be measured at one location and maintained at a minimum of 20 Pa. Pressure tube sensors should be located at the same distance away from test articles as the plate thermometers.*

Fully-developed fires will always produce a positive pressure gradient across ceilings and a majority of the boundary height relative to ambient conditions. In these areas of positive pressure, hot gases are driven through small openings that develop in the assembly causing damage to the internal portions of the assembly. Hot gas migration through the assembly may also give rise to ignition on the unexposed side of the assembly in these local areas of weakness. As a result, it is recommended that furnace tests be performed with a positive furnace pressure so that the effects of hot gas transmission through the assembly can be observed.

The differential pressure between ambient and a compartment containing a hot gas layer will vary due to hydrostatics through the following relation,

$$\Delta P = g\left(\rho_f - \rho_a\right)h \qquad (1)$$

where g is the gravitational constant (9.81 m/s^2), ρ_f is the gas density inside the fire compartment, ρ_a is the ambient gas density at the same elevation, h is the elevation above a datum where the pressure between ambient and the compartment is equal (i.e., neutral plane) (m). Applying the ideal gas law to Equation (1), the differential pressure can be transformed into a function of temperature,

$$\Delta P = 352.8g\left(\frac{1}{T_f} - \frac{1}{T_a}\right)h \qquad (2)$$

with T_f being the gas temperature inside the fire compartment (K), T_a being the ambient gas temperature (293 K), and the coefficient 352.8 kg/m^3-K being the reference density multiplied by the reference temperature.

In a compartment fire, the differential pressure per unit height above the neutral plane will be 7.5-9.0 Pa/m with a temperature of 800–1200^{o}C, respectively. From ISO 834 and EN1363-1, furnaces have a similar increase in differential pressure with height (8–8.5 Pa/m); though this will obviously be a function of temperature inside the furnace. In vertical furnace tests, there will be a pressure distribution along the height of the test article. As a result, it is recommended that pressure be measured at two elevations within the furnace to quantify the pressure gradient within the furnace during the test.

At an elevation 2.4 m (8 ft) above the neutral plane of a compartment fire, the pressure will be approximately 18–22 Pa for gas temperatures in the range of 800–1200^{o}C. These pressures are similar to the 20 Pa pressure recommended in ISO 834 and EN 1363-1 for horizontal furnaces. In vertical furnace tests, ISO 834 and EN 1363-1 stipulate that the neutral plane inside the furnace should be located 0.50 m above the bottom test article but the pressures at the top of the test article should not be greater than 20 Pa. When necessary, the neutral plane inside the furnace will be moved upward to ensure that the pressure at the top of the test article does not exceed 20 Pa. In real fires, elevations along a wall greater than 2.4 (8 ft) above the neutral plane can have pressures in excess of 20 Pa when gas temperatures range from 800–1200^{o}C. Therefore, in wall tests it is recommended that the entire wall be kept at positive pressure (i.e., neutral plane at the bottom of the test article) with no limit on the pressure at the top of the test article.

In furnace tests, it is recommended that the differential furnace pressure be positive across the entire test article. The furnace differential pressure should be measured through a furnace pressure measurement and a laboratory pressure measurement at the same elevation. The furnace pressure should be measured using the tube sensor provided in ISO 834 and EN1363-1. The tube sensor should be located inside the furnace where it will not be subject to direct impingement of the convection currents from flames or in the path of the exhaust gases directly out of the burners. Pressure tubes should be horizontal both in the furnace and as they exit through the furnace wall, making the tubing elevation the same both on the inside and outside of the furnace. Any vertical section of tube should be at room temperature. In a vertical furnace, pressure should be measured at the bottom of the test specimen and the top of the test specimen. The neutral plane in the furnace should be maintained at the bottom of the test specimen with no limit on the pressure at the top of the specimen. In a horizontal furnace, the furnace pressure should be measured at one location immediately below the test assembly and maintained at a minimum of 20 Pa. Pressure tube sensors should be located at the same distance away from test articles as the plate thermometers.

Furnace Oxygen Concentration

> *Recommendation T-3: Furnace oxygen concentration should be measured in the furnace stack and maintained at greater than 6% during the test. Gas samples should be continuously drawn out of the duct through a sampling line and measured using a paramagnetic type oxygen analyzer. The recommended sampling probe should be similar to the sampling probe used in duct measurements of hood calorimeters*.

A range of oxygen levels may exist during the course of a compartment fire. This may vary from zero to several percent in the upper portions of a compartment during fully-developed fires (Gross and Robertson, 1965). From a fire resistance perspective, one of the implications of the presence of oxygen is that it allows char oxidation to occur which results in faster degradation of material. This has been noted in furnace testing to result in marked differences in fire resistance performance of wood stud assemblies. In furnace testing, it is also desirable to have excess oxygen within the furnace to allow combustible test articles to burn as they could in compartment fires.

It is recommended that the oxygen concentration during the test be above 6% during the furnace test. This was developed based on oxygen concentration requirements in other fire resistance test standards as well as oxygen concentrations measured in the upper-layer of fully-developed fires. The fire resistance standard EN 1363-1 requires that a minimum oxygen concentration of 4% be maintained within the test furnace during the course of the fire test.

Gross and Robertson (1965) measured oxygen concentrations ranging from 0–11% in fully-developed compartment fires. Based on these results, and taking into account that a combustible assembly may deplete some oxygen in the furnace, furnace oxygen concentrations should be maintained at or above 6% during the test.

Unexposed Side Temperatures

> *Recommendation T-4: The unexposed side temperatures should be measured with a thermocouple placed between the specimen and a noncombustible, insulating pad. The insulating pad should be a low density, low thermal conductivity material with known thermal properties. The pads should be approximately 0.15 m (6 in.) square and 25 mm (1-in.) thick and placed in at least three locations that provide a range of heat-transfer performance.*

The ignition of combustible materials on the unexposed side of an assembly is one of the standard measures of fire resistance performance. In performance-based design, items may be in contact with the assembly or may always be offset from the assembly. To support calculations where items may be in contact with the assembly, the unexposed side temperature should be measured with a noncombustible, insulating pad mounted onto the unexposed side. This data can be used by engineers to demonstrate that their models are capable of predicting the heat-transfer through the assembly with a material on the unexposed side blocking heat and mass transfer losses.

Ignition of materials due to hot surfaces has been reviewed by Schwartz and Lie (1985) and Babrauskas (2007). Ignition was characterized as either visible glowing or flaming. The temperatures range from 300°C to as high as 950°C. The materials that ignited close to 300°C were cotton waste at 298°C and a roof assembly (five layers of roofing felt, bitumen, and 2-in. polystyrene foam) at 325°C.

The difference in temperatures of materials when ignited by hot surfaces, and those measured by ASTM E 119 insulation pads, was reviewed by Schwartz and Lie (1985). This included testing conducted at UL and NRC-Canada. In all tests, the materials were placed on the unexposed side of concrete and were exposed to an ASTM E 119 fire exposure. The effects of drafts on ignition temperatures were not explored. Results from the two series of tests are provided in Figures 2 and 3. Most of the tests at UL were glowing ignition, while all the tests at NRC-Canada were flaming ignition. Ignition times in most tests were after 1–2 hours of exposure. As seen in these figures, the material temperature was higher than the temperature measured using the ASTM E 119 pad. The exceptions to this were the tests with wooden strips and the roofing assembly test. In the tests with the wooden sticks, the sticks bowed away from the concrete, resulting in a lower material temperature.

There was no apparent physical explanation for the magnitude of the deviation between the material ignition temperature and the ASTM pad temperature. Considering all of the data, the material ignition temperature was on average 61°C higher than temperatures measured using the ASTM E 119 pad with a standard error of ±64°C. This makes the potential disagreement between the pad temperature and the material temperature at ignition as much as 125°C.

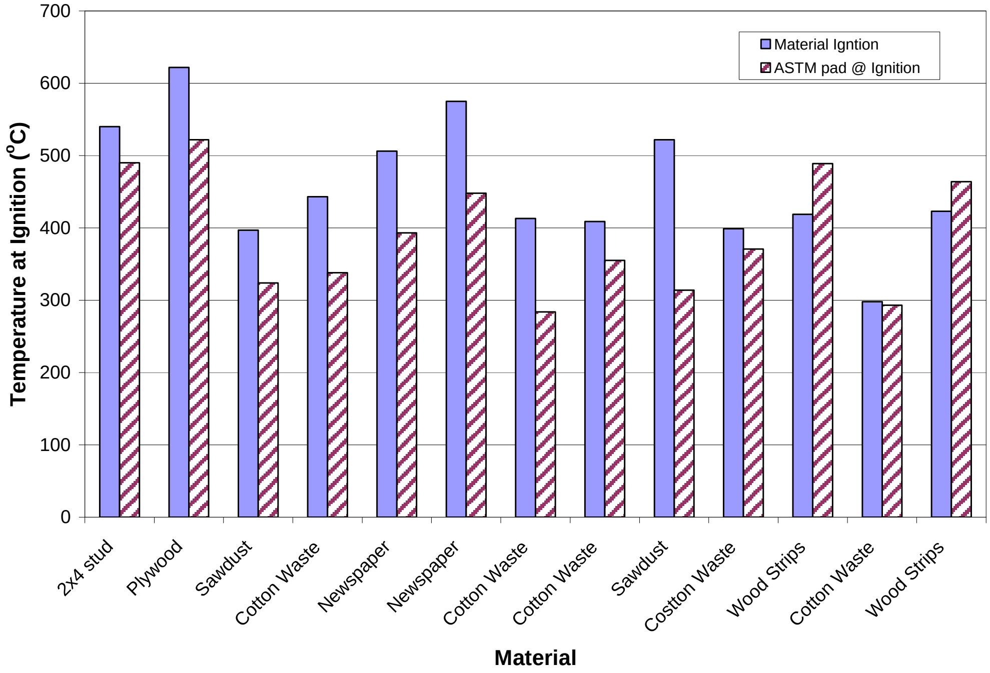


Figure 2. UL tests measuring temperature of material ignition and ASTM E 119 temperature.

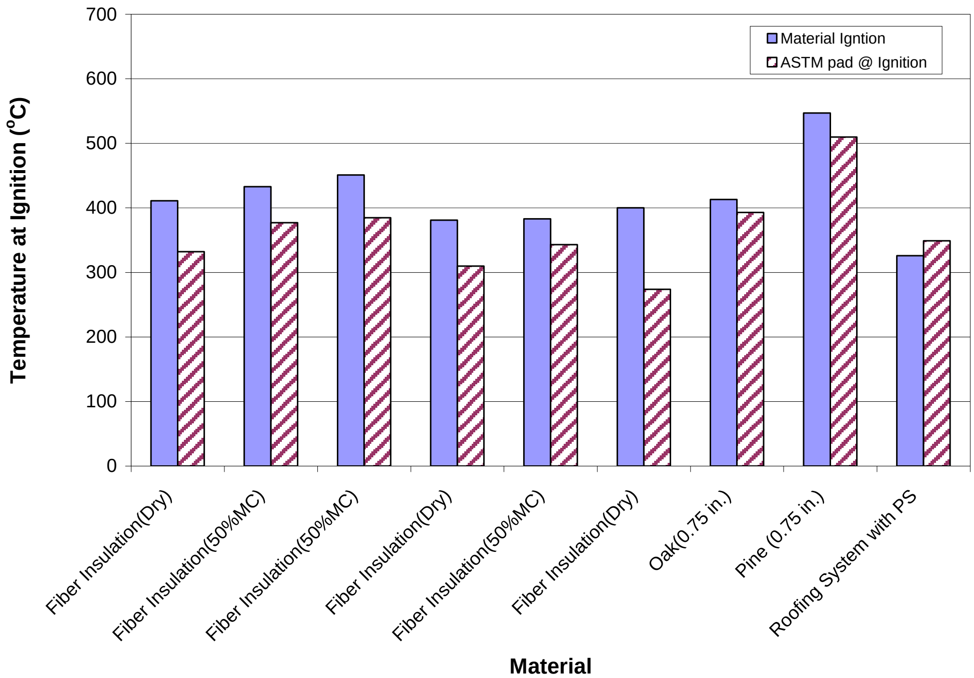


Figure 3. NRC-Canada tests on material ignition in contact with concrete along with ASTM E 119 pad temperatures.

The recommended unexposed side temperatures should be measured using a noncombustible, insulating pad. The pad should be 0.15 m (6 in.) square, which is similar in size to the ASTM pad. However, the thickness should be increased to about 25 mm (1.0-in.) so that temperatures are closer to those measured for actual materials in contact with the unexposed side of the assembly. The board should be a low density, low conductivity ceramic fiber board with known thermal properties. Some recommended boards include UNIFRAX Duraboard LD and FireMaster board made by Thermal Ceramics. The board should be mechanically attached to the unexposed side of the assembly with a bare bead, glass braid, 24-gauge, Type K thermocouple sandwich between the assembly and the board. If significant moisture is expected on the unexposed side, the bare bead thermocouple can be replace with a 1.0 mm diameter, Type K Inconel-sheathed thermocouple.

Total Heat Flux off the Unexposed Side

Recommendation T-5: The total heat flux from the unexposed side of the assembly should be measured using a Schmidt-Boelter type water-cooled total heat flux gauge. At a minimum, a heat flux gauge should be placed near the center of the test article and as close as possible to the unexposed side. In cases where the assembly contains a transparent section, a heat flux gauge should also be placed at the center of the transparent section as close as possible to the unexposed surface.

Heat transmitted off the unexposed side of the assembly may pre-heat and ignite materials located close to the assembly or may impede the movement of people by the assembly. This will be particularly important in assemblies, which contain sections that are transparent (e.g., glazing). This data can be used by engineers to demonstrate that their models are capable of predicting the heat-transfer off the unexposed side of the assembly and through transparent areas of the assembly.

The total heat flux gauge should be a Schmidt-Boelter water-cooled total heat flux gauge, with a 0-25 kW/m^2 range. A range of 0–100 kW/m^2 should be used for assemblies that include glazing. To ensure a high view factor between the gauge and the unexposed side of the test article, the gauge should be located as close as possible to (within 0.15 to 0.3 m) and near the center of the assembly. With radiation calculations being sensitive to the offset between the surface and heat flux gauge, the distance the heat flux gauge is located from the unexposed side surface should be recorded so that the data can be used for model validation.

Furnace Velocity

Recommendation T-6: Velocity measurements inside the furnace should not be made.

While it is important to create a realistic convective environment in the furnace, it is difficult to conduct meaningful velocity measurements in the furnace where the flow is expected to be complex. As a result, no velocity measurements are recommended inside the furnace. (See furnace burner recommendations below for additional information).

Temperature Profile through Test Specimen

Recommendation T-7: Temperatures should be measured through the thickness of the test assembly at locations that are representative of the different heat-transfer paths within the assembly. Repeat temperature profiles are recommended in case some thermocouples fail during the test.

Predicting the correct temperature profile is a critical aspect of predicting heat transmission through the assembly as well as the structural response. Temperature data can be used to demonstrate that the thermal properties being used in the heat-transfer analysis are appropriate. In cases where materials may lose integrity (i.e., fall off the exposed side), the through-thickness temperature data can be used to understand when such failures may occur and could be used to assist in developing/validating constitutive models to predict these failures. The strength of materials is also strongly influenced by temperature; therefore, predicting the correct temperatures will affect the predicted structural response.

The temperature through the depth of the test article should be measured at a minimum of two locations. Temperatures should be measured at locations that will provide a method for validating the heat-transfer through the assembly. Test articles that have a relatively uniform composition (e.g., concrete) will likely require two temperature profiles, while assemblies with studs will require at least four temperature (i.e., one at the stud, one between studs, and repeat measurements at a similar location). Internal temperatures should be measured at no less than three locations along the specimen thickness. For a specimen that consists of layers of materials, the temperature should be measured at each material interface. More complicated structural members (e.g., I-beams) will likely need thermocouples at several locations to provide sufficient data to validate the heat-transfer model. At each location, thermocouples in a profile should be within 0.075 m (3 in.) of the profile location.

The surface temperature on the exposed side of the specimen should be measured with a ceramic braid, 24-gauge, and Type K bare bead thermocouple. The thermocouple bead as well as the lead wire inside the furnace should be placed in contact with exposed surface of the test surface of the test article.

The surface temperature on the unexposed side of the specimen should be measured using an optical pyrometer with a wavelength range suitable for accurately measuring the surface temperature on the unexposed side.

Internal temperatures should be measured using Inconel-sheathed Type K thermocouple, with a sheath diameter of 1.0 mm. Inconel-sheathed thermocouples are required to prevent thermocouples from shorting out due to moisture in specimen materials. Thermocouples must remain in the plane of measurement for at least 50 mm (2 in.). If possible, thermocouples should be applied during construction and should be extended out of the side of the specimen. When thermocouples must be fed out of the unexposed side of the test article, the area around the thermocouple must be sealed to prevent premature hot gas transmission through the assembly at this location.

Gas Temperature Measurement

Recommendation T-8: Gas temperatures on the exposed and unexposed side of the test specimen should be measured using aspirated thermocouples. Gas temperatures should be measured at each location where a temperature profile is being measured. Aspirated thermocouples should be placed as close as possible to the test article surface.

Heat-transfer analysis of the assemblies may require the use of the gas temperature on both sides of the test article. Depending on the analysis, gas temperature may be needed to calculate the appropriate heat-transfer coefficient and may be used in defining the boundary condition. Gas temperatures should be measured as close as possible to the boundary surface to obtain a measure of the temperature affecting the convective heat-transfer at the surface. Using aspirated thermocouples with a high aspiration velocity provides a measure of the actual gas temperature without the effects of radiation from the surroundings. This gas temperature measurement will be used to support heat-transfer calculations but will not be used to control furnace conditions.

3.2 Furnace Construction and Operation

Furnace Time-Temperature Exposure Curve

Recommendation T-9: The furnace time-temperature exposure should linearly increase to 1200°C in six minutes and remain constant at 1200°C for the remainder of the test.

Performance-based design analysis should be performed using models that have been shown to predict product performance over the expected temperature range. At high temperatures, material behavior can become unpredictable and material failures may occur that were not expected based on data trends at lower temperatures. As a result, using models to predict material behavior outside their validation temperature range is not acceptable engineering practice. Fully-developed compartment fires may produce gas temperatures that range from 500°C to in excess of 1200°C. The gas temperature reached inside a compartment will depend on compartment geometry as well as its contents. To perform analysis on an assembly that may be exposed to compartment fire conditions, the model should be validated to gas temperatures that represent an upper-bound to those expected in a compartment fires. Historically, furnace fire exposures inside buildings have not been representative of the rate of rise and magnitude of temperatures in compartment fires. However, furnace fire exposure curves for products used in off-shore platforms as well as tunnel applications, are more consistent with the rise time and temperature levels measured in these environments. The proposed curve provides an upper-bound time-temperature curve that is consistent with the rise time and levels of temperatures possible in compartment fires. This curve can be used to evaluate the performance of products under higher temperatures that these products may be exposed to during compartment fires and can serve to validate model predictive capability for this product over the expected temperature range.

Furnace Exposures

There are several furnace fire exposures used throughout the world to evaluate the fire resistance of products. These fire exposures have peak temperatures ranging from 1050°C to

1350°C after a three-hour exposure, see Figure 4. The type of exposure used depends on the end-use application of the product. Tunnel and off-shore oil rig applications have the highest temperature, most severe fire exposures, while less severe exposures are used for different building applications.

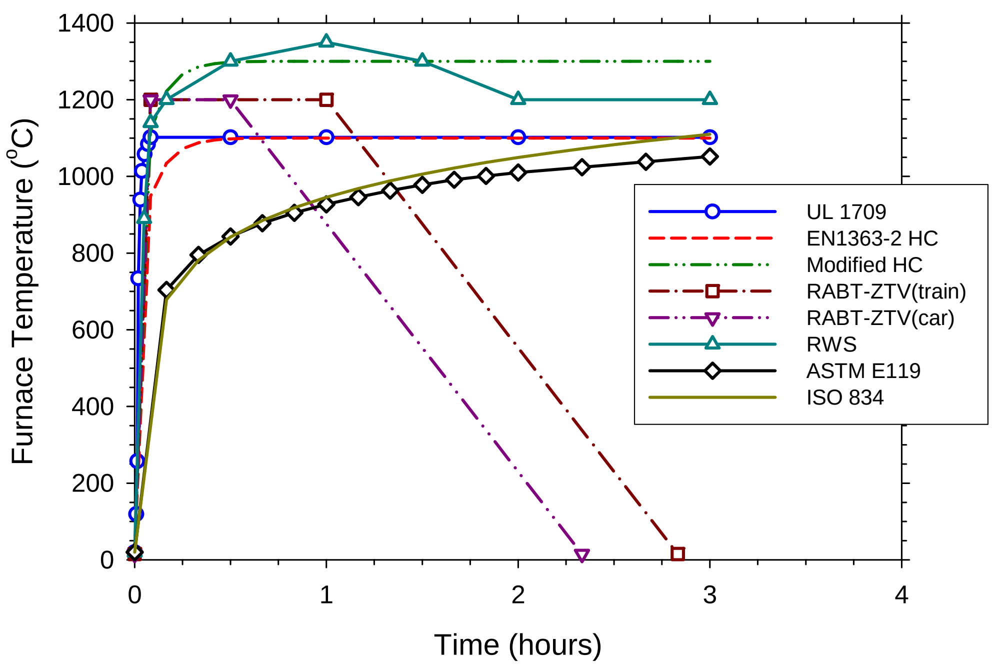


Figure 4. Furnace time-temperature exposure curves.

The ASTM E 119 and ISO 834 time-temperature curves are perhaps the most common furnace exposures used in fire resistance testing. These furnace exposures are used to evaluate the fire resistance of structural elements on buildings, ships, and in some transportation applications (e.g., railcars). ASTM E 119 is primarily used in North America, while ISO 834 is used more internationally (e.g., Europe and Australia). As seen in Figure 4, the two time-temperature curves are similar with the ISO 834 temperatures being slightly higher at times greater than one hour. The ASTM E 119 furnace exposure is measured using shielded thermocouples, while the ISO 834 furnace exposure is measured using sheathed thermocouples.

Though the time-temperature curves in these tests are similar, the actual heat flux exposure early in the ASTM E 119 fire exposure is more severe due to the type of thermocouples used to control the furnace (Harmathy et al., 1987, Babrauskas and Williamson, 1978). The European standard EN1363-1 uses the ISO 834 time-temperature curve, but the furnace is controlled using plate thermometers. Plate thermometers provide a more severe exposure compared with ISO 834 thermocouples for the test duration (Fromy and Curtat, 1999, van der Luer and Twilt, 1999). Sultan (2006) found that plate thermometers resulted in a slightly less severe exposure during the first 10 minutes of the test, compared with ASTM E 119 shielded thermocouples. Thereafter, the thermal exposures were the same for the plate thermometer and the E 119 thermocouples.

The total heat flux measured in an ASTM E 119 furnace test is provided in Figure 5 for a wall and floor furnace. Total heat fluxes were measured using a water-cooled Gardon gauge. In this test, gaseous fuel was used and the temperature was controlled with ASTM E 119 shielded thermocouples (Sultan, 2004). The wall furnace was lined with ceramic fiber while the floor furnace was lined with brick. The same furnace controlled with a plate thermometer provided similar heat flux levels at times after 10 minutes. Also provided in the plot is the blackbody heat flux based on the furnace temperatures specified in ASTM E 119. As seen in the **figure**, the blackbody heat flux is similar to heat fluxes measured in the furnace except during the initial 10 minutes.

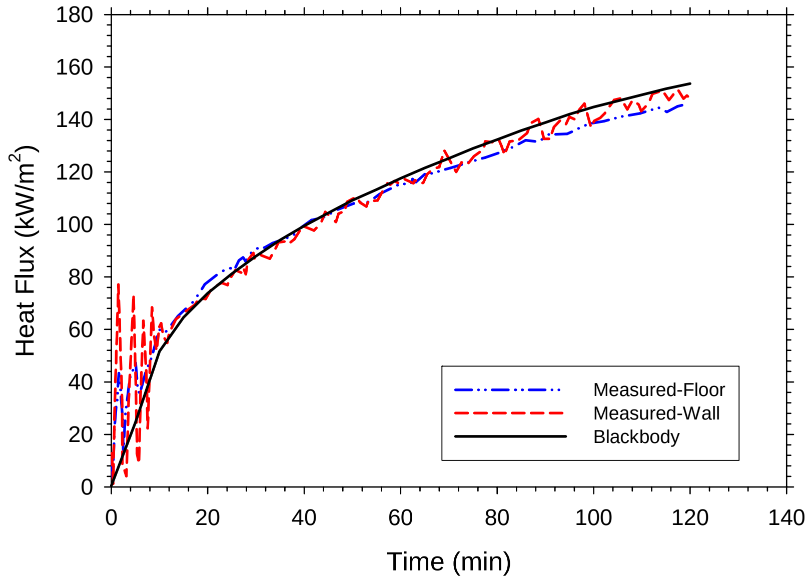


Figure 5. Heat flux measured during ASTM E 119 furnace exposure in floor and wall furnaces Blackbody heat flux was calculated from ASTM E 119 furnace temperature curve.

The higher temperature fire exposure curves in Figure 4 are used to evaluate products used in petrochemical, off-shore oil platform, and some tunnel applications. The UL 1709 hydrocarbon pool fire exposure and the EN 1363-2 hydrocarbon curve (HC), are typically used for off-shore oil platform applications, while the other higher temperature curves are used to represent a large fire inside a tunnel.

The UL 1709 and EN 1363-2 both have a maximum gas temperature of 1100°C; however, the UL 1709 exposure reaches 1100°C faster than the EN 1363-2 exposure. The UL 1709 reaches a peak temperature of 1100°C in 5 minutes, while the EN 1363-2 is approximately 1100°C after 25 minutes. Unique among the fire resistance standards, UL 1709 also has a heat flux requirement. During a calibration test with a UL 1709 exposure, the heat flux as measured from a water-cooled heat flux gauge mounted to a calibration specimen, must be 204±16 kW/m^2 while the furnace temperature is 1093±111°C. This heat flux is approximately equal to the blackbody heat flux at the furnace temperature (i.e., 1093°C results in a blackbody flux of 197 kW/m^2).

The curves for tunnel applications have peak temperatures that range from 1200–1350°C. The RABT-ZTV curves were developed in Germany to represent different vehicle fires in tunnels. These curves reach a peak temperature of 1200°C in 5 minutes and remain at 1200°C for 30–60 minutes. Thereafter, the temperatures decrease linearly with time to ambient conditions after 2.5–3.0 hours. Estimated peak heat fluxes, as the blackbody flux using the peak furnace temperature, in these tests are 267 kW/m^2. A modified version of the EN1363-2 HC curve has been used in France to represent fires in tunnels. The Modified HC curve peaks at 1300°C instead of 1100°C. Estimated peak heat flux in this test, based on the blackbody flux using the peak furnace temperature, is 347 kW/m^2. The RWS fire curve was developed by the Rijkswaterstaat, Ministry of Transport in Netherlands based on results from testing conducted by TNO in the Netherlands. The RWS curve peaks at a temperature 1350°C, which is the highest of all time-temperature curves. Estimated peak heat flux in this test, based on the blackbody flux using the peak furnace temperature, is 393 kW/m^2. The potential for these temperatures in tunnel fires was verified through vehicle testing in the Runehamar test series, where temperatures ranging from 1280–1365°C were measured (Lonnermark and Ingason, 2005).

Compartment Fires

Gas temperatures in compartment fires will be dependent on a number of variables including fuel type, compartment size, compartment boundary thermal properties, ventilation (i.e., door size), and fire stoichiometry.

Thomas and Heselden (1972) evaluated the effect compartment geometry (compartment and door size) on the gas temperature. Figure 6 contains the results of tests on wood cribs (Thomas and Heselden, 1972) as well as non-cellulosic materials (Bullen and Thomas, 1978). Through these tests, the gas temperature was determined to be a function of the opening factor,

$$O = \frac{A_T}{A\sqrt{H}} \tag{3}$$

where A_T is the internal surface area of the walls and ceiling excluding the door area (m^2), A is the area of the door (m^2), and H is the door height (m). The highest gas temperatures were measured at an opening factor in the 10–20 range. At lower opening factors, larger door sizes prevented the development of high gas temperatures due to higher air flow into the compartment and more heat loss through the door. At opening factors greater than 10, limiting the ventilation reduced the fire size that could be supported inside the compartment, thus reducing the maximum gas temperature that could be produced.

The impact of fire stoichiometry and fuel type can be seen in Figure 6 through the tests on the plastics and alcohol (Bullen and Thomas, 1978). In these tests, the opening factor is constant but the fuel type and stoichiometry of the fire is being varied. As seen in the figure, gas temperatures can vary by 200°C by changing these variables. The highest gas temperatures will be produced by fuels that require less energy to volatilize and when the compartment fire has an equivalence ratio equal to one (i.e., stoichiometric burning).

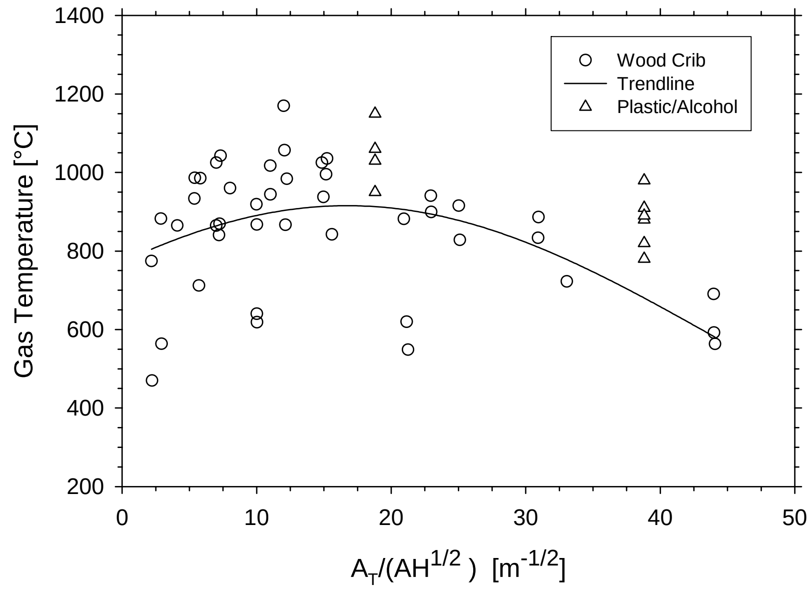


Figure 6. Compartment fire gas temperatures as a function of opening factor.

The SFPE committee on Standard on Calculating Fire Exposures to Structures has compiled a database of 139 compartment fire tests. This database was used to evaluate the appropriate furnace exposure. As seen in Figure 7, the fuels in these tests ranged from wood cribs, to furniture, to plastics. Compartments included in this database were mostly large-scale as shown in Figure 8.

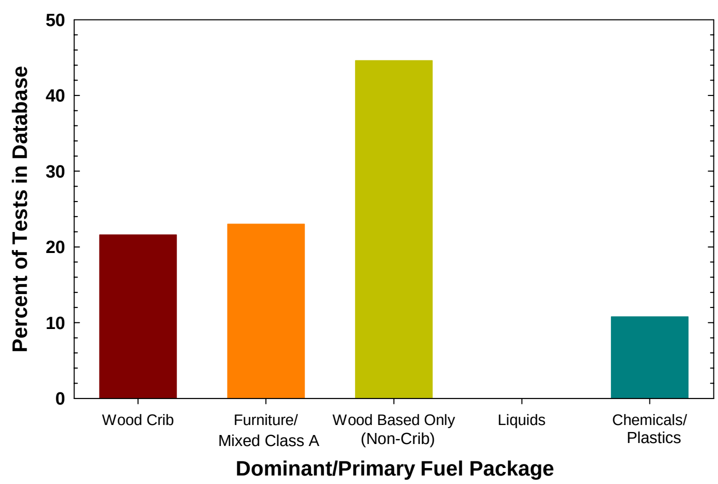
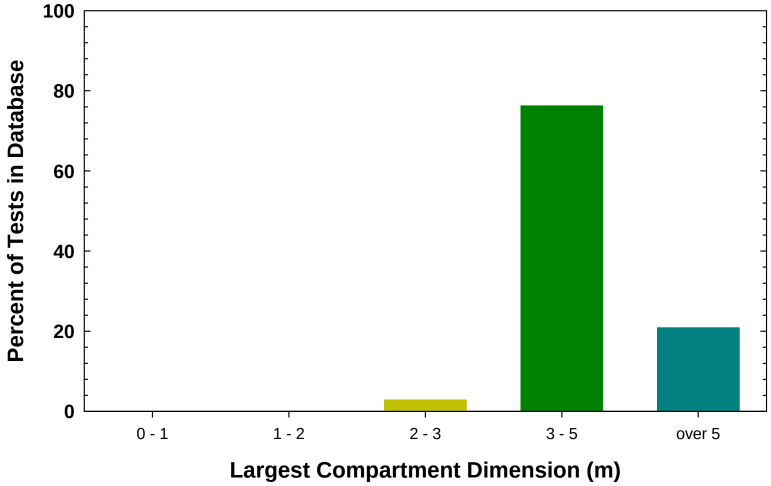
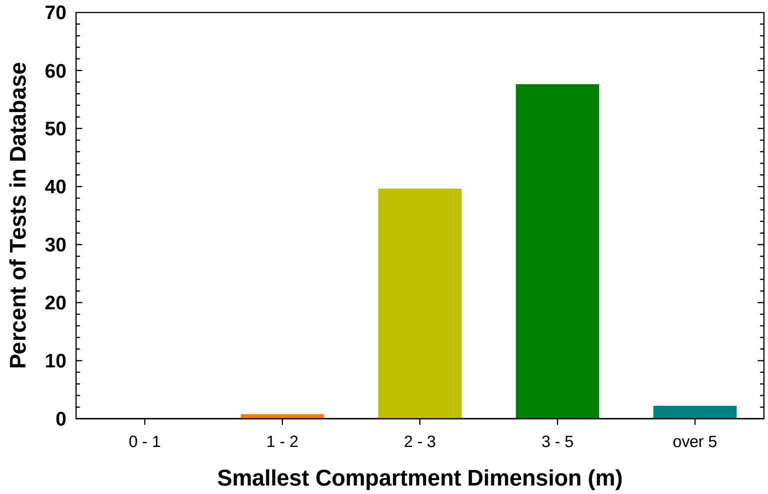


Figure 7. Fuels burned in compartment fire tests.



(a)

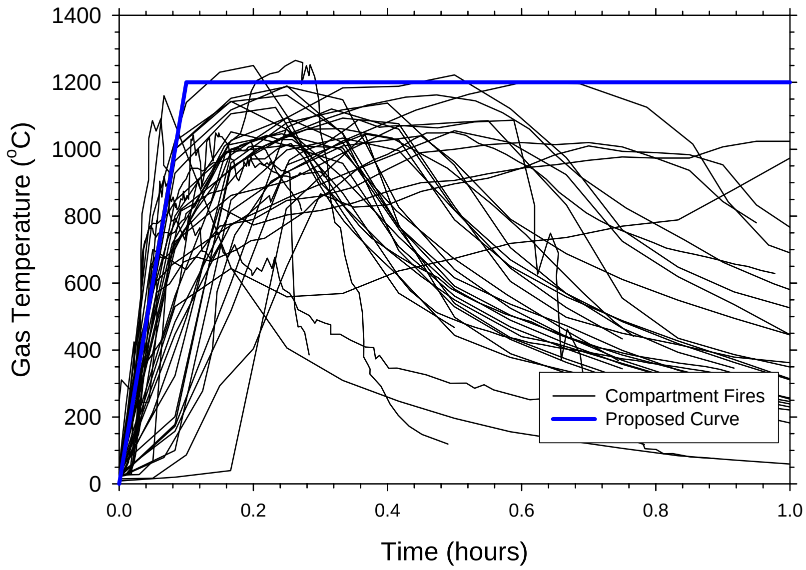


(b)

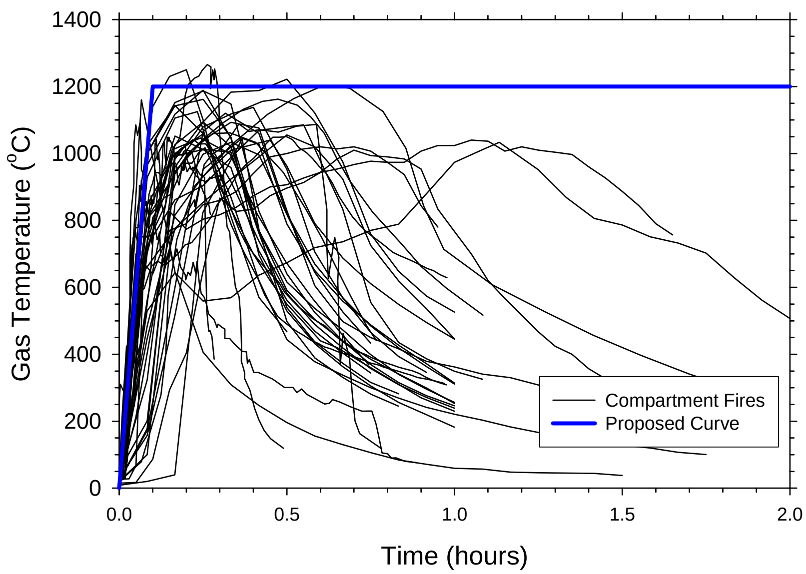
Figure 8. Compartment dimensions in compartment fire tests.

A plot of the average gas temperature as a function of time for tests with average temperatures exceeding 1000°C is provided in Figure 9. Figure 10 is a plot of the peak gas temperatures measured in these same tests. As shown in these figures, in many tests there is a rapid rise in gas temperature during the initial five minutes of the fire with temperatures in several tests exceeding 1000°C at this time. Post-flashover gas temperatures exist in many tests for 1–2 hours before decaying. Figures 9 and 10 also contain the proposed furnace time-temperature exposure, which increases linearly to 1200°C in six minutes and remains constant at 1200°C for the remainder of the test.

As seen in Figures 9 and 10, the proposed time-temperature curve provides a reasonable upper-bound to the test data.

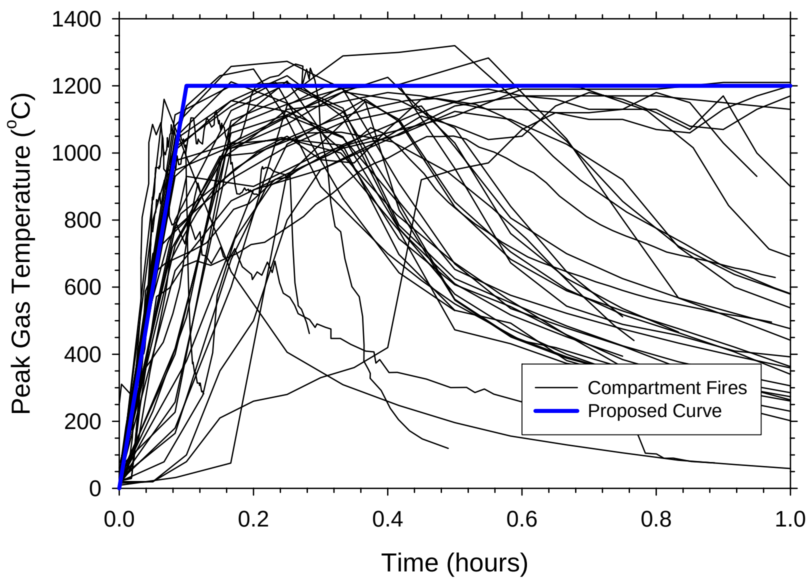


(a)

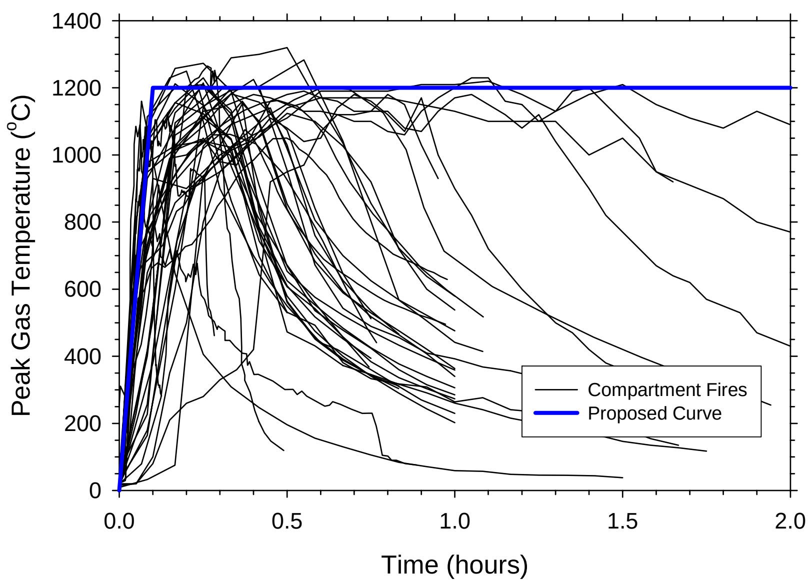


(b)

Figure 9. Average gas temperature in compartment fires as a function of time compared with the proposed time-temperature curve (a) after 1 hour and (b) after 2 hours.



(a)



(b)

Figure 10. Peak gas temperature in compartment fires as a function of time compared with the proposed time-temperature curve (a) after 1 hour and (b) after 2 hours.

Heat flux levels to the walls and ceiling of a compartment containing a fully-developed fire were measured by Tanaka et al. (1985). Tests were performed using a propane gas burner in a full-scale compartment (2.4 m high, 2.4 m wide and 3.66 m deep) with different door sizes. Heat fluxes were measured using Schmidt-Boelter type, water-cooled, total heat flux gauges. Gas temperatures in tests where heat flux was measured, ranged from 150°C–1100°C. Through these data, the heat flux at the top of the walls and ceiling in the compartment is reasonably estimated by the blackbody heat flux using the gas layer temperature. As a result, heat fluxes inside a compartment with a gas temperature of 1200°C would be expected to be 267 kW/m^2.

Effect of Exposure on Product Performance

The use of a severe exposure condition to evaluate materials or assemblies will provide some assurance that for most materials, performance under a less severe exposure will not result in a degradation of performance. When extrapolating performance from one fire exposure to a more severe fire exposure, there are no assurances that the performance of materials or assemblies will be predictable. Some materials may perform well at elevated temperatures, while other materials may expand, contract, warp, spall, go through phase changes, debond, or crack; fasteners may fail, and lose integrity and fall off from the surface. Many of these types of phenomena and failure cannot be predicted using the current state-of-the-art models. Therefore, testing products at the highest temperature level expected is currently the only way to demonstrate the performance of a material.

Materials that perform well at elevated temperature may just need to be thicker to obtain the desired level of performance at higher temperature. The UL Fire Resistance Directory provides design listings (i.e., minimum product thicknesses) which will provide a specific fire resistance rating when tested in accordance with various standard fire test methods, such as ASTM E 119 and UL 1709. Some products have been tested against these two standards, specifically for structural steel column protection. Broad product categories of materials include sprayed fire-resistive materials, intumescent coatings, intumescent mat products, and high-temperature board products. In all design listings reviewed, it becomes apparent that as the exposure severity increases (from ASTM E 119 to UL 1709), the minimum material thickness required to achieve the same hourly fire resistance rating must also increase.

An example of this is demonstrated in Table 1 by the increase in thickness of the amount of fireproofing required to protect a steel member when exposed to a UL 1709-type exposure versus an ASTM E 119-type exposure condition. For the same material, the thickness required to protect a W10 x 49 steel column increases as the fire exposure becomes more severe.

Table 1. Fireproofing Thickness for Steel Member

Rating Time (hrs.)	**E 119 Thickness (in.) [UL, 2006a]**	**UL 1709 Thickness (in.) [UL, 2006b]**
1	0.69	1.0
2	1.13	1.38
3	1.56	1.75
4	1.94	2.13

Other materials may only provide adequate performance over a specific temperature. At higher temperatures, the material may behave unexpectedly. One example of this was the use of mineral fiber insulation used on fire zone boundaries of U.S. Navy ships. A 1-in. thickness of mineral wool insulation provided a 30-minute fire-resistance rated bulkhead/deck when tested per the ASTM E 119 fire exposure (Scheffey et al., 1991). In the early 1990s, the U.S. Navy reevaluated the fire exposure potential for bulkheads and decks based on lessons learned from the USS Stark incident. This work effort lead the U.S. Navy to require a UL 1709 fire exposure to evaluate insulation materials. In 1993, additional test work showed that 1 in. of mineral wool insulation, when exposed to the UL 1709 fire exposure, provided a fire resistance rating of approximately 9.5 minutes and a 2-in. thickness of mineral wool provided a fire-resistance rating of approximately 11 minutes (Beitel et al., 1993). This significant reduction in performance was a result of the mineral wool exhibiting a phase change at the higher UL 1709 temperatures and melting/vaporizing off the steel base assembly. Thus, it is very clear that materials and their performance can change when the fire exposure conditions change.

Another example of differing material performance at elevated temperatures is the study performed by Nyman (2002) on the fire performance of several gypsum wallboard assemblies when exposed to compartment fires. The failure times and mode in the furnace tests were compared with those measured and observed in the compartment fire tests. Furnace tests were conducted at the Building and Research Association of New Zealand (BRANZ) using the AS 1530 Part 4 fire resistance test procedure, which is similar to the ISO 834 test method. The compartment fire testing was also conducted at BRANZ. In these tests, the compartments had dimensions of 2.4 m x 3.6 m x 2.4 m high, and a single doorway (size varied), provided ventilation of the compartment. The various walls and ceilings in each compartment were constructed using different assemblies such that several different constructions could be tested in a single compartment test. The fire sources consisted of a combination of textile-covered, polyurethane foam and wood cribs.

Table 2 provides a summary of several of these assemblies and the test results. The failure time in the compartment fire tests was shorter in the three assemblies shown in Table 2. In addition, the failure mode was different in the compartment fire tests compared with the furnace test. Assembly #1 failed due to unexposed surface temperature rise in both the furnace test and in the compartment tests. Assemblies #3 and #7 failed due to unexposed surface temperature rise in the furnace test, but in the compartment tests failure was judged to have occurred due to integrity failure. In these cases, it was determined that the steel studs experienced rapid and sizable deflections causing the gypsum plasterboard to fail. Figures 11–13 contain plots of compartment fire gas temperatures in the center of the room in the three tests where these assemblies were included. The plots show the gas temperatures in the upper part of the room are generally higher that than the ISO 834 fire exposure curve. The higher gas temperatures in the compartment fire tests had an impact not only on the time to failure but also on the mode of failure.

Table 2. Fire Performance of Gypsum Board in Standard Tests and Compartment Fire Tests

Assembly No.	Description	Failure Time (min) and Mode	
		Furnace Test	Compartment Fire*
1	1 layer of 10-mm "Fyreline" plasterboard on each side of 90 x 45-mm timber studs at 600 mm OC – load bearing	42 (heat transmission)	21/18 (heat transmission)
3	1 layer of 13-mm Standard plasterboard on each side of 63 x 34-mm steel studs at 600 mm OC – non-load bearing	34 (heat transmission)	19/17 (integrity**)
7	1 layer of 13-mm "Fyreline" plasterboard on each side of 63 x 34 mm steel studs at 600-mm OC – non-load bearing	63 (heat transmission)	35 (integrity**)

*Failure time room test – Assemblies 1 and 3 – First time is from Compartment Test #1 and second time is from Compartment Test #3. Failure time for Assembly 7 is from Compartment Test #2.
**Integrity failure due to steel studs deflecting causing plasterboard to fall off on exposed surface.

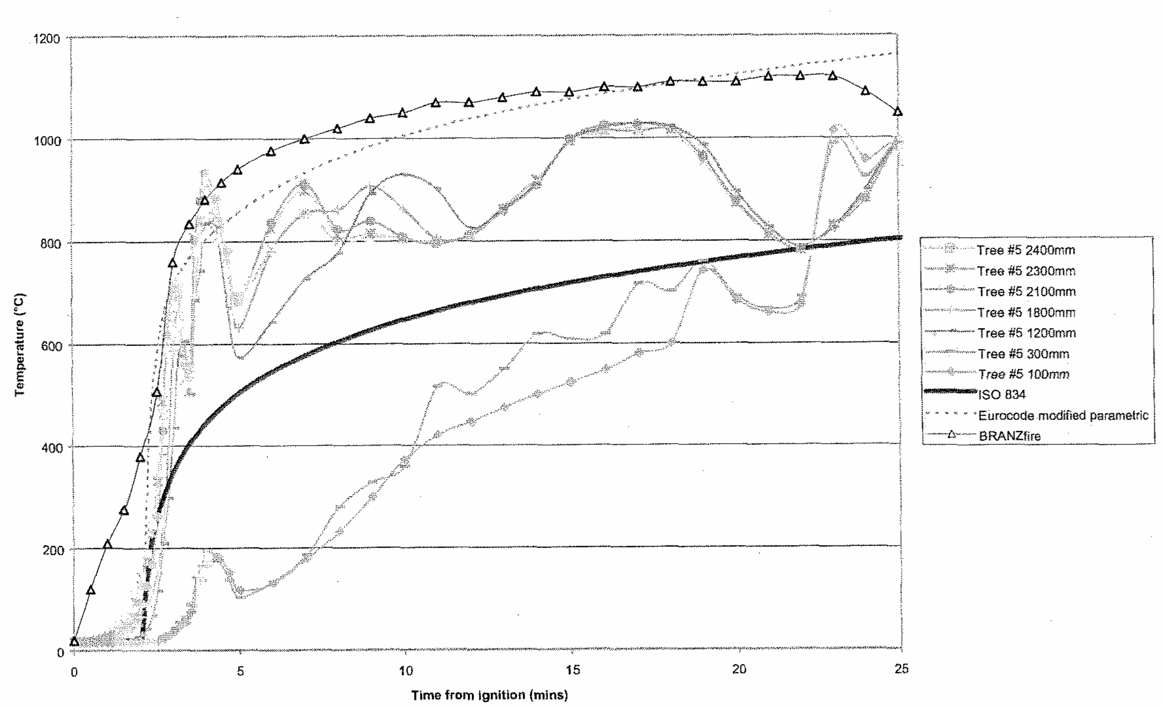


Figure 11. Compartment Test #1 exposure at tree 5.

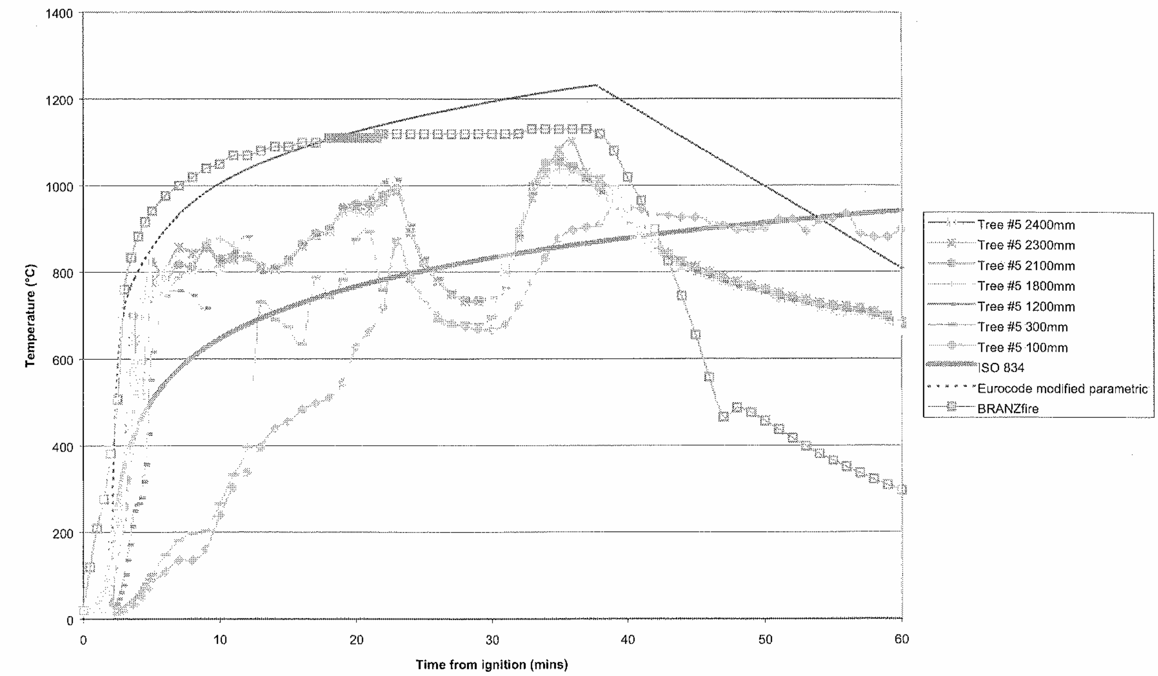


Figure 12. Compartment Test #2 exposure at tree 5.

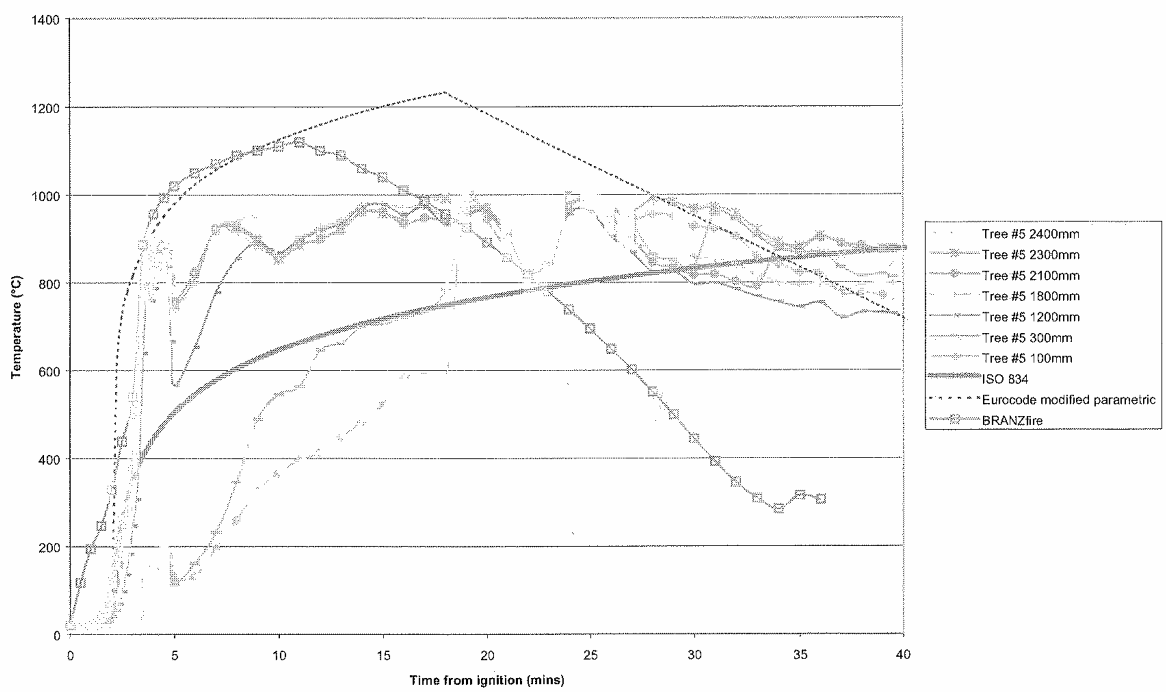


Figure 13. Compartment Test #3 exposure at tree 5.

Intumescent materials are another type of material used to provide acceptable fire resistance performance for structural elements; however, the performance of these materials may be highly variable from product to product. Two broad classes of intumescent materials have been specifically developed for distinctly different markets. Both are used for the protection of structural steel, however, the exposure conditions for which they have been designed are significantly different. Thin-film intumescent materials have been specifically designed for use in the less-severe ASTM E 119 fire exposure conditions. Epoxy-based intumescents were designed to withstand the more severe UL 1709 fire exposure. Many epoxy-based intumescents that are listed under UL 1709 ,also have ASTM E 119 listings. However, there are numerous other intumescent coatings that have ASTM E 119 listings but do not have UL 1709 ratings. Though some of these coatings may not be capable of achieving a UL 1709 rating due to the environmental exposure requirements, many ASTM E 119 listed intumescents (not listed in UL 1709) may not produce durable chars or have adhesion properties sufficient to survive the UL 1709 fire exposure. The formation and degradation of these chars as well as the adhesion of the intumescent are not readily modeled and predicted performance is only recommended over the range of conditions at which it has been tested.

Calibration Test

Recommendation T-10: A calibration test should be conducted with a noncombustible boundary containing instrumentation to quantify the thermal exposure. Instrumentation installed in the boundary should include total heat flux gauges and calibration boards instrumented with thermocouples. Instrumentation should be installed in at least five locations (center of each quadrant and center of the boundary) to quantify the furnace exposure. The calibration test should be performed for one–hour using the required furnace exposure and instrumentation.

Modeling the heat-transfer through a test article exposed to furnace conditions requires an understanding of the exposure provided by the furnace to the test article. Despite all efforts to construct furnaces similarly, each furnace will likely produce different exposure environments. As a result, a calibration test is required on each furnace to quantify the exposure level produced by the furnace. The calibration test is instrumented to provide heat flux levels and gas temperatures produced by the furnace. In addition, temperatures will be measured through the thickness of noncombustible board with known properties to provide model validation data. Instrumentation will be placed at five locations over the sample surface to provide information on the uniformity of the environment produced by the furnace.

The noncombustible boundary with instrumentation is shown in Figure 14. The noncombustible boundary should be constructed of steel studs covered with two layers of 15.9-mm (0.625-in.) thick Type X drywall and 50.8-mm (2-in.) thick ceramic fiber insulation on the exposed surface. Instrumentation will be installed in the noncombustible boundary in at least five locations including the center of each quadrant and the center of the entire boundary. Instrumentation will include total heat flux gauge, an aspirated thermocouple on the exposed and unexposed side of the boundary, and a calibration board installed with thermocouples.

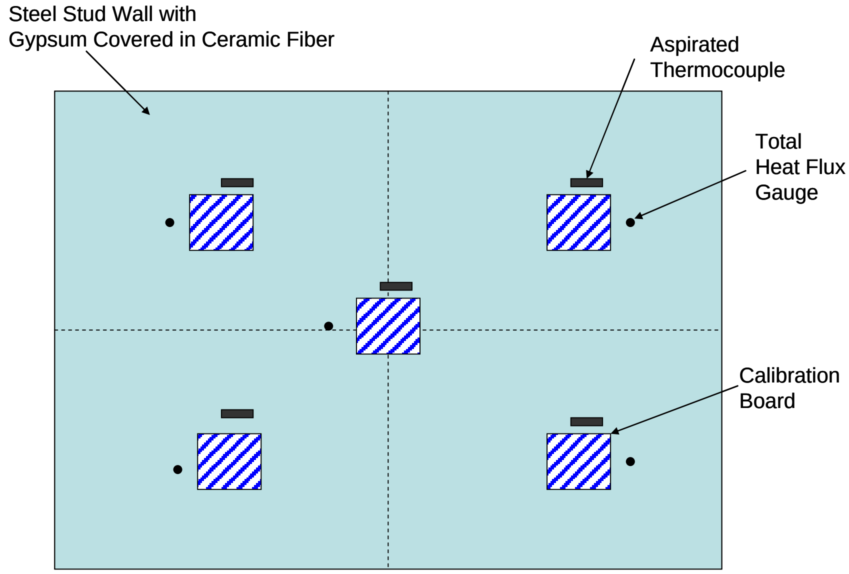


Figure 14. Calibration test noncombustible boundary with instrumentation.

Calibration boards should be located in the center of each quadrant of the noncombustible boundary and the center of the entire boundary. Total heat flux gauges should be installed in the noncombustible boundary at the mid-height and approximately 0.10 m (4 in.) from the side of each calibration board. Total heat flux gauges should be water-cooled Schmidt-Boelter type heat flux gauges with an upper range of 300 kW/m^2. Aspirated thermocouples should be located just below the top of the calibration board, within 25 mm (1 in.), with the thermocouple as close as possible to the calibration board to measure the gas temperature governing the convection across the sample. The location of the gas temperature measurement should be consistent with what will be used in the furnace testing on actual test articles.

Calibration boards should be 0.46-m (18-in.) by 0.46-m (18-in.) by 50.8-mm (2-in.) thick ceramic board. Examples of some acceptable boards include UNIFRAX Duraboard LD and FireMaster board made by Thermal Ceramics. The calibration boards should be installed in the noncombustible boundary so that the surface of the calibration board is flush with the surface of the ceramic fiber insulation on the exposed surface. Calibration boards should have a thermocouple installed at the exposed surface and internally at depths of 6.4 mm (0.25 in.), 12.7 mm (0.5 in.), 19.0 mm (0.75 in.), 25.4 mm (1.0 in.), and 38.1 mm (1.5 in.). The exposed surface thermocouple should be a 24-gauge bare bead thermocouple with at least 50.8 mm (2 in.) of thermocouple wire in the plane of measurement. The leads of the wire should be pushed through board for attachment to the data acquisition. Internal thermocouples should be 1.0-mm diameter Inconel-sheathed thermocouples. The unexposed side temperature should be measured using an optical pyrometer. All temperature measurements should be within 0.075 m (3 in.) of the center of the calibration board. After thermocouples are installed, the boards should be oven dried and then placed in a desicator until testing.

Furnace Lining Material

Recommendation T-11: All interior furnace surfaces should be lined with a ceramic fiber material.

Fire resistance furnaces have traditionally been lined with high temperature refractory brick materials commonly used in commercial furnaces. These refractory bricks are a low-density material (approximately 50 lbs/ft^3 (775 kg/m^3) and have a maximum operating temperature of approximately 2600°F (1425°C). When used in a fire resistance furnace, the refractory brick has a high thermal inertia, relative to the fire exposure period (typically 1 to 2 hours). This thermal inertia results in the refractory brick absorbing significant amounts of heat during the initial portions of the test (first 15 minutes), producing a dominantly convective heat environment within the test furnace. The furnace environment within the furnace transitions to a highly radiative environment once the brick temperature equalizes with the furnace air temperature.

To minimize the heating time of the furnace apparatus, thus resulting in less heat loss/absorption to the furnace walls, lining the inside surfaces of the furnace with a ceramic fiber insulating material is recommended. Experimental studies reported by Harada et al. (1997) demonstrated that a key aspect of the furnace environment was the absorption coefficient of the furnace gas, k, which is a function of gas temperature and the composition of the furnace gas. Tests conducted in a furnace lined with a ceramic fiber insulation material demonstrated small variation in measured test specimen temperatures as a function of furnace depth, with variations decreasing as the furnace depth increases. A similar trend was observed in furnaces lined with refractory brick, however, the temperature measurement variations increased for the similar exposure conditions. These tests demonstrate the ability of the ceramic fiber to heat up faster, resulting in a more uniform exposure temperature, and the development of a radiation dominant furnace environment. Analysis conducted by Babrauskas and Williamson (1978) support the use of ceramic fiber insulation materials used as the lining materials on developing a more uniform heat flux within the test furnace which results in improved furnace control.

The major conclusion from the work reported by Harada et al.(1997), indicated that the wall lining material was the dominant factor that influenced the heat impact on the exposed surface of the test specimen. Wall lining materials with a low thermal inertia, such as ceramic fiber insulating material, will result in improved furnace environment uniformity.

Minimum Furnace Depth

Recommendation T-12: The minimum furnace depth should be 4 ft (1.2 m).

Studies conducted by Harada et al. (1997) and Fromy and Curtat (1999) investigated the effect of furnace depth on the furnace environment. The work by Harada et al. (1997) evaluated furnace depths of 0.6 ft,(0.17 m), 1.6 ft (0.5 m), 3 ft (0.95 m), and 9.8 ft (3.0 m). The results of the tests indicated that as the furnace depth increased, the radiative heat increased proportionally. Furnace depths slightly greater than 4 ft (1.2 m) showed a convergence in the predicted specimen surface temperatures. The non-dimensional furnace depth parameter, kD, relates the furnace environment with the furnace depth. As kD increases, the exposed face specimen temperature uniformity converges.

Fromy and Curat (1999) reported the results of testing conducted in furnaces having depths of 2 ft (0.6 m), 4 ft (1.2 m), and 5 ft (1.5 m). As the depth of the furnace increased, variations in the exposed surface temperature decreased. These results indicated that as the depth of the furnace increased, the furnace environment volume became more uniform, and local effect from burners and re-radiation from the furnace walls decreased.

By increasing the non-dimensional furnace depth factor, kD, a more uniform furnace environment can be produced. The studies reported above indicate that a minimum furnace depth of 4 ft (1.2 m) would be expected to produce a uniform furnace environment which will reduce uncertainties and variability in the test conduct related to furnace construction.

Burner Fuel

Recommendation T-13: Propane gas should be used as the furnace fuel in all fire resistance furnaces.

Furnaces in the U.S. and in Europe use a variety of fuels to provide the heat input into the test furnace. In the U.S. gaseous fuel, either natural gas or propane, is used as the burner fuel. In some overseas furnaces, liquid fuels (heavy oil or kerosene) are used. Testing conducted by Cooke (1994) evaluated the thermal environment impact on a calibration sample in a number of furnaces located overseas. Two of the furnaces used natural gas as the burner fuel and one furnace used oil. The results of the testing did not specifically focus on the impact of the burner fuel on the furnace environment and performance of the calibration specimen, however, it was noted that the oil-fired furnace produced a more thermally-severe furnace environment compared to the natural gas fired environment. Numerical studies conducted by Sultan and Denham (1997), Sultan, Harmathy, and Mehaffey (1986), and Sultan (1996) all recognize that the absorption coefficient for the furnace hot gasses will vary with the type of burner fuel. Typically, the absorption coefficient is lower for gaseous fuels and higher for liquid fuels. As the furnace gas absorption coefficient increases, the severity of the exposure increases correspondingly. Systematic studies of propane versus natural gas do not appear to be available in the literature. Such a study would be of value to the fire resistance testing community.

Recognizing that liquid fuels will produce a more severe fire exposure, there exist practical operational and safety issues related to using liquid fuels sprayed into a closed environment. The spraying of a liquid fuel into a furnace may result in the build-up of residue on the furnace walls as a function of time, which may lead to increased maintenance costs. Safety systems would need to be implemented to insure the spraying system can be adequately secured upon termination of a fire test. Commercial gas-fueled burners are readily available with appropriate safeguards for ensuring gas flow is secured upon termination of a test. The burning of liquid fuels may not be as clean as gaseous fuels, therefore, requiring additional environmental considerations for the utilization. Many municipalities already contain the infrastructure to provide natural gas via underground supply lines or liquid propane via truck. Of the two, storage of liquid propane, used with an appropriate vaporization system, can maximize the on-site storage capability for conducting large-scale furnace testing.

Type of Burner

Recommendation T-14: Pre-mixed burners should be used in all fire resistance furnaces.

Two basic types of burners are currently used in existing fire resistance test furnaces; pre-mixed burners and diffusion burners. Control of the furnace temperature using diffusion burners typically involves adjusting the raw gas flow into the furnace to maintain the required temperature level. With this type of burner set-up, openings into the test specimen may require flowing additional raw gas into the furnace to maintain the furnace temperature. This can result in incomplete combustion within the test furnace. The installation of the "burners" in the test furnace requires careful placement as these burners typically produce a large flame plume, which depending on the relative location of the test sample to the burners, may result in undesirable localized heating effects.

Pre-mixed burners carefully control the amount of fuel and combustion air injected into the burner and into the test furnace resulting in a very uniform flame shape and heating capability. This results in a burner flame, which is easily controllable, and with combustion that is more complete. The air-gas mixture can be adjusted to suit a range of furnace conditions, providing operational flexibility not available with diffusion burners. These burners also produce high gas velocities inside the furnace, which is desired to produce an environment similar to that of a fully-developed compartment fires.

Secondary Air Capability

Recommendation T-15: When necessary, a means for providing secondary air should be provided such that the minimum oxygen content within a furnace is not less than 6%.

Maintaining a minimum oxygen concentration within the test furnace is desired to produce conditions that could be obtained in compartment fires and to support the combustion and char oxidation of combustible test samples such as wood. See Section 3.1.1 for a detailed discussion. A minimum oxygen concentration of 6% was determined to be reasonable. A secondary airflow path into the furnace may be required to maintain this oxygen level, especially in cases where the test article is combustible. Sufficient oxygen make-up air should be available to maintain oxygen levels with oxygen depletion due to burning test articles.

Exhaust Control

Recommendation T-16: A means for controlling the internal furnace pressure (e.g., damper in exhaust stack) should be provided.

Fully-developed fires will always produce a positive pressure gradient across ceilings and a majority of the boundary height relative to ambient conditions. In these areas of positive pressure, hot gases are driven through small openings that develop in the assembly causing damage to the internal portions of the assembly. Hot gas migration through the assembly may also give rise to ignition on the unexposed side of the assembly in these local areas of weakness. As a result, it is recommended that furnace tests be performed with a positive furnace pressure so that the effects of hot gas transmission through the assembly can be observed.

Furnaces should contain a means for controlling the pressure inside the furnace during the test. As described in Section 3.1.1, a positive furnace pressure (relative to the laboratory) will be maintained across the entire test article in both vertical and horizontal tests. In vertical tests, the neutral plane in the furnace needs to be maintained at the bottom of the test article to have the entire test article at positive pressure. There should be no limit on the pressure at the top of the test article; for a 2.4-m (8-ft) high-test article the pressure at the top will be approximately 18–22 Pa depending on the gas temperature. In horizontal tests, the furnace should be maintained at 20 Pa during the entire test. The damper system should be designed and demonstrated to be capable of meeting these requirements, with some lead way to account for leakage through the assembly.

3.3 Thermal Properties of Materials

Recommendation T-17: The thermal and physical properties of materials in the test article assembly should be measured. Thermal properties (conductivity, specific heat capacity, heat of decomposition) should be measured at temperatures as close to the highest temperature the material is expected to reach during the test. Physical properties (density, moisture content, expansion/contraction, decomposition kinetics) should also be measured as a function of temperature up to temperatures the material is expected to reach during the test. Thermal property test should be performed on materials taken from the same lot of materials used to construct the test article.

The accuracy in predicting the heat-transfer through the test article assembly during the test, as well as other exposure conditions will be dependent on knowledge of thermal properties of materials in the assembly. Thermal properties should be known over the temperature range at which the materials are expected to be exposed.

Thermal properties for noncombustible materials can be obtained as a function of temperature. However, thermal properties are more difficult to obtain for materials that lose mass through either moisture-loss or degradation or materials that are deformable or not dimensionally stable. Several methods have been developed to determine thermal properties of materials at elevated temperatures with limited success on thermal properties in excess of 800^{o}C (Henderson et al., 1981, 1982, 1983, Kokkala and Baroudi, 1993, Lundkvist et al., 1991, Jansson, 2004, Lattimer and Ouellette, 2004, 2006, Mehaffey et al., 1994, Sheppard and Gandhi, 1993). All of these methods are inverse heat-transfer methods where a model is used along with material temperatures measured under controlled conditions to determine the thermal properties required to obtain the measured response. Particular problems have been cited when attempting to measure properties of materials that degrade at particular temperatures. To overcome this difficulty, Henderson et al. (1982, 1983) and Lattimer and Ouellette (2004, 2006) conducted thermal property measurements on undegraded samples up to temperatures where degradation was expected. Thermal properties were determined for a degraded sample over the entire temperature range, and the thermal properties during degradation were calculated based on the fraction of degradation.

4.0 TEST METHOD RECOMMENDATIONS – STRUCTURAL PERFORMANCE

The test requirements, with respect to the structural aspects of the test method, involve measurements/instrumentation, test procedures, and test documentation. These requirements relate to the production of data that can directly support PBSFE. The recommendations are followed by a discussion of the issue and the basis for the recommendation. The test procedures are subdivided into instrumentation, general, and load/scale issues.

4.1 Instrumentation

<u>Assembly End Restraint</u>

> *Recommendation S-1: Place load cells at the assembly end boundaries to record magnitude of thermal restraining forces throughout test duration: minimum of three cells at one edge of furnace for the top, center, and bottom of a middle beam or stud of assembly.*

Structural modeling of the test results requires the inclusion of boundary conditions. Without these, no meaningful predictions of the test can be performed and as such, validation of the model through comparison with the results of furnace fire testing is not possible.

The fire test results recently reported in NIST NCSTAR 1-6B, as well as those from some non-standard fire tests, such as Cardington (University of Edinburgh, 2000 and Bailey, 2004) bring close scrutiny to issues of end conditions. A fully unrestrained end condition clearly represents a unique boundary condition of free expansion without any thermally-induced reactions, but the restrained condition includes a wide range of potential thermal restraints, from moderately stiff to fully rigid (Lim, Buchanan, and Moss (2004).

Another common source of confusion, particularly to structural engineers and architects, is that thermal restraint is not necessarily synonymous with structural end restraint: simple and modest steel shear connections for beam framing, which are considered to be rotationally unrestrained with negligible moment-resisting strength, have been shown to represent adequate thermally restrained conditions for most cases of both composite and non-composite steel-concrete floor systems (Gewain and Troup, 2001).

The default assembly support condition is just simple bearing on the furnace boundary. For the default bearing or end-connected assembly support condition, a complete description and quantitative characterization of the actual physical restraint provided during the fire test is very pertinent to the fire response of the assembly. Use of load cells at the restrained assembly boundaries to measure the thermally-induced forces that develop during the test would be quite illuminating in recording the assembly-to-frame interface conditions. A minimum of three load cells at a beam or stud end location within the assembly interior is recommended to measure both the total axial thrust and bending moments that occur from the thermal restraint. Additional such instrumentation for other beam or stud ends would serve to confirm similar restraint in other parts of the assembly or to demonstrate its variability. This information will provide quantitative structural data that can be converted for use in PBSFE relative to actual connections and assembly support stiffness.

Deflections

Recommendation S-2: Record, as a minimum, the time-history of transverse deflections at mid-span in all primary structural members (beams, joists, columns, and wall studs) of the assembly, together with axial shortening of loaded columns and wall studs.

Besides strength, the stiffness of a fire-resistive assembly is an important performance factor. Assembly deflections are not only a lead indicator of structural distress in the element tested, but large deflections also can lead to damage of its fire protection materials as well as damage to adjacent construction. Even without failure of the tested assembly, large fire-induced deflections can cause breaches of adjacent horizontal and/or vertical fire barriers, thereby leading to fire propagation into additional compartments. Therefore, transverse (out of plane) deflections of the structural members (beams, joists, wall studs, or columns) should be recorded by transducers, at least at their mid-spans, to provide the time-history of the deflection profile. For multiple beams, joists, or studs within an assembly, each member should be so instrumented, or at least those within the central, more flexible, region of the assembly. For axially loaded walls and columns in compression, the time-history of axial shortening at the load points should also be required.

Digital photo or video has additional value, especially in recording lateral or torsional deflections. Subsequent image analysis can provide quantitative deflection data.

Strain Gauges

Recommendation S-3: Require high-temperature strain gauges at critical sections (typically ends and/or mid-span) of main structural members (beams, joists, columns, wall studs) and of other important load transfer elements (shear studs, metal deck, floor slabs and reinforcement, and connections).

Strains in the primary structural member section (beam/joist, wall stud, or column) should be monitored with high-temperature strain gauges, at least at both of the outside section edges and at its mid-depth, at the end supports and mid-span. Strains in the metal deck, concrete slab, any shear studs (for composite steel beams) and/or steel reinforcement in the concrete slab or wall should also be instrumented at supports and mid-span, as a minimum. Such strain data provides key information on load paths, identifies the local member areas where inelastic (yielding) material response is occurring and whether it is tensile or compressive, thereby revealing the critical structural locations for force redistribution and resistance mechanisms with time. Measured strains can also be related by compatibility to thermally-induced elongations and assembly restraint to better quantify these test assembly variables. Such localized and detailed structural response information cannot be deduced solely from measured deflections that are more representative of the overall gross response.

Non-standard fire tests, such as the Cardington building tests conducted in the UK over the last 10 years (University of Edinburgh, 2000 and BRE 215-741), usually supplement thermocouple and deflection results with strain readings for such purposes. Special high-temperature strain gauges are available for applications up to about 500–600ºC. Beams and columns, concrete slabs and its reinforcing mesh or rebar, and any connection elements can be instrumented for strain. Figure 15 shows strain data for bolts in steel connection at elevated temperatures from BRE 215-741.

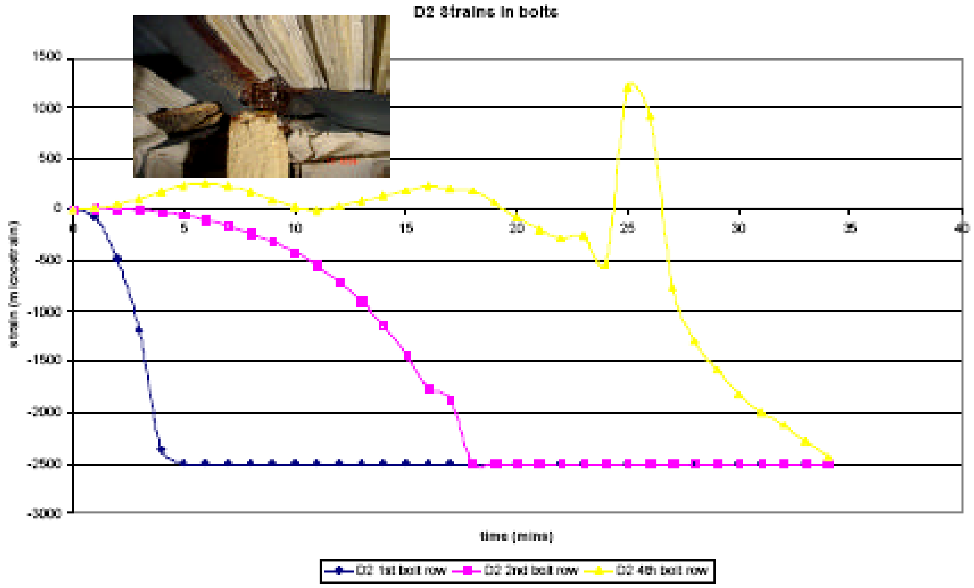


Figure 15. Bolt strain data from BRE 215-741.

This level of test data acquisition and documentation, as summarized in Table 3 and Figure 16, should be provided.

Table 3. Test Instrumentation Recommended for Acquisition of Structural Performance Data (see Figure 16)

Measurement	Instrumentation
Time-history of transverse (out-of-plane) deflections for all structural members	*Transducers at assembly mid-span (minimum) for each member*
Time-history of axial shortening for axially loaded walls and columns	*Transducers at assembly load point (min)*
Measure thermal restraint forces and bending moments at structural member end	*Minimum of three load cells at beam or wall stud end, located at center of section and at both outside edges.*
Time-history of strains in primary member section (beam, column or wall stud), metal deck, shear studs, steel rebar in concrete	*High-temperature strain gages at outside edges and mid-depth of main structural section, centrally located in deck and rebar, base of shear studs - at end supports and mid-span (min) – see Figure 3*

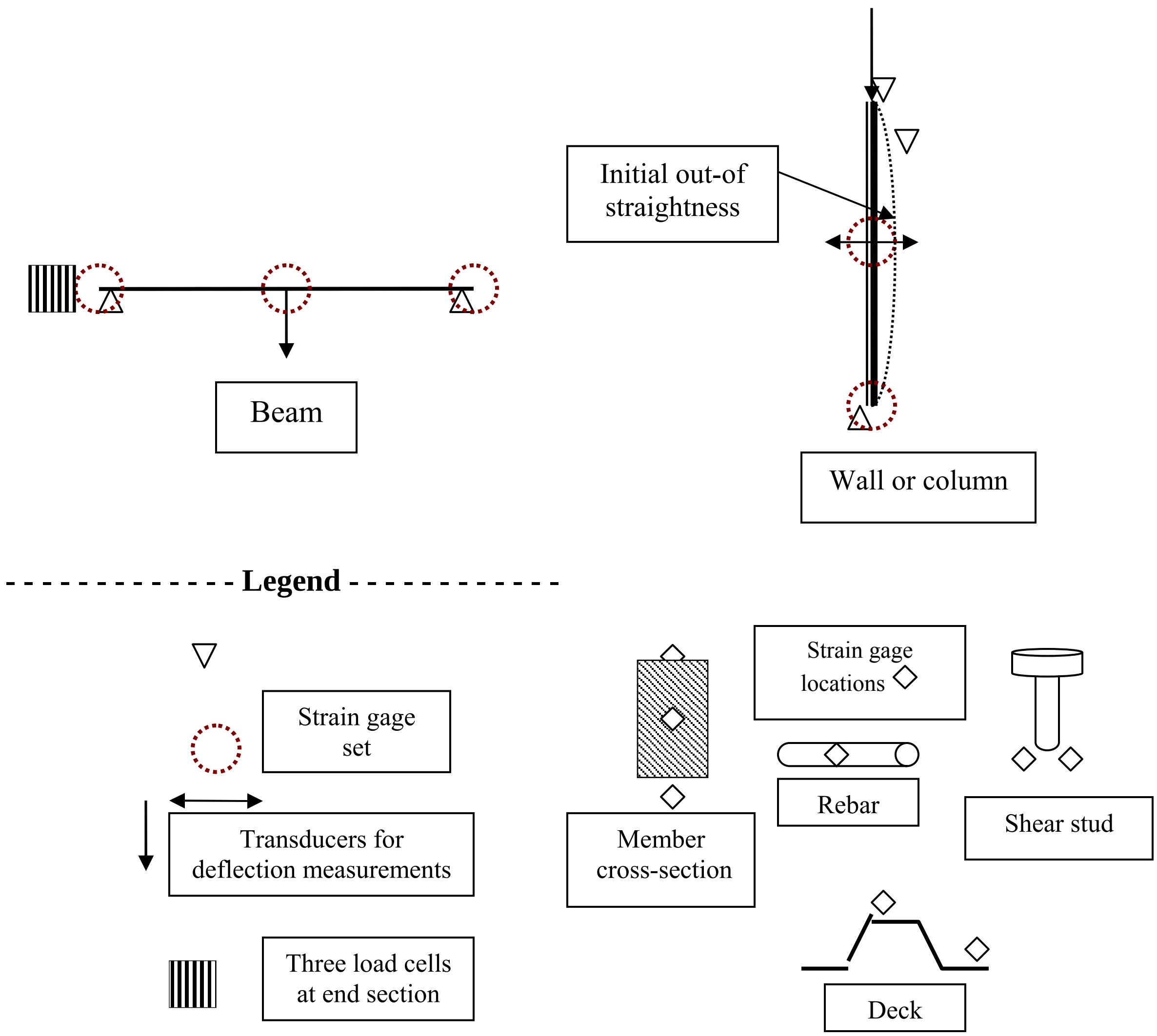


Figure 16. Illustration of recommended additional instrumentation for structural fire performance.

4.2 Furnace Operation and Load/Scale

Standardized Assembly Load Application

Recommendation S-4: Superimposed loading on all assemblies should only be applied through mechanical or hydraulically-controlled apparatus.

In addition to hydraulic/mechanical equipment, current testing practices often include use of other types of floor or beam load application, such as water-filled tanks, concrete blocks, or sand bags. While there may be some merit or convenience in using the latter for lightly loaded specimens not tested to their maximum design limit, use of such constant weights is inherently less accurate and consistent than load control equipment that has been properly calibrated and serviced. Inconsistencies and differences in the load application methodology alone may lead to discrepancies between tests and/or laboratories. The bulky natural weights can obscure needed detailed observations of the assembly's unexposed side condition relative to any openings, cracks, spalling, or fire penetration. At larger floor/beam deflections during the fire exposure, lateral contact among the stacked weights can be induced which would alter the actual gravity load distribution on the assembly. Moreover, in fire tests that reach actual structural failure, the danger to personnel and damage potential to the laboratory furnace is less with controlled loads than with stacked tank, block, and bag weights, whose support and stability cannot be readily maintained after floor/roof collapse.

For all these reasons of control, accuracy, and safety, it is recommended that loading be standardized and restricted to only hydraulic/mechanical means. It is recognized that to attain the desired pattern of uniformly distributed floor design loading in this manner, it will necessitate a series of multiple jacks, with corresponding spreader and reaction beam configurations. Appropriate guidance in this regard must still be developed to avoid assembly overload from too few or inadequately positioned concentrated loads that do not reproduce the intended characteristic response of uniformly distributed design loads.

Specification of Maximum Superimposed Design Load

> *Recommendation S-5: The standard should require the maximum assembly design load to be based on the greater of the design load computed from either allowable stress design or limit states-LRFD and the controlling strength failure mode to be used for each type of assembly construction.*

As with the thermal aspects of the test, it is necessary to provide loads that create the maximum allowable structural conditions so that potential serious failure modes can be realized in the test. Lesser loading would not provide full expression of assembly response potentials, leading to the potential for unanticipated failure modes in the field.

Over the last couple of decades, the alternative ultimate strength, limit states, or LRFD approach has evolved into an equally acceptable methodology that can result in different design solutions from working stress. In particular, it is possible to realize large maximum design load increases with the newer limit states/LRFD of up to 33–50% for some situations, such as composite steel-concrete beams. With this development and the broad acceptance in U.S. building codes of both design methods, there is no longer a unique maximum design load for a given assembly that is independent of the selected design method (ultimate strength or working stress). In some cases, it is also not clear which strength failure mode is to be considered for the assembly design.

Canada currently only allows use of limit states design, and has accordingly revised its CAN/ULC-S101-04 standard to specify how maximum assembly loads for standard fire tests are to be determined. It also addresses the typical strength limit states (bending, shear, compression, or tension) for which maximum design strength of the different assembly elements are to be computed. The latter guidance would be particularly helpful in the structural loading and analysis of multiple-part members, such as open-web joists, trusses, and non-standard girders. Additional provisions in this regard are needed in any test method in support of PBSFE. The conservative resolution of this issue in the presence of two structural design alternatives in the U.S. is to specify the maximum assembly design load as the highest load produced by working stress or limit states/LRFD, based on actual tested ambient material strength. In most typical cases, this maximum design load would be based on the ultimate strength/limit states/LRFD methods. Since testing to structural failure is the objective, restricted load tests at substantially less than the full design level may not reach this endpoint, or do so at significantly prolonged fire exposure times.

As a minimum, for purposes of PBSFE development, the applied load magnitude, type, and its design basis, as employed in the test, would add much needed clarity to the experimental results.

Minimum Assembly Size

> *Recommendation S-6: Specified minimum sizes of construction assemblies should be as follows: walls and paritions-100 sq ft with neither dimension less than 9 ft, columns – not less than 9 ft length, floors/roofs – 180 sq ft, with neither dimension less than 12 ft, beams – not less than 12 ft-span length. Standards-making bodies should consider the formation of furnace classes to recognize furnace capabilities larger than the minimum size.*

While ever-larger furnaces and test assemblies are desirable to limit the extent of the scaling extrapolation required, the realities are that existing laboratory facilities were built for the current E 119, and similar ISO 834, minimum assembly size requirements (Beitel and Iwankiw, 2002). Marginal size changes from the nominal 10 x 12 ft vertical furnaces for wall and columns tests and 14 x 17-ft horizontal furnaces for floor/roof tests would be substantially meaningless toward enhancing the fidelity of test results. Only rather large increases of at least 2–3 times the current limits would enable more fully capturing the nature of continuous building construction. However, these greatly-increased assembly sizes would necessitate major new capital expenditures on bigger furnaces and ancillary test equipment, with the recurring expense of fire testing accordingly escalating. These major budget and cost factors are likely to constrain the demand and short-term availability of necessary facilities for large tests.

At this time, while fire testing development of larger assemblies is certainly encouraged, it is felt that this goal can best be accomplished in the near future within the context of special purpose projects, and not on a regular recurring basis. It is concluded that sufficient benefits for PBSFE can be more practically achieved in the shorter term through the other recommendations and without any change in the minimum assembly size.

Given the clear value of larger test specimens, it is desirable to create a number of furnace size classes so that the construction and use of larger furnaces can be recognized and the enhanced value of larger-scale testing can be reflected in the V&V requirements for models to be employed in PBSFE.

Size Effects and Experimental Scaling

Recommendation S-7: Employ dimensional scaling principles in the design of the test assembly to represent the actual construction applications.

Laboratory furnaces are limited in size and depth, and this necessarily constrains the dimensions of assemblies that can be tested (Beitel and Iwankiw, 2002). Consequently, to date, most tests have been conducted full-scale on relatively small, shallow (not more than about 18 inches depth) and shorter span assemblies (less than about 17 ft) Restrictions have been imposed on the minimum structural sizes for which the rated assembly is applicable. However, it is known that long and short span floors/beams and walls/columns (often expressed in terms of a slenderness ratio of unbraced length divided by section depth or by its radius of gyration) can exhibit different structural behavior and have different strength limit states. The assembly depth can thereby be related to its span length as a contributing factor to the structural behavior. Bending and stability are the primary response modes for longer members, while shorter members are controlled by shear and axial section capacity.

In order to observe the full possible range of structural fire behavior, effects of longer spans and/or the larger assembly depths, which are actually used in construction, should be evaluated, since these could be more critical than shorter assembly spans and smaller depths. This approach would involve fire testing scaled specimens under load, which better represent reality. These geometric variables can be tested in practical furnace size and laboratory facility constraints using reduced-scale loaded assemblies and scaling laws to represent deeper trusses, bigger or taller columns and walls.

Dimensional analysis and structural similitude techniques to enable experimental test result correlations between full-size prototypes and scaled physical models have existed since the early-mid 20th century (Handbook on Experimental Mechanics, 1987, Bazant et al., 1996, Simitses and Rezaeepazhand, 1992) Preservation of key non-dimensional parameter(s) in the governing response equation(s) controls the experimental set-up and correlation of results. The fundamental differential equation for equilibrium of an elastic beam-column is given in Eq. 4, without regard to sign convention of the individual terms, and subject to material first yielding limits for axial and bending stresses:

$$\begin{aligned} &EI\frac{d^2y}{dx^2} = Py(x) + M(x) \\ &\text{subject to} \\ &P \le F_y A \text{ and} \\ &M(x) \le F_y S \end{aligned} \qquad (4)$$

where

$E\,I$ = elastic bending stiffness of the structural member, assumed as constant for prismatic section (force*lengths^2)

$\frac{d^2y}{dx^2}$ = second derivative of transverse member deflection relative to length, (length^{-1}) also known as curvature of neutral surface

P = centrally applied axial load, (force)

y(x) = transverse member deflection, function of length, x, along member, (length)|

M(x) = bending moment from continuity, axial load eccentricity and/or transverse member loads, function of length, x, along member, (force*length)

F_y = material yield stress, (force/length^2)

A = member cross-section area, (length^2)

S = member section modulus, (length^3)

Elastic column stability for compressive axial loads is influenced by the secondary bending term, P y(x), which disappears for a pure beam with no axial force (P=0). For assessment of ultimate member structural strength and failure, utilization, or demand-to-capacity, ratio is the key invariant. If the model and prototype are built from the same materials, this ratio can be simply replaced by stress level. For these conditions and if structural member dimension of the model relative to prototype, $0<s<1.0$, is the primary scaling variable for its cross section and span length, the following scaling is necessary for complete test similitude and dimensional consistency of Eq. 4:

- Member span, length: s
- Member section area (A), length^2: s^2
- Moment of inertia (I) of member, length^4: s^4
- Concentrated load (P), force: s^2
- Line load, force/length: s
- Bending moment (M), force*length, and section modulus (S), length^3: s^3
- Uniformly distributed load, stress, and E (Young's Modulus), force/length^2: 1.0

Scaling (½-size floor truss depth and span, with doubling of applied load to produce equivalent steel stresses) was successfully employed in the recent NIST WTC floor truss fire resistance testing. (NIST NCSTAR 1-6B) Appropriate test provisions for furnace-scaled assembly testing should be developed, along with guidelines for application of results. Criteria for how and when large geometric changes in assembly span and depth can affect their fire resistance should be formulated, along with requirements for when assemblies must undergo additional scaled tests to account for these possible size effects in their fire resistance rating in lieu of extrapolation. Floor systems and columns appear to be the most likely candidates for such reduced scale testing. However, it is recognized that consistent scaling of concrete floor slabs may be problematic due to lack of sufficient control over aggregate size and internal moisture/humidity content. Furnace-scaled specimens can be considered to be about approximately ½ to ¼ size of the real prototype.

Some adaptation of full-scale to reduced, furnace-scaled fire testing of assemblies (in particular for beams, roofs, and composite steel-concrete floors) should be accomplished in the relative short-term. It would provide much needed supporting data to supplement or replace the current extrapolation of results of larger and heavier construction.

General guidance on the design of scaled furnace assemblies is needed by the fire resistance testing community and this is included as a general recommendation in Section 6.2.

4.3 General

Mandatory Fire Testing Under Design Load to Structural Failure

> *Recommendation S-8: All assembly fire tests should be conducted under maximum design load until an imminent or actual structural failure limit state is attained, or until an major integrity breach occurs, irrespective of the assembly's other thermal conditions.*

Oftentimes, the limiting criterion for a fire resistance rating time is either thermal or the test is simply terminated because a desired rating time target had been achieved. Under these circumstances, structural failure of the fire test assembly is never reached. The importance of continuing fire tests to structural failure, despite any rating time considerations, lies in gaining a fuller understanding of the actual structural limit states that can be encountered as the assembly reaches its failure time. These ultimate fire performance facts are not at all evident when the test is prematurely stopped, sometimes well in advance of even any visible structural distress. All loaded fire tests should continue until an imminent or actual structural limit state (failure condition) is reached.

In the recent NIST WTC collapses investigation (NIST NCSTAR 1-6B), four standard fire resistance tests were conducted on the floor truss system with different protection thicknesses and test conditions. While the E 119-based rating time was determined to be between ¾–2 hrs., the floors continued to support load without collapse for over 2 hours.

This observation, among others, reinforces the need to test to failure and to clearly identify the structural failure time and failure mode. The type of actual or imminent structural failure mode (bending, stability, fracture) or assembly integrity breach (burn-through or flame penetration through assembly or the furnace enclosure) should be clearly identified and reported.

The practical implication of this approach is that test duration should be limited by laboratory safety. Termination of a test would be indicated by fire penetration or burn-through of the assembly, or other breaches of the furnace enclosure or test apparatus that would pose a danger to the laboratory staff and facility. This structural failure/integrity endpoint of the test would generate much additional valuable information at a relatively small increment of effort. The time, mode and mechanism of the assembly failure should be clearly described (ductile, brittle, in bending, shear, tension, squash, or buckling) and documented as part of the standard.

Actual Strength of Assembly Structural Materials at Ambient Temperature

Recommendation S-9: Material strength tests should be performed on samples extracted from the primary structural assembly members to determine their actual mechanical properties at ambient (including yield and ultimate strength, and elastic modulus).

Typical structural testing requires knowledge of the actual stress-strain properties and dimensions of the specimen material(s) at ambient temperatures. This mechanical property data is needed to accurately correlate the experimental results to predictor equations or analyses that utilize the material's yield or ultimate strength. Simple use of the minimum specified strength gradation of the structural material for this purpose is inadequate and could be grossly misleading for interpretation of the results, especially if the actual strength is substantially different (either more or less) from its nominal value. Current standards have no detailed requirements for determination of actual strength properties of the test assembly's structural materials, other than the general recording of their physical properties. The latter is mostly interpreted as being identification of the materials and their product designations, together with overall assembly dimensions. Often, the characteristic 28-day compression strength of poured concrete has been experimentally verified through standard ASTM C 39 cylinder tests and reported. However, the real steel, wood, or masonry properties of test assemblies commonly are not more precisely documented other than their nominal size and grade designation. Yet, it is possible, even currently probable for some lower grade, mild structural steels such as ASTM A 36, that their actual material strength may be 50% higher than its minimum nominal value. (ANSI/AISC 341-05). Petterson and Wittenveen (1979) cited examples in the 1970s of such artificial increases in fire resistance rating time achieved principally because the base structural material had an actual strength 25% higher than nominal.

Use of production mill certificates that show measured ambient strength of the material origination lot of the structural member is more reliable than mere dependence on nominal values, but due to potential variability within the lot as well as piece identification and tracking errors, this may also not be necessarily representative of the material to be fire tested. The best approach is to require standard ASTM strength tests of material samples used in the assembly construction, to include:

a. ASTM A 370-06, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products;*
b. ASTM E 8-04, *Standard Test Methods for Tension Testing of Metallic Materials;*
c. ASTM C 31/C31M-06, *Standard Practice for Making and Curing Concrete Test Specimens in the Field,* American Society for Testing and Materials, West Conshohocken, PA;
d. ASTM C 39/C39M-05e1, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens;*
e. ASTM C 1314-03b, *Standard Test Method for Compressive Strength of Masonry Prisms;* and
f. ASTM D 198-05a, *Standard Test Methods of Static Tests of Lumber in Structural Sizes*.

Explicit requirements for structural material strength determination to this effect should be provided in the test standard.

Determination of Structural Properties at Elevated Temperatures

> *Recommendation S-10: Material strength tests should be performed on materials used in the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus).*

The major mechanical properties needed for structural fire resistance engineering are yield and ultimate strength, Young's (elastic) modulus, and stress-strain curves. The first two strength and stiffness parameters as a function of temperature, may be deduced from a series of stress-strain data. All materials exhibit degradation of their ambient mechanical properties with higher temperatures, and this representation, often depicted as a percentage of ambient, or so-called retention ratio, is crucial to an accurate modeling of fire resistance, and ultimately any fire-induced collapse prediction.

In contrast to long-standing test standards for determination of ambient material strength, such as A370-06 tensile testing for steel, none exists for such applications at high temperatures. The determination of high temperature mechanical properties requires a heating apparatus (oven) in combination with the conventional load testing equipment. The material specimen can either be heated to certain uniform temperatures and then load-tested until failure to develop a family of stress-strain curve for those temperatures, or it can be loaded at various constant levels inside an oven and heated to increasing temperatures until a creep failure occurs. A correlation could be made between these two sets of high temperature results.

Published information exists from various sources, domestic and international, on the "typical" mechanical properties of traditional structural materials (commonly steel, concrete, wood or masonry) at the high temperatures that could be experienced during a fire exposure. (SFPE, 2002 and ASCE Manual #78, 1992, among others). However, many of these tests were done decades ago, on generic material grades customary for that time and country, and with experimental procedures that were not entirely consistent for all, including differences in applied strain rates, instrumentation, data interpretation, and consideration of creep. This accounts for some of the additional scatter of these reported results. While it has been demonstrated that material retention ratios at high temperatures can be similar within a given material class, a substantially different response can be manifest in a separate class of the same material. For example, SFPE (2002) and other literature show that high strength concrete and steel will perform differently at high temperatures than their lower "normal" strength counterparts. Therefore, a related uncertainty of how far to extrapolate existing retention ratio data to other conventional material grades, types, or species or to specialty products, i.e., what are the specific limits of existing data applicability. Of course, as newer construction materials evolve into more common practice, such as resin-based, polymer composites, steel-concrete composite construction, steel cables or pre-stressing strands, fiber-reinforced concrete or even more higher strength steels and concretes, their high-temperature mechanical properties will need to be established.

To resolve these issues, supplemental high temperature testing for mechanical properties of the test assembly materials could be made mandatory, in general. However, this would severely burden every E 119 test and likely produce many redundant results. A more efficient alternative is central development within a separate program the standard procedures for such testing of these properties to conduct sufficient high temperature experiments of the common construction materials and grades, compile and publish the results for engineering applications. The recent WTC investigation Report NIST NCSTAR 1-3D provides an excellent central source of test data and available references on mild structural steel, together with revised best-fit formulations for the basic steel mechanical properties as a function of temperature, including the rarely reported Poisson's ratio. As the common construction materials and grades are likely to change over time, this high temperature material testing and official documentation should be periodically repeated, perhaps every 10–20 years, for validation and/or recalibration. If modern material property data is not available, it will be necessary for the materials to be tested in conjunction with the furnace testing.

In addition to the basic mechanical properties at elevated temperatures, the gross behavior of the assembly materials during the test fire exposure must be described, especially with regard to its damage/degradation through spalling, charring, and the like. This is further discussed under documentation.

Inclusion of Load Eccentricity for Walls and Columns

> *Recommendation S-11: Require column and wall tests to be conducted with a minimum d/6 eccentricity of axial compression load from centerline, where d is the depth of column or wall.*

Most of the structural column fire resistance ratings have been derived from tests on unloaded, nominally straight specimens that are fully engulfed (uniformly heated) in the fire, and that are subject only to temperature endpoints. Use of this type of critical steel temperature test obscures a great deal of real fire response information for the member. Effects of accidental load eccentricity, initial column curvature or imperfections, column mechanical strength properties, length slenderness ratio, and type of structural failure (squash or stability/buckling) under fire exposures are relatively unknown.

In addition, compression members can potentially experience non-uniform heating in real fires (for example, in perimeter framing or tall columns subjected to lower, partial height heating), which will cause bowing curvatures (Cooke, 1988) due to thermal gradients through the section depth (see Figure 17). These induced thermal curvatures reduce the strength of the members due to P-delta effects, and hence, influence the stability of the columns. Such thermal effects will depend on whether the fire totally engulfs a given structural column, in which case similar thermal exposures on all sides can be expected, (uniform heating) or if not, gives rise to the non-uniform heating cases.

This behavior at elevated temperatures, as well as the adherence of the fire protection material under lateral column deflections, will only become manifest when columns are tested until actual/incipient failure under maximum design load and without temperature limits. The benefit of using different strength grades of column materials for fire resistance will also become better established.

As illustrated in Figure 17, non-uniform heating can be full height, but incomplete fire exposure of entire column section contour or a partial height exposure of some or all the section contour. Loaded column tests with non-uniform heating are expected to show asymmetric structural response and failure mechanisms that are not obviated from the currently unloaded, uniformly-critical E 119 temperature tests with their idealized conditions. Similar performance differences can exist for some wall assemblies due to non-uniform heating, applied load and deformation, even for non-loadbearing elements such as those that may be used as fire separations for large record storage compartments (Beyler and Iwankiw, 2005). Bailey (2004) reported that during the Cardington building tests in the UK, a non-loadbearing compartment wall failed during the fire due to large deflections imposed from adjacent beam framing.

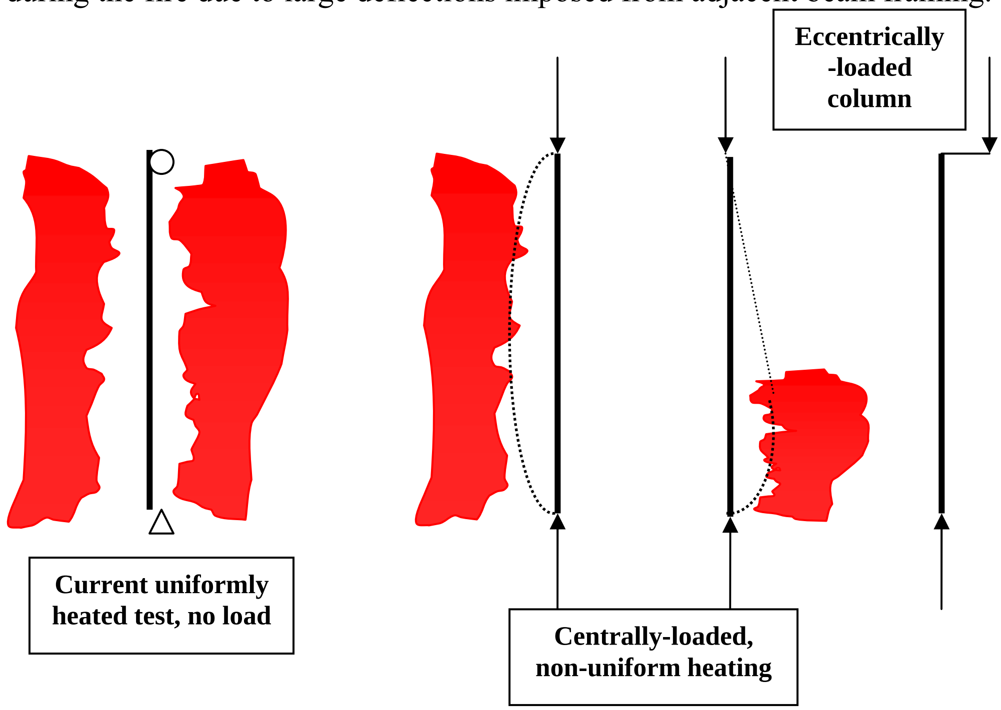


Figure 17. Column fire-testing alternatives.

A number of recent papers have addressed the fire resistance of light wood and steel-framed walls. In Alfawakhiri et al. (1999), and Alfawakhiri and Sultan (1999), the authors cite the paucity of experimental data on loadbearing light-frame walls with steel studs. Greater research focus in this area is endorsed, along with more complete instrumentation of standard test assemblies for structural property and response variables in order to expand performance-based fire design options. Clancy (2002a and 2002b), Clancy and Young (2004) developed predictive time to failure models and comparison tests on wood stud walls with gypsum board. Buckling effects, wall crookedness, stud size, spacing, charring, variability of wood and gypsum properties, as well as loadbearing and non-loadbearing applications were studied. Kodur et al. (1999), Alfawakhiri and Sultan (2000), Sultan (1995), and Alfawakhiri et al. (2000) present additional standard fire test results for lightweight steel framed walls, along with analytical modeling that correlates with this test data. Feng et al. (2003) and Feng and Wang (2005) reported experimental and analytical findings on cold-formed steel wall studs with gypsum board. Effects of channel section sizes and spacing, thermal bowing, stability and loading were examined under standard fire exposures.

Provision for investigating loaded column and wall response under non-uniform fire exposure should be studied, as this may be a more severe condition than uniform heating. In the interim, a surrogate approach for simulation of wall and column assembly strength degradation due to geometric imperfections and additional non-uniform heating effects is the imposition of a minimum eccentricity for compressive loads. Minimum compressive load eccentricity is already required in some test standards and structural design methods.

At this time, in view of the eccentricity requirements contained in ASTM E 72 for wall panel strength tests and those implied in ACI 318 for structural concrete design in compression, a load eccentricity of d/6 from the wall or column centerline is recommended, where d is the actual depth of the wall stud perpendicular to the wall or the largest depth of the column. This d/6 value also has a theoretical engineering basis in the so-called "kern" distance for a compressively loaded rectangular section, which is the maximum eccentricity in such a member that will still maintain all combined material stresses in compression, without any net tension from the eccentric bending. This load eccentricity should be applied toward the assembly side such as to magnify the fire and thermally-induced effects as a worst case. Steel and concrete members will bow towards the fire-exposed side due to thermal gradients and steel expansion; hence, the compressive load eccentricity should be applied away from the furnace to exaggerate this curvature. On the other hand, wood tends to bow away from the fire due to asymmetric charring deterioration; hence, its d/6 load eccentricity should be applied towards the furnace. Prior to the test, any initial wall or column geometric imperfections, such as vertical out-of straightness, should be measured and documented.

<u>No Hose Stream Test Requirement for Walls and Partitions</u>

> *Recommendation S-12: Hose stream test procedure and its acceptance criteria for walls and partitions are no longer required.*

The hose stream test provides little substantive information to either current life safety practices or PBSFE. The interpretation of its results is not well defined, and the hose stream application may be conducted after two alternative fire exposure durations. The use of the hose stream test is in direct conflict with the requirements of the "test to failure" approach adopted here.

<u>Structural Instrumentation Check/Calibration</u>

> *Recommendation S-13: Prior to initiation of fire test, check/calibrate all of assembly's structural instrumentation (transducers, strain gauges, load cells) under superimposed load.*

The functionality and accuracy of all the structural instrumentation installed on the assembly should be checked under load immediately prior to the fire ignition. This process should include comparison of the expected elastic deflections and strains of the structural members under load to those recorded just prior to the fire test. Any installation corrections or replacements of instrumentation can then be made, as needed. An easy method for similar pre-test verification of the load cells (for boundary restraint) should be developed and implemented.

5.0 TEST METHOD RECOMMENDATIONS – TEST DOCUMENTATION

The proposed test requirements for procedures, instrumentation, or load/scale issues will all necessarily require accompanying documentation, as outlined herein in 5.1–5.6.

5.1 Furnace Description

- Lining (T-11)
- Dimensions (T-12)
- Gas type (T-13)
- Burner description (T-14)
- Secondary air flow rate (T-15)

5.2 Furnace Exposure Conditions and Instrumentation

- Furnace temperature measurement (T-1)
- Target fire exposure curve including tolerances (T-9)
- Pressure measurement and location(T-2)
- Oxygen concentration sampling description and analyzer for measurement (T-3)

5.3 Calibration Test Results

- Thermal (T-10)
- Structural (S-13)

5.4 Specimen/assembly Description

- General – size/dimensions (S-6), ambient material strengths (S-9)

All the test assembly original conditions (structural framing and span, loading, end supports) should be accurately provided. In addition, the description and major properties of the fire protection materials should be provided. For compressively-loaded assemblies (walls and columns), initial-out-straightness of the test assembly and other imperfections should be regularly measured and recorded, as this could be an important factor in its ultimate strength.

- Instrumentation (type and locations) – thermal (T-4, T-5, T-7, and T-8) and structural (S-1, S-2, and S-3)
- Superimposed loading – design basis and magnitude, application means (S-4, S-5, S-11)
- Conditioning – e.g., curing of concrete, of protective materials, etc.

5.5 Test Results

- Time-history records of all measured values
- Pertinent visual observations – discoloration, damage and detachment of protective and structural materials, cracking, spalling, buckling, creation of gaps-openings, flame and gas penetration, other unusual behavior

During the test, the time of occurrence and type of major structural damage, such as local buckling of steel, detachment of metal deck from slab, spalling or crushing of concrete, fractures and cracks, splitting or ignition/charring of wood and the like should be documented. The ignition and charring of wood is well-documented. However, though research literature on fire-induced concrete spalling exists, such as the more recent contributions of Bostrom et al. (2004), and Breunese and Fellinger (2004), such spalling damage in concrete is still not known in sufficient scientific rigor to be predictable or controllable. Therefore, if spalling in concrete or other unusual high temperature material behavior is manifest during the fire test, the nature and occurrence time of this phenomenon, along with its accompanying conditions should be documented.

Equally important, other observations on degradation, damage, distortion or detachment of the fire protection material, that could accelerate thermal penetration of the assembly during the test, should be made.

- Identification of Structural Failure Endpoint Time and Mode(s) (S-8)
- Other – photographs, videos, identification of any malfunctioning of instrumentation or test apparatus, possibly sample extraction of residual assembly materials

5.6 Post-Test Inspection

- Thermal damage – material state, char extent and depths, spalling area and depths, burn-through areas, missing/detached protection material, etc.
- Structural – local and global damage (cracking, spalling, buckling, fractures, char-reduced sections, etc.)

The ambient, post-test (cold) condition of the assembly should be well-documented, in particular all the fire protection and structural damage, and final displaced configuration of the assembly. This information would reveal any changes and additional damage from thermal contraction after the fire and during the cooling stage.

6.0 GENERAL RESEARCH RECOMMENDATIONS IN SUPPORT OF PBSFE

While the objective of this project was to develop recommendations for testing in support of PBSFE, a number of general research topics were brought to light in the course of the work. These topics are introduced in the following subsections for reference. The topics are neither complete nor novel, but bear enumeration.

6.1 Develop Guidelines for Definition of Imminent Structural Failure

Recommendation S-8 calls for testing under full design load until structural failure is reached, or until an integrity/safety breach occurs. Much is left to the subjective judgment of the laboratory staff or the test sponsor as to when structural failure is imminent immediately prior to any total specimen collapse. The purpose of this recommendation is to develop a common set of Guidelines that can be used in the determination of imminent failure. The Guidelines are intended to facilitate safe and effective laboratory operations and provide greater test termination consistency among laboratories.

Large, uncontrolled deflections are usually the best indicator of an imminent failure. Harmathy (1967) addresses such for steel beam supported floors. In contrast to ductile failures that develop more gradually, brittle fractures or instability can occur almost instantaneously without forewarning and are much less predictable. The laboratory is usually very careful in trying to prevent full assembly collapse in order to avoid any personnel injuries and to safeguard its furnace and instrumentation. That is why a reliable predictive limit for imminent structural failure of the test assembly, at least for ductile response, is desirable. These, and more general unresolved issues in practice with identification of structural "failure" during a fire, were raised by Lane (2003).

Rapidly increasing ("runaway") deflections and loss of stiffness can often be seen real-time during the fire test on the plot of assembly deflection time-history. Current standards do not provide any definitive criteria on exactly when ductile deflections are to be regarded as being uncontrolled, with failure being imminent. Ryan and Robertson (1959) had developed arguably the first deflection failure criteria for steel beams tested in a standard E 119 fire test under full load (Ryan and Robertson, 1959). One of these postulated limits is the magnitude of the maximum beam transverse deflection, formulated from curve fit of test data in consistent length units of inches as

$$\delta = \frac{L^2}{800d} \qquad (5)$$

where

δ = maximum beam transverse deflection during the fire exposure, in
L = beam span length, in
d = beam section depth, in

Due to the difficulty of representing in a simplified manner all the other specimen design variables, such as material properties, member sizes, and end connection restraint for this critical deflection value, Ryan and Robertson (1959) proposed a second accompanying limit that checks the rate of transverse deflection. This criterion draws from the experience that specimen failure is imminent when the deflection itself is not only sufficiently large, but also when it starts increasing at a rapid, or "runaway" rate, indicated by the slope of the deflection time-history curve. Such an accelerated rate of deflection signals pending beam instability. This second limit postulated by Ryan and Robertson, 1959, is expressed as the hourly rate of fire induced deflection equaling or exceeding $L^2/(150d)$. The authors recommend the structural failure time of the beam, floor or roof assembly be taken as the time when both of these limiting criteria are exceeded.

These, or comparable, beam, floor and roof deflection criteria should be developed for adoption to explicitly define imminent structural failure for ductile materials. Several international fire standards, such as ISO 834, BS 476 and DIN 4102, have already included similar type of deflection-based criteria for "loadbearing capacity," not only for members in bending, but also for axially loaded elements in compression (columns and walls). These ISO 834 limits are shown in Eq. 6, with both criteria necessary to be exceeded for failure identification. These deflection limits are substantially higher than those originally proposed by Ryan and Robertson (1959). For flexural elements and $D \geq L/30$:

$$D = \frac{L^2}{400d} \qquad \frac{dD}{dt} = \frac{L^2}{9000d} \tag{6}$$

where

D, dD/dt = limiting flexural deflection, mm, and rate of deflection, mm/min, respectively
L = clear span of assembly, mm
d = bending section depth, mm

For axially loaded elements:

$$C = \frac{h}{100} \qquad \frac{dC}{dt} = \frac{3h}{1000} \tag{7}$$

where

C, dC/dt = limiting axial shortening, mm, and rate of axial shortening, mm/min, respectively
h = initial element height, mm

These and additional recommendations should be developed as Guidelines to minimize risk of sudden brittle fractures or stability collapses in order to preserve general safety and mitigate damage to the laboratory facility. In addition to any specific deflection-based indexes, monitoring and interpretation of temperature readings, observations on the physical deterioration of the assembly, duration of the fire exposure, and similar factors should be addressed. The resulting Guidelines will provide a common and rational platform for identification of the imminent structural failure test endpoint for typical conditions.

6.2 Develop Guidance for the Design of Furnace Assemblies and Application of Results

Test method provisions for furnace-scaled assembly testing and guidelines for application of results should be developed. Criteria should be provided for when and how furnace-scaled fire tests can be used and interpreted relative to actual construction via extrapolation of results to larger and heavier assemblies. This need follows directly from Recommendation S-7 to employ dimensional scaling principles in the design of the test assembly to represent the actual construction applications.

6.3 Conduct a Round-robin using the Furnace Calibration Test Method

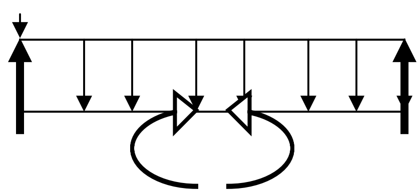
A round-robin using the furnace calibration test (Recommendation T-10) would provide important data and evaluation of the relative operating performance of existing laboratory furnace. Given the differences in size, depth, fuels, burners etc of the existing furnaces, the round-robin would also serve to evaluate the potential effects of not controlling the furnace operation as recommended in this report. The round-robin would provide testing and statistical analysis in support of test method development, standardization, and analysis of variances.

6.4 Develop Test Procedure and Data on Fire Performance of Common Structural Connections

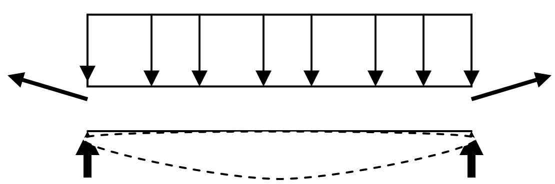
FEMA 403 and NIST NCSTAR 1-6B identify structural connections under fire exposures as a vital area for further study. Very few fire tests have been conducted on assemblies with real end connections, in place of the common insertion of the assembly frame into the furnace. Most assemblies typically have simple bearing supports butted against the test frame for floors and roofs, or to the load device for walls. While the current prescriptive code provisions in the U.S. requiring fire protection of connections to be at the same level as for the most highly rated adjoining structural member have generally been considered adequate, the fire response of connections, of its constitutive elements and details (bolts, welds, reinforcing bars and development lengths, ties, etc.) is not well understood or developed. Moreover, the ductility, or lack thereof, of connections under potentially very high strain demands and reduced strength at elevated temperatures could be a critical factor in the integrity assessment of adjacent structural member(s) and framing, as well as for development of any secondary load redistribution paths. The Cardington building tests amply demonstrated this aspect of real structural fire performance (University of Edinburgh, 2000 and BRE 215-741).

End connections and member splices are conventionally detailed only for the design loads required by the applicable building code, which primarily involve shear forces and/or bending moments for moment frames, axial tension or compression and/or shear for braced frames and trusses. Columns typically carry only compression loads, but may experience uplift for some braced frame conditions. Ordinary structural design for beams and floors does not regularly include the secondary effects of larger axial tension forces and strains from catenary action (see Figure 18) that are likely to become manifest only under the final strength limit states of fire exposure, blast, or impacts. One example of this type of tensile limit state in a connection is the beam splice failure during the 9-11 disasters in WTC 5, as described in the FEMA 403 Report.

One approach to acquire fire performance data on connections is to require every assembly to be detailed and tested with real connections. However, development of standard provisions for such would be rather difficult, given the wide variety of alternative connection types and details, and it would regularly encumber every test. It is likely better to allow the assembly supports to continue being of the customary fitted/bearing type within the test frame, or at the sponsor's discretion, use of actual structural connections should be permitted.



Bending/Shear at Service Conditions



Catenary Action at Ultimate

Figure 18. Change in floor system resistance from primary bending to catenary action.

A seemingly more viable alternative is to develop in a special research study a unique set of fire test criteria and results for a suite of typical steel connectors (mechanical fasteners, welds, shear studs), connections and steel reinforcing details (longitudinal rebar, shear stirrups, ties, etc.) for steel, concrete and masonry that form typical simple (shear only) and rigid (moment-resisting) connections, composed of different base materials in beam-to-beam and beam-to-column designs. This could be done within or separate from the standard review. Given suitable instrumentation and loading, important new information on connection ductility, force transfer mechanisms, and their ultimate failure limit states under load and high temperature exposures would be thereby obtained, including effects from cooling after the fire. These connection results could supplement the conventional assembly ratings, and form a basic set of input properties for modeling of connections in PBSFE.

6.5 Develop and Standardize Test Methods for High Temperature Thermal, Physical, and Structural Properties of Materials

In support of Recommendations T-17 and S-10, test methods for high temperature thermal, physical, and structural properties of materials are needed. Thermal properties (conductivity, specific heat capacity, heat of decomposition) need to be measured at temperatures as close to the highest temperature the material is expected to reach. Physical properties (density, moisture content, expansion/contraction, decomposition kinetics) also need to be measured as a function of temperature up to temperatures the material is expected to reach. Material strength tests need to be performed on materials used in the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus.

While there are a number of test methods available for these measurements, none of them are fully satisfactory and none are accepted as standards for this use. Research is needed to develop and evaluate the available methods. This will support the selection of the best methods that can then be subjected to V&V and ultimately become accepted standard test methods for this application.

6.6 Compile Fire Test Database

Compilation of a comprehensive database on all fire tests of an assembly, including those that were not successful, is recommended. Fire resistance data and rating results from any fire test can differ, sometimes quite markedly from one identical test to another, both in terms of recorded thermal and structural performance. This is due to the many random experimental variables and inaccuracies (laboratory facilities and practices, furnace temperatures and pressures, loading, instrumentation, test frame boundary conditions), combined with differences in actual material properties and workmanship quality of the individual assembly construction. At times, multiple fire resistance tests have been conducted for an assembly to achieve a desired rating outcome, and only the single best "passing" test is used as the benchmark for the fire resistance listing.

The actual "track" record, including any failed or unsatisfactory tests, assembly modifications, and variability of fire tests should be compiled in a database. This information would serve to not only assess the test variability, but also provide additional model validation benchmarks.

The database will not only provide a much better understanding of fire performance, but also give invaluable specific results against which structural fire design and analysis tools can be validated and calibrated.

6.7 Analyze Repeatability (Scatter) of Tests

A rigorous statistical study of the random variations in standard fire tests (as compiled in the database) should be performed to determine the expected probability distribution of experimental results for identical or similar assemblies. To the extent possible, the variability of all the experimental and assembly-specific factors should be established. Such rationally assigned statistics of the published test data could be used to improve interpolation of existing test results and to assess validation accuracy of analytical models, whose solutions otherwise may not exactly match the output of any single test.

7.0 SUMMARY OF RECOMMENDATIONS

7.1 Furnace Instrumentation Recommendations

Recommendation T-1: Furnace Temperature Control – Plate thermometers should be used to measure furnace temperature and control the furnace exposure. There should be nine plate thermometers equally distributed across the test specimen surface. Plate thermometers are typically placed 0.10 m (4 in.) away from the sample; however, a larger spacing is desired to prevent them from potentially being damaged by failing test articles. Testing needs to be performed to demonstrate that a larger spacing does not affect the thermometer measurement.

Recommendation T-2: Furnace Differential Pressure – Tests should be performed with a positive furnace pressure (relative to laboratory conditions) across the entire test article. All furnace pressures should be measured using the tube sensor provided in ISO 834 and EN1363-1. In a vertical furnace, pressure should be measured at the bottom and top of the test specimen. The neutral plane in the furnace should be maintained at the bottom of the test specimen with no limit on the pressure at the top of the specimen. In a horizontal furnace, the furnace pressure should be measured at one location and maintained at 20 Pa. Pressure tube sensors should be located at the same distance away from test articles as the plate thermometers.

Recommendation T-3: Furnace Oxygen Concentration – Furnace oxygen concentration should be measured in the furnace stack and maintained at greater than 6% during the test. Gas samples should be continuously drawn out of the duct through a sampling line and measured using a paramagnetic type oxygen analyzer. The recommended sampling probe should be similar to the sampling probe used in duct measurements of hood calorimeters.

Recommendation T-4: Unexposed Side Temperatures – The unexposed side temperatures should be measured with a thermocouple placed between the specimen and a noncombustible, insulating pad. The insulating pad should be a low density, low thermal conductivity material with known thermal properties. The pads should be approximately 0.15 m (6 in.) square and 25 mm (1 in.) thick and placed in at least three locations that provide a range of heat-transfer performance.

Recommendation T-5: Total Heat Flux off the Unexposed Side – The total heat flux off the unexposed side of the assembly should be measured using a Schmidt-Boelter type water-cooled total heat flux gauge. At a minimum, a heat flux gauge should be placed near the center of the test article and as close as possible to the unexposed side. In cases where the assembly contains a transparent section, a heat flux gauge should also be placed at the center of the transparent section as close as possible to the unexposed surface.

Recommendation T-6: Furnace Velocity – Velocity measurements inside the furnace should not be made.

Recommendation T-7: Temperature Profile through Test Specimen – Temperatures should be measured through the thickness of the test assembly at locations that are representative of the different heat-transfer paths within the assembly. Repeat temperature profiles are recommended in case some thermocouples fail during the test.

Recommendation T-8: Gas Temperature Measurement – Gas temperatures on the exposed and unexposed side of the test specimen should be measured using aspirated thermocouples. Gas temperatures should be measured at each location where a temperature profile is being measured. Aspirated thermocouples should be placed as close as possible to the test article surface.

7.2 Furnace Operations Recommendations

Recommendation T-9: Furnace Time-Temperature Exposure Curve – The furnace time-temperature exposure should linearly increase to 1200°C in six minutes and remain constant at 1200°C for the remainder of the test.

Recommendation T-10: Calibration Test – A calibration test should be conducted with a noncombustible boundary containing instrumentation to quantify the thermal exposure. Instrumentation installed in the boundary should include total heat flux gauges and calibration boards instrumented with thermocouples. Instrumentation should be installed in at least five locations (center of each quadrant and center of the boundary) to quantify the furnace exposure. The calibration test should be performed for one-hour using the required furnace exposure and instrumentation.

Recommendation T-11: Furnace Lining Material – All interior furnace surfaces should be lined with a ceramic fiber material.

Recommendation T-12: Minimum Furnace Depth – The minimum furnace depth should be 4 ft (1.2 m).

Recommendation T-13: Burner Fuel – Propane gas should be used as the furnace fuel in all fire resistance furnaces.

Recommendation T-14: Type of Burner – Pre-mixed burners should be used in all fire resistance furnaces.

Recommendation T-15: Secondary Air Capability – When necessary, a means for providing secondary air should be provided such that the minimum oxygen content within a furnace is not less than 6%.

Recommendation T-16: Exhaust Control – A means for controlling the internal furnace pressure (e.g., damper in exhaust stack) should be provided.

Recommendation T-17: Thermal Properties of Materials – The thermal and physical properties of materials in the test article assembly should be measured. Thermal properties (conductivity, specific heat capacity, heat of decomposition) should be measured at temperatures as close to the highest temperature the material is expected to reach during the test. Physical properties (density, moisture content, expansion/contraction, decomposition kinetics) should also be measured as a function of temperature up to temperatures the material is expected to reach during the test. Thermal property test should be performed on materials taken from the same lot of materials used to construct the test article.

7.3 Structural Instrumentation Recommendations

Recommendation S-1: Assembly End Restraint – Place load cells at the assembly end boundaries to record magnitude of thermal restraining forces throughout test duration: minimum of three cells at one edge of furnace for the top, center, and bottom of a middle beam or stud of assembly.

Recommendation S-2: Deflections – Record, as a minimum, the time-history of transverse deflections at mid-span in all primary structural members (beams, joists, columns, and wall studs) of the assembly, together with axial shortening of loaded columns and wall studs.

Recommendation S-3: Strain Gauges – Require high-temperature strain gauges at critical sections (typically ends and/or mid-span) of main structural members (beams, joists, columns, wall studs) and of other important load transfer elements (shear studs, metal deck, floor slabs and reinforcement, and connections).

7.4 Structural Operations Recommendations

Recommendation S-4: Standardized Assembly Load Application – Superimposed loading on all assemblies should only be applied through mechanical or hydraulically controlled apparatus.

Recommendation S-5: Standardized Assembly Loading – The standard should require the maximum assembly design load to be based on the greater of the design load computed from either allowable stress design or limit states-LRFD and the controlling strength failure mode to be used for each type of assembly construction.

Recommendation S-6: Minimum Assembly Size – Specified minimum sizes of construction assemblies should be as follows: walls and partitions – 100 sq ft with neither dimension less than 9 ft, columns – not less than 9 ft. length, floors/roofs – 180 sq ft, with neither dimension less than 12 ft, beams – not less than 12 ft span length. Standards making bodies should consider the formation of furnace classes to recognize furnace capabilities larger than the minimum size.

Recommendation S-7: Size Effects and Experimental Scaling – Employ dimensional scaling principles in the design of the test assembly to represent the actual construction applications.

Recommendation S-8: Mandatory Fire Testing Under Design Load to Structural Failure – All assembly fire tests should be conducted under maximum design load until an imminent or actual structural failure limit state is attained, or until an major integrity breach occurs, irrespective of the assembly's other thermal conditions.

Recommendation S-9: Actual Strength of Assembly Structural Materials at Ambient Temperature – Require material strength tests be performed on samples extracted from the primary structural assembly members to determine their actual mechanical properties at ambient (including yield and ultimate strength, and elastic modulus).

Recommendation S-10: Determination of Structural Properties at Elevated Temperatures – Material strength tests should be performed on materials used in the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus).

Recommendation S-11: Inclusion of Load Eccentricity for Walls and Columns – Require column and wall tests to be conducted with a minimum d/6 eccentricity of axial compression load from centerline, where d is the depth of column or wall.

Recommendation S-12: No Hose Stream Test Requirement for Walls and Partitions – Hose stream test procedure and its acceptance criteria for walls and partitions are no longer required.

Recommendation S-13: Structural Instrumentation Check/Calibration – Prior to initiation of fire test, check/calibrate all of assembly's structural instrumentation (transducers, strain gauges, load cells) under superimposed load.

7.5 Recommendations Potentially Applicable to Existing Test Methods

While the objective of this project was to develop requirements for testing in support of PBSFE, many of the recommendations could be implemented within the context of the existing tests used in prescriptive design. The recommendations developed here fall into three categories; 1) fully capable of being implemented in existing test methods, 2) potentially capable of being implemented into existing test methods with minor modifications to the test standard, and 3) require major modifications to existing test standards. The category classification of the recommendations is shown in Table 4.

Recommendations falling into Category 1 are generally recommendations that add instrumentation that is not required in the existing standards. The recommendations do not restrict what is allowed in any way, but rather supplement the requirements of existing tests.

Recommendations falling into Category 2 are incremental changes or restrictions that go beyond the requirements of the existing test methods, but would not require major modifications to the test standard.

Recommendations falling into Category 3 are major departures from the existing test methods that could not be accommodated as incremental changes.

Table 4. Applicability to Existing Test Methods

Recommendation	Category
T-1: Furnace Temperature Control	2
T-2: Furnace Differential Pressure	2
T-3: Furnace Oxygen Concentration	2
T-4: Unexposed Side Temperatures	2
T-5: Total Heat Flux off the Unexposed Side	1
T-6: Furnace Velocity	1
T-7: Temperature Profile through Test Specimen	1
T-8: Gas Temperature Measurement	1
T-9: Furnace Time-Temperature Exposure Curve	3
T-10: Calibration Test	2
T-11: Furnace Lining Material	2
T-12: Minimum Furnace Depth	2
T-13: Burner Fuel	2
T-14: Type of Burner	2
T-15: Secondary Air Capability	2
T-16: Exhaust Control	2
T-17: Thermal Properties of Materials	1
S-1: Assembly End Restraint Measurement	1
S-2: Deflections	1
S-3: Strain Gauges	1
S-4: Standardized Assembly Load Application	2
S-5: Standardized Assembly Loading	2
S-6: Assembly Size	2
S-7: Size Effects and Experimental Scaling	2
S-8: Fire Testing to Structural Failure	2
S-9: Actual Strength of Structural Materials at Ambient Temperature	1
S-10: Determination of Structural Properties at Elevated Temperatures	1
S-11: Inclusion of Load Eccentricity for Walls and Columns	2
S-12: No Hose Stream Test Requirement for Walls and Partitions	2
S-13: Structural Instrumentation Check/Calibration	1
Test Documentation	1

Category 1- supplemental to existing test method
Category 2- incremental changes or restrictions to existing test method
Category 3- major departure from the existing test

8.0 PROPOSED EXPERIMENTAL RESEARCH

A test plan outline involving composite concrete slab/steel beam floor assemblies and gypsum-protected load bearing steel-stud walls assemblies has been developed to evaluate the feasibility and value of the instrumentation and operations recommendations. The test plan outline also calls for reporting consistent with the documentation recommendations of this report. The test plan outline is provided in this section of the report. Other experimental research proposals are included in the general research recommendations of Section 6.

8.1 Test Plan Outline

This test method is intended to support the continuing development and use of Performance-Based Structural Fire Engineering (PBSFE). This supplementary test plan outline reflects the majority of the recommendations for enhanced fire resistance testing of building construction assemblies. Its objective is to provide the key variables and configuration of two test assemblies for a series of fire tests intended to further explore, validate and/or refine the test recommendations and criteria.

As specified by the Fire Protection Research Foundation (FPRF) for this Project, light frame walls and composite steel/concrete floors are to serve as the generic two assembly types for this testing assessment. HAI selected the particular construction described herein based on their representative nature of the assemblies of interest, the specifics of which can be adjusted at the discretion of FPRF, including the identification of particular proprietary products. These selections of the test assemblies were made based on their prevalent fire resistance rated construction as determined from HAI project experience including listings in the 2007 UL Fire Resistance Directory.

This test plan outline contains the essential information for FPRF to plan the test program and to finalize assembly details and test series parameters. The specific nature of the assemblies, variables to be changed, number of repeat tests, and intended test duration are all important considerations in this regard that are addressed. To avoid repetition, it is assumed that the reader is familiar with and has ready access to the HAI report (Beyler et al., 2007). For the sake of brevity, the test requirements simply reference the parent report and its various itemized recommendations, which contain their background and more specific details.

This outline provides general test requirements and those specific to the light frame wall and the composite floor assemblies.

8.1.1 General Requirements

The general requirements are:

- The minimum furnace depth (both horizontal and vertical furnaces) is 4 ft (Per Recommendation # T-12)
- All interior furnace surfaces are to be lined with ceramic fiber materials. (Per Recommendation # T-11)
- The furnaces will be fired using propane gas. (Per Recommendation # T-13)

- The furnaces will use premixed burners. (Per Recommendation # T-14)
- The furnaces will be equipped with a controlled source of secondary air for minimum oxygen content of 6% throughout test. (Per Recommendation # T-3 & T-15)
- Furnace shall be fired to follow the recommended time/temperature curve. (Per Recommendation # T-9)
- Plate thermometers will measure and control the fire exposure. (Per Recommendation # T-1)
- The fire tests will be conducted under positive furnace pressure across the entire test assembly, with laboratory capability to accordingly monitor and adjust pressure. (Per Recommendation # T-2 & T-16)
- Velocity measurements within the furnace are not required. (Per Recommendation # T-8)
- Minimum assembly sizes shall be as specified in ASTM E 119. (Per Recommendation # S-6)
- Both temperatures and heat flux on the unexposed side of the assembly be measured and recorded. (Per Recommendation # T-4 & T-5)
- Aspirated thermocouples will record the gas temperatures on the exposed and unexposed sides. (Per Recommendation # T-8)
- Temperature profiles through the assembly be measured and recorded. (Per Recommendation # T-7)
- Prior to the test, a general calibration of the thermal instrumentation is required. In this calibration test, plate thermometers used to control the furnace shall be installed at the location desired in the actual testing with some select measurements at other distances from the test article to evaluate the impact of thermometer offset on furnace temperature measurement. (Per Recommendation # T-10)
- The structural instrumentation requires load cells for measuring thermal end restraint, transducers for deflection data and high-temperature strain-gages at critical assembly locations. See specific test details below for locations. (Per Recommendation # S-1, S-2 & S-3)
- The live load shall be applied via hydraulic/mechanical equipment. (Per Recommendation # S-4)
- The maximum assembly design load shall be based on the ultimate strength/LRFD method. (Per Recommendation # S-5)
- For walls, a specific compression load eccentricity shall be used. (Per Recommendation # S-12)
- No hose stream test shall be conducted. (Per Recommendation # S-14)
- Continue the test until either an actual or an imminent structural failure occurs or occurrence of a major breach in the assembly or until safety considerations dictate. Unless other guidelines or criteria for imminent failure in ductile bending and axial compression are determined, the deflection-based limits described in Recommendation S-9 be used. (Per Recommendation # S-8 & S-9)
- Supplementary testing of the key protection and structural materials is necessary to identify their relevant ambient and high-temperature properties. Samples of materials

used in constructing the assemblies should be set aside for use in conducting thermal and mechanical property testing. (Per Recommendation # T-17, S-10 and S-11)

- Test documentation includes assembly dimensions, construction and instrumentation details, initial conditions, raw and processed data of all instrumentation, photos, and visual observations of damage, unusual behavior, and failure mode(s).
- Each test assembly will be run in duplicate in order to assess reproducibility of results, and possibly to correct any problems with the first iteration.

8.1.2 Light Frame Walls

Light frame walls consist of either wood or cold-formed steel studs protected by gypsum board or plaster. Consequently, heavy concrete or masonry walls are not considered to be within this category of building construction.

The strategy for planning this set of wall tests is to evaluate the performance of the common construction of this type using the proposed test procedure. Since the test procedure focuses on both thermal and structural performance during fire exposure, it was necessary for the wall assemblies to be load bearing and be tested at their maximum design load. It was also decided to use cold-formed steel studs rather than wood studs due to the wide use of steel studs and the much greater variability of wood stud properties.

Common fire-resistance rated light wall construction is typically constructed by applying gypsum wallboard to each side of the steel studs. Test Wall Assembly No. 1 will have one layer of ⅝ inch thick, Type X gypsum board on each side of the studs and a layer of 3.5-inch thick mineral wool insulation (4 lb/ft^3 density) installed in the cavities. Test Wall Assembly No. 2 and Wall Assembly No. 3 will have two layers of ⅝ inch thick, Type X gypsum board on each side of the studs and a layer of 3.5-inch thick mineral wool insulation (4 lb/ft^3 density) installed in the cavities. Each wall will have overall dimensions of 10 ft, high x 12 ft wide.

Table 5 provides a summary of the test wall assemblies.

Table 5. Test Matrix – Wall Assemblies

Test No.	Studs	Cavity Insulation	Gypsum Wallboard Facers	Loading
1A	Steel – 3½-in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	1 layer of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Centrally
1B	Steel – 3½-in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	1 layer of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Centrally
2A	Steel – 3½ in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	2 layers of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Centrally
2B	Steel – 3½-in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	2 layers of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Centrally
3A	Steel – 3½-in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	2 layers of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Eccentrically
3B	Steel – 3½-in. deep, 20-ga., 24-in. OC	3½-inch thick - (4 lb/ft3 density)	2 layers of ⅝-in. thick, Type X on each face – Vertically applied – joints staggered	Eccentrically

In order to assess the potentially adverse effects of compressive load eccentricity as recommended in Recommendation S-12, a centrally loaded wall configuration will also be tested with eccentrically applied maximum design load for direct comparison with the predecessor assembly. At this time, in view of the eccentricity requirements in ASTM E 72 for wall panel strength tests and those implied in ACI 318 for structural concrete design in compression, a load eccentricity of d/6 off the wall centerline is recommended, where d is the actual depth of the wall stud perpendicular to the wall (see Figure 19) .

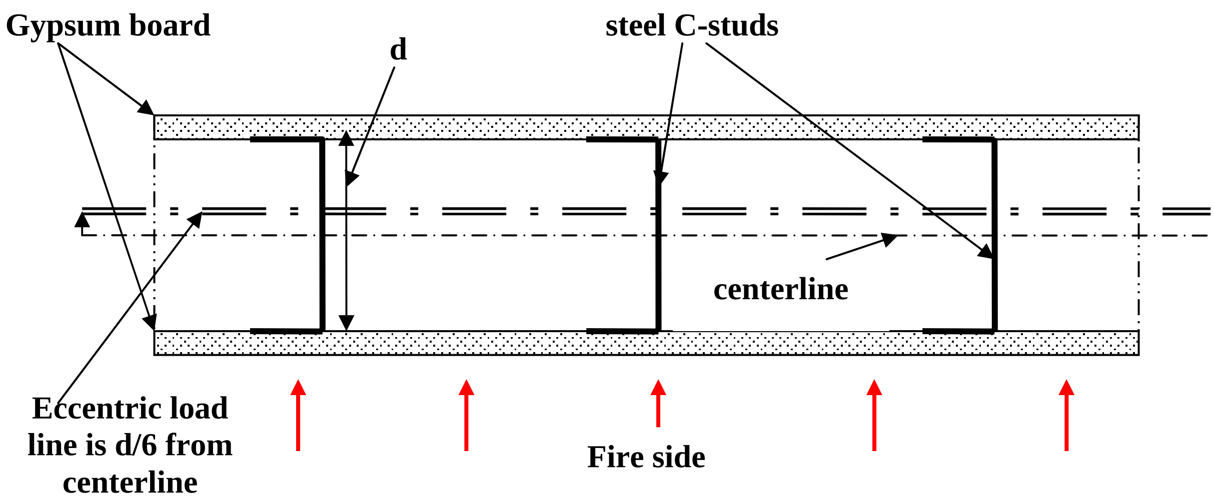


Figure 19. Cross-section of Proposed Wall Assembly, including Eccentric Load Line (away from fireside for steel studs only) – (cavity insulation not shown).

Instrumentation of each wall will consist of:

1. Structural Instrumentation: (see Figure 20)

   a. Deflections – transducer at mid-span of each wall stud for transverse deflection, and at top of studs for axial shortening (2/stud x 6 studs = 12 total)

   b. Strain gauges for steel wall studs – for central and approx. ¼-points of wall - both flanges and center of web, at both stud ends and at mid-span (3 studs x 3 locations x 3/location = 27 total)

   c. Restraint - load cells at top, middle and bottom of wall stud on one end (3 total)

2. Thermocouples for assembly, see Figures 20 and 21, (in addition to furnace control thermocouples) – (78 total)

   a. Wall studs – at both flanges and mid-web, for central and approx. ¼-points of wall, at mid-span and both ends

   b. Gypsum board and cavity insulation (see Figure 21) – for central and approx. ¼-points of wall, at mid-height and both ends, at stud and 12 inches away from these 3 studs, at exterior and interior of exposed and unexposed sides, and at middle of wall cavity insulation

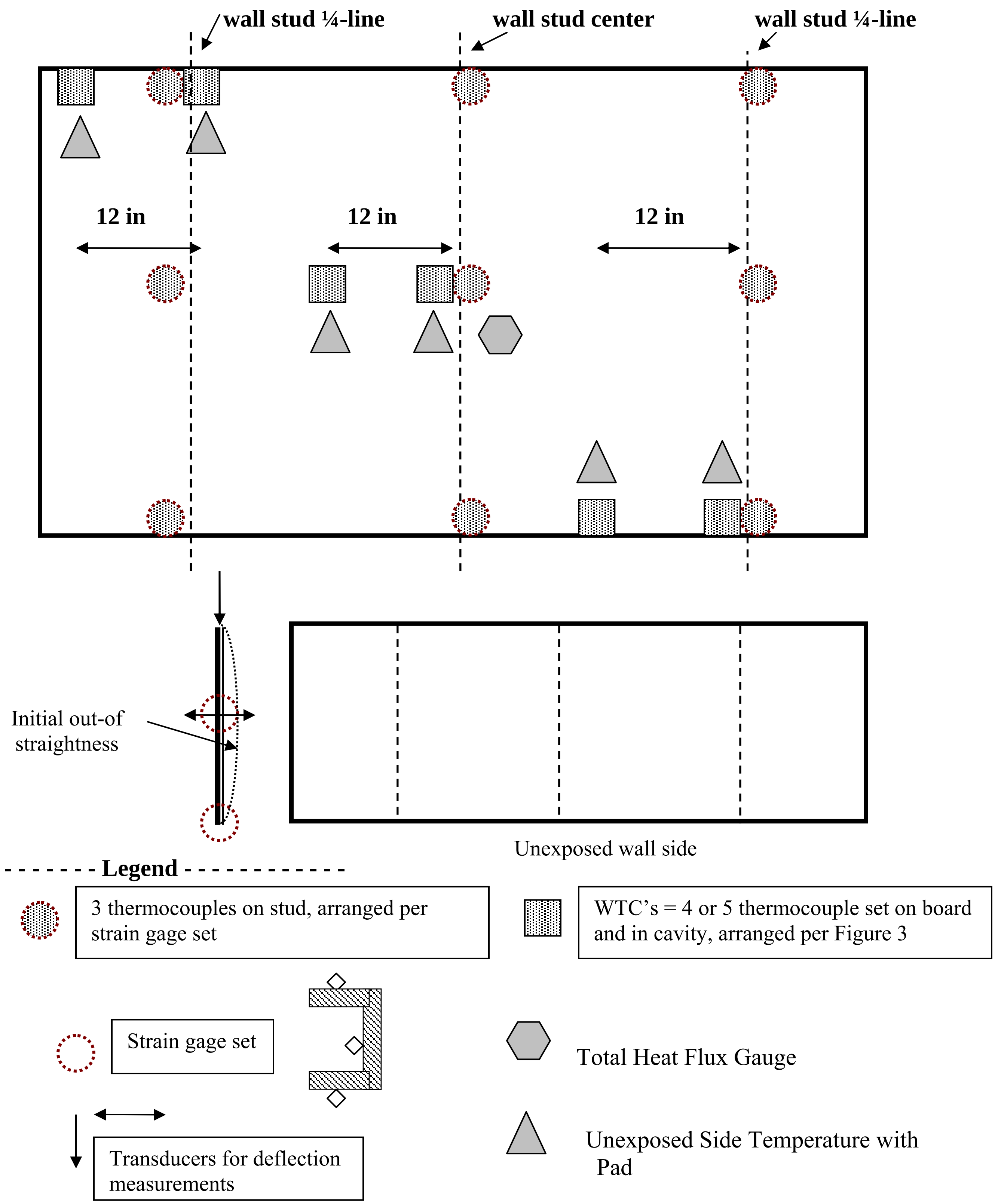


Figure 20. Elevation Layout of Structural and Thermal Instrumentation for Wall Assemblies.

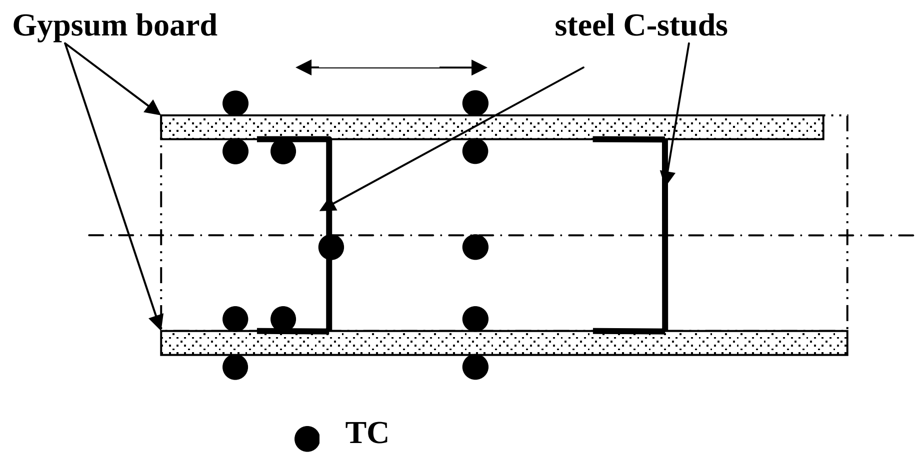


Figure 21. Cross-section for thermocouple (TC) layout – Wall No. 1.

The instrumentation for Wall Assembly No. 2 and No. 3 is similar to that for Wall assembly No. 1 except for additional TCs added between the layers of gypsum wallboard. This is shown in Figure 22.

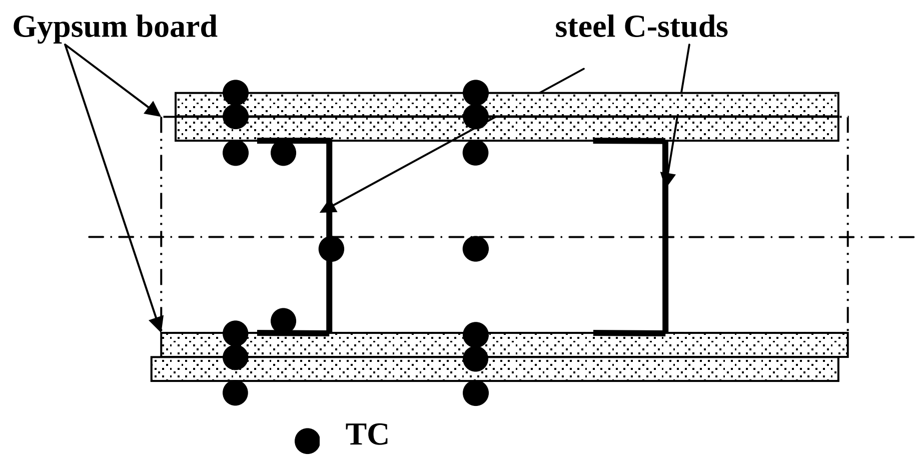


Figure 22. Cross-section for thermocouple (TC) layout – Wall Nos. 2 & 3.

8.1.3 Composite Steel Beam with Concrete Floor

This type of very common floor construction generically consists of either a poured in-place concrete on metal deck supported by protected, steel wide flange beams or joists or a poured in-place reinforced concrete slab supported by protected, steel wide flange beams or joists. Composite action between the concrete and deck and between the concrete and beams (through shear studs) is typically employed for efficiency. Since the reinforced concrete slab composite floor assembly could exhibit different thermal restraining forces and concrete slab response (spalling) than the concrete on metal deck assembly, it was decided to employ both types of floor construction in this test series.

The selection of the floor assembly details (concrete weight and thickness, depth of metal deck, etc.) and minimum spray-applied fire resistive material (SFRM) thickness on the beams will largely depend on its required level of fire resistance. A range of such protected assemblies is available for floor designs. For purposes of establishing the complete description of the test assembly configuration, it was decided to base this prototype on approximately a conventional 2-hr. restrained assembly and 2-hr. unrestrained beam commonly required for this type of floor system, with protection enhancements due to the more severe proposed fire exposure. Therefore, the proposed baseline floor assemblies are as follows:

The first assembly will employ a metal deck and its construction is proposed to be:

1. Poured in place concrete: normal strength, either normal weight (NWC) or lightweight (LWC), with thickness above metal deck of 4 ½ inches (NWC) to 3 ¼ inches (LWC), with 6 x 6, 10 x 10 SWG welded wire fabric

2. Unprotected steel floor deck: 3 inches deep, galvanized composite units of 24-inch width, blend of cellular and fluted, ribs perpendicular to supporting steel beam

3. Rolled steel beam, probably W8 x 28 shape, Grade 50 (ASTM A 992 or equivalent), with shear studs for composite action with concrete

4. SFRM – on beam only, minimum 35 pcf density, installed per appropriate UL XR ratings for UL 1709 exposure, contour protection thickness to be determined (about 1 inch)

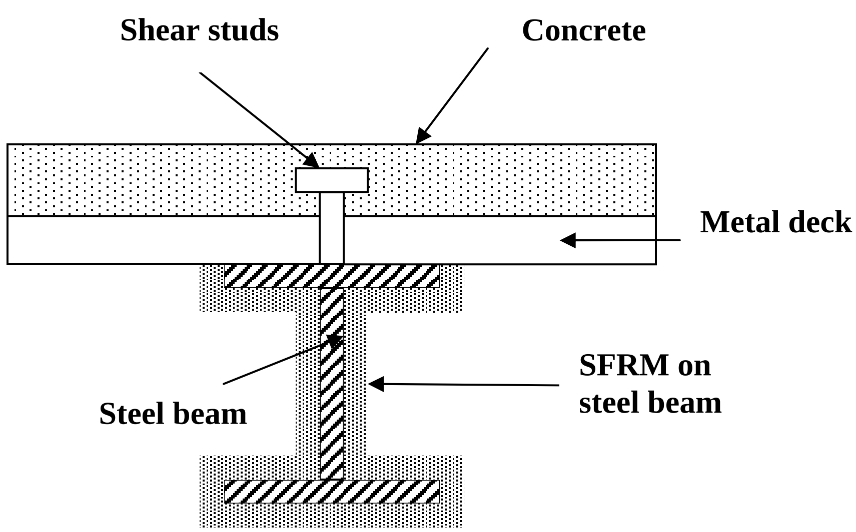


Figure 23. Cross-section of concrete/metal deck & steel beam composite floor assembly.

The second test assembly will not employ a metal deck and its construction is proposed to be:

1. Poured in place concrete slab (unprotected): 5 inch thickness, normal strength, either normal weight (NWC) or lightweight (LWC), with reinforcing steel bars designed per ACI 318 provisions

2. Rolled steel beam, probably W8x28 shape, Grade 50 (ASTM A 992 or equivalent), with shear studs for composite action with concrete

3. SFRM – on beam only, minimum 35 pcf density, installed per appropriate UL XR ratings for UL 1709 exposure, contour protection thickness to be determined (about 1 inch)

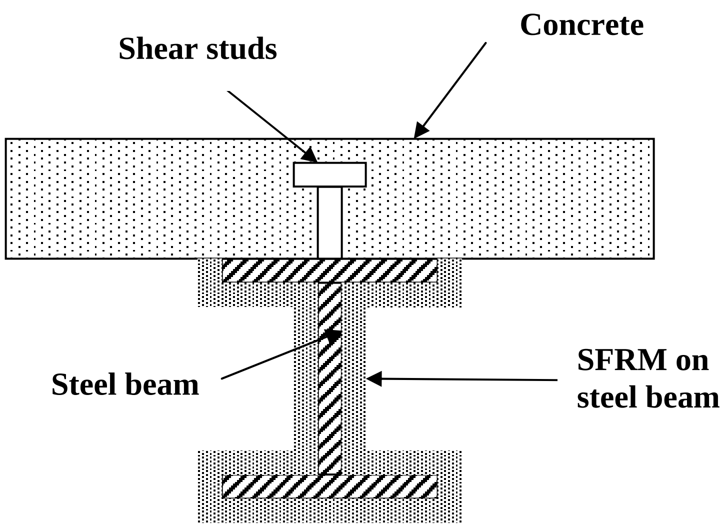


Figure 24. Cross-section of reinforced concrete & steel beam composite floor assembly.

Table 6 provides a summary of the test floor assemblies.

Table 6. Test Matrix – Floor Assemblies

Test No	Floor Assembly
4A	Concrete floor with metal deck
4B	Concrete floor with metal deck
5A	Reinforced concrete slab
5B	Reinforced concrete slab

The instrumentation for the concrete/metal deck floor assembly will consist of:

1. Structural Instrumentation: (see Figures 25 and 26)

   a. Deflections – transducer at mid-span of steel beam, at center of each side of metal deck's mid-span (3 total)

b. Strain gauges – (27 total)

   i. Steel beam – middle of top and bottom flanges, and center of web – at both beam ends and at mid-span (9 subtotal)

   ii. Metal deck – at above mid-span deflection locations, bottom and top rib surfaces (6 subtotal)

   iii. Shear studs – bottom of two studs near beam mid-span, bottom of two studs near each quarter-points of beam span (6 subtotal)

   iv. Concrete – top and middle of thickness above deck, at mid-span of beam; at top and middle thickness above deck at deck mid-span locations (6 subtotal)

c. Restraint – load cells at top, middle and bottom of beam on one end (3 subtotal)

2. Thermocouples for assembly (in addition to furnace control thermocouples) (48 total):

   a. Beam – top and bottom flanges, and mid-web at mid-span and at each quarter-points of span

   b. Deck – same as for strain gauge locations

   c. Concrete – same as for strain gauge locations

The instrumentation for the reinforced concrete floor assembly will consist of:

1. Structural Instrumentation: (see Figures 25, 26)

   a. Deflections – transducer at mid-span of steel beam, at center of each side of slab's mid-span (3 total)

   b. Strain gauges – (27 total)

      i. Steel beam – middle of top and bottom flanges, and center of web – at both beam ends and at mid-span (9 subtotal)

      ii. Shear studs – bottom of two studs near beam mid-span, bottom of two studs near each quarter-points of beam span (6 subtotal)

      iii. Concrete – at top, middle and bottom of slab thickness, at mid-span of beam; and at the two slab mid-span locations for deflections (9 subtotal)

      iv. Steel reinforcing bars – over beam mid-span and at center of each side of slab's mid-span (3 subtotal)

v. Restraint – load cells at top, middle and bottom of beam on one end (3 total)

2. Thermocouples for assembly (in addition to furnace control thermocouples) (48 total):

   a. Beam – top and bottom flanges, and mid-web at mid-span and at each quarter-points of span

   b. Concrete slab – same as for strain gauge locations

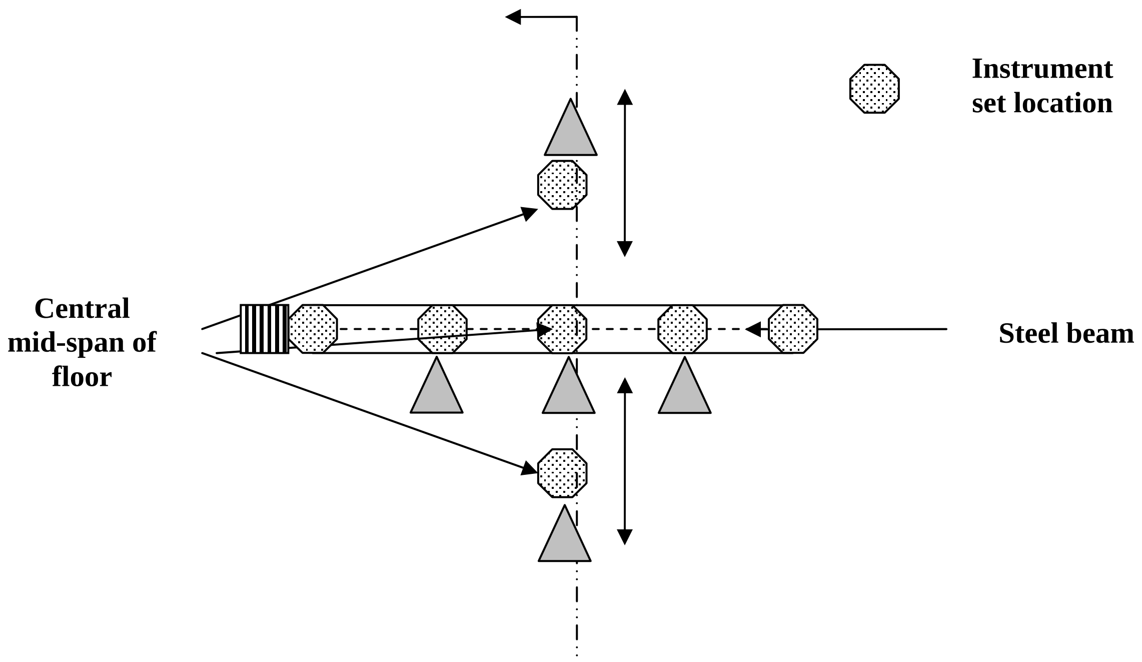


Figure 25. Schematic plan view of instrumentation set locations for deflections, strain gauges and thermocouples of floor assembly.

← **Section**

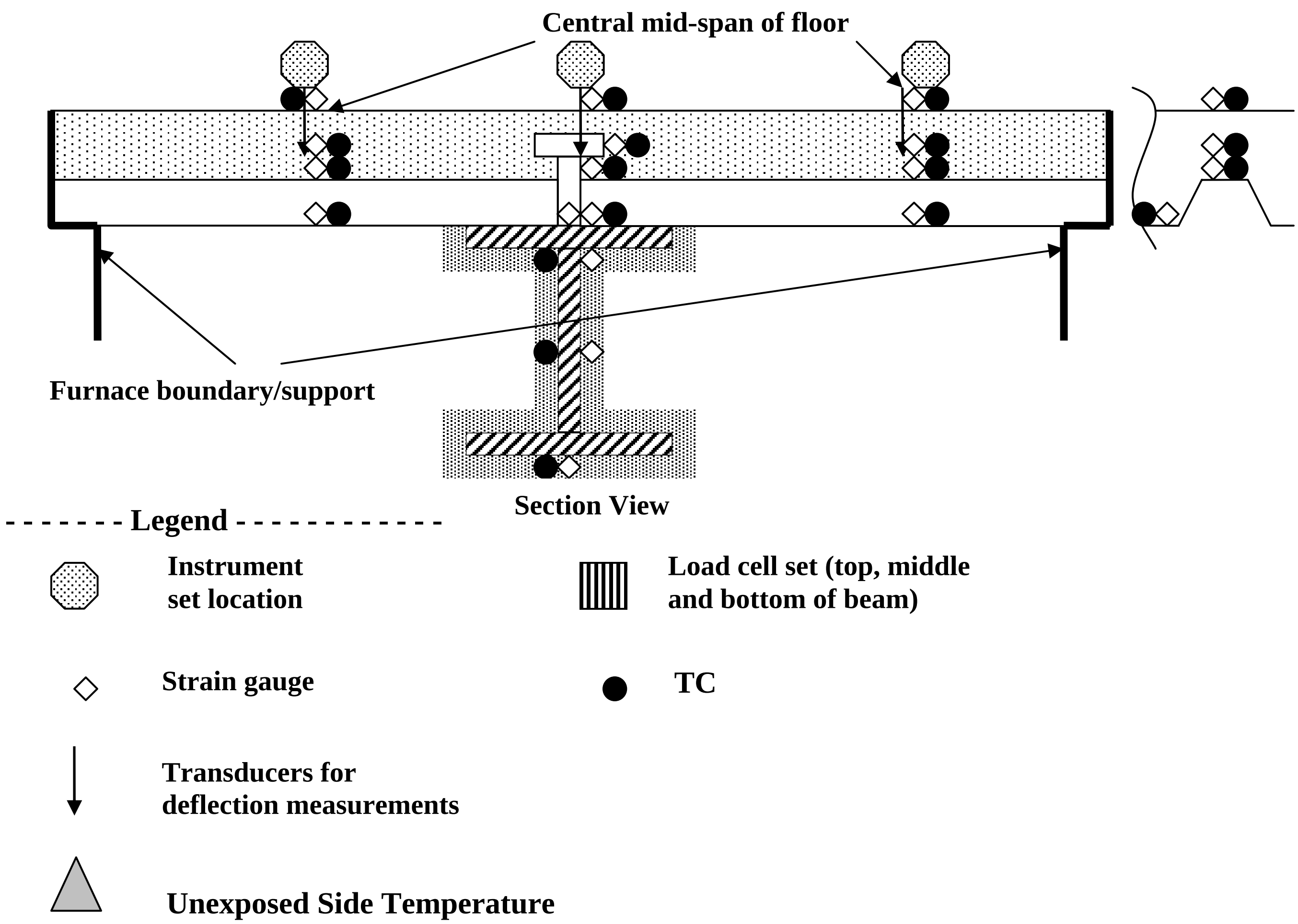


Figure 26. Schematic section view of instrumentation set locations for deflections, strain gauges, and thermocouples of floor assembly.

<u>Cost Estimates</u>

At this point in time, it is not possible to provide a precise cost per test due to many factors such as costs for materials, instrumentation, lab capabilities to meet requirements, etc. However, based on HAI's experience with these types of tests, and assuming, the laboratory has the capability to meet the test requirements, it is estimated that approximate test costs are:

- Furnace calibration tests – 2 @ $20,000 per test
- Wall assembly tests – 6 @ $25,000 per test
- Floor assembly tests – 4 @ $50,000 per test

9.0 SUMMARY

Based upon this investigation it is indeed possible for fire resistance testing to provide critical data for use in performance-based structural fire engineering. The needs of PBSFE differ from the prescriptive design approach. This investigation has identified seventeen specific test method recommendations relating to thermal aspects of fire resistance testing, including instrumentation and operation of the furnace. In addition thirteen specific test method recommendations relating to the structural aspects, including structural instrumentation and operation of the furnace. In addition, recommendations for documentation of test procedures and results were provided. A number of general research areas that would serve the development of PBSFE were identified. Collectively, the recommendations and research areas identified provide a way forward to the achievement of PBSFE.

10.0 REFERENCES

ACI 318–02 (2002), *Building Code Requirements for Structural Concrete*, American Concrete Institute (ACI), Farmington Hills, MI.

Alfawakhiri, F., Sultan, M., and Kodur, V. (2000), "Loadbearing LSF Walls Exposed to Standard Fire," *Proceedings of the 3rd Structural Specialty Conference of the Canadian Society for Civil Engineering*, London, Ontario.

Alfawakhiri, F. and Sultan, M. (1999), "Fire Resistance of Loadbearing Steel Stud Walls Protected with Gypsum Board," *Proceedings of Fire and Materials '99, 6th International Conference and Exhibition,* San Antonio, TX.

Alfawakhiri, F. and Sultan, M. (2000), "Fire Resistance of Loadbearing LSF Assemblies," *Proceedings of the Fifteenth International Specialty Conference on Cold–formed Steel Structures*, St. Louis, MO.

Alfawakhiri, F., Sultan, M., MacKinnon, D. (1999), "Fire Resistance of Loadbearing Steel Stud Walls Protected with Gypsum Board: a Review," *Fire Technology*, **35**, (4), pp. 308–334.

ANSI/AISC 341–05 (2005), *Seismic Provisions for Structural Steel Buildings*, Including Supplement No. 1, American Institute of Steel Construction, March 9, 2005 and Rev. Nov. 16, 2005, Chicago, IL.

ASCE (1992), *Manual and Reports on Engineering Practice No. 78,* Lie, T., (ed.), *Structural Fire Protection*, American Society of Civil Engineers, New York, NY.

ASTM A 370–06 (2006), *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, American Society for Testing and Materials, West Conshohocken, PA.

10.1.1.1.1 ASTM C 1314–03b (2003), *Standard Test Method for Compressive Strength of Masonry Prisms*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM C 31/C31M–06 (2006), *Standard Practice for Making and Curing Concrete Test Specimens in the Field,* American Society for Testing and Materials, West Conshohocken, PA.

10.1.1.1.2 ASTM C 39/C39M–05e1 (2005), *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, American Society for Testing and Materials, West Conshohocken, PA.

10.1.1.1.3 ASTM D 198–05a (2005), *Standard Test Methods of Static Tests of Lumber in Structural Sizes*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 605 (2006), *Standard Test Methods for Thickness and Density of Sprayed Fire Resistive Material Applied to Structural Members*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 736 (2006), *Standard Test Method for Cohesion/Adhesion of Sprayed Fire Resistive Materials Applied to Structural Members,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 119 (2007), *Standard Test Method for Fire Tests of Building Construction and Materials*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 72 (2007), *Standard Test Methods of Conducting Strength Tests of Panels for Building Construction,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 8–04 (2004), *Standard Test Methods for Tension Testing of Metallic Materials,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM F 606–06 (2006), *Standard Test Methods for Determining the Mechanical Properties of Externally- and Internally-threaded Fasteners, Washers, Direct Tension Indicators, and Rivets*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM E 1269–01 (2003), *Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetery*, American Society for Testing and Materials, West Conshohocken, PA.

Babrauskas, V. and Williamson, B. (1978), "Temperature Measurement in Fire Test Furnaces," *Fire Technology*, **13** (3), pp. 226–238.

Babrauskas, V. (2007), "Unexposed-face Temperature Criteria in Fire Resistance Tests: Reappraisal," *Fire and Materials*, San Francisco.

Bailey, C. (2004), "Structural Fire Design: Core or Specialist Subject?" *The Structural Engineer*.

Beitel, J. and Iwankiw, N., (2002), "Analysis of Needs and Existing Capabilities for Full-scale Fire Resistance Testing," Hughes Associates, Report NIST GCR 02–843.

Beitel, J., Scheffey, J., and Leonard, J., (1993) "Fire Resistance Tests of Insulation Subjected to UL 1709 Fire Exposure," NRL Ltr Rpt Ser 6180/312, Naval Research Laboratory, Washington, DC.

Berhinig, R. (2003) "Value of Fire Resistance Testing," *Proceedings of Designing Structures for Fire Conference*, Baltimore, MD, Society of Fire Protection Engineers and Structural Engineering Institute.

Beyler, C., and Iwankiw, N. (2005), "Record Storage Compartmentation Study," Hughes Associates, Inc. Report to National Fire Protection Association Research Foundation.

Bletzacker, R. W. (1963), "Effect of Structural Restraint, Stiffness and Composite Action on the Fire Resistance of Steel Construction," Ohio State Univ., Columbus, Report to American Iron and Steel Institute, Washington, DC.

Bostrom, L., Wickstrom, U., and Adl-Zarrabi, B. (2004), "Effect of Specimen Size and Loading Conditions on Spalling of Concrete," *Proceedings of the Third International Workshop: Structures in Fire*, Paper S5–3, pp. 235–247, Ottawa, Canada.

BRE 715-241 (2004), *Results and Observations from Full–scale Fire Tests at BRE Cardington, 16, January, 2003*, Building Research Establishment, Ltd.

Breunese, A., and Fellinger, J. (2004), "Spalling of Concrete–An Overview of Ongoing Research in the Netherlands," *Proceedings of the Third International Workshop: Structures in Fire*, Paper S5–4, pp. 249–258, Ottawa, Canada.

BS 476, (Parts 20–23) (1987), *Fire Tests on Building Materials and Structures*, British Standards Institution.

Buchanan, A. (2001), *Structural Design for Fire Safety,* John Wiley & Sons, Ltd.

Bullen, M. and Thomas, P. (1978), "Compartment Fires with Non-cellulosic Fuels," *17th Symposium (International) on Combustion*, The Combustion Institute, pp. 1139–1148.

CAN/ULC–S101–04 (2004), *Standard Methods of Fire Endurance Tests of Building Construction and Materials*, Underwriters Laboratories of Canada.

Clancy, P. and Young, S. (2004), "Full-scale Experiments for Evaluating Theoretical Fire Wall Models," *Fire and Materials*, **38**, pp. 431–458, John Wiley & Sons, Ltd.

Clancy, P. (2002a), "Probability of Failure with Time for Wood Framed Walls in Real Fire," *Journal of Fire Protection Engineering*, **12**, pp. 197–222, Society of Fire Protection Engineers.

Clancy, P. (2002b), "A Parametric Study on the Time-to-Failure of Wood Framed Walls in Fire," *Fire Technology*, **38**, pp. 243–269.

Cooke, G. (1994), "Can Harmonization of Fire Resistance Furnaces be Achieved by Plate Thermometer Control?" *Fire Safety Science – Proceedings of the Fourth International Symposium*, IAFSS, pp. 1195–1207.

Cooke, G. (1988), "Thermal Bowing and How It Affects the Design of Fire Separating Construction," Fire Research Station, Borehamwood, England, *Fire and Materials*, **13**, pp. 230–236.

Davies, J., and Dewhurst, D. (1996), "Furnace Characterization and the Harmonization of Fire Resistance Testing," *Interflam '96*, pp. 921–925.

DIN 4102 (1990), Fire Behaviour of Building Materials and Building Components, Deustsches Institut fur Normung (DIN).

DiNenno, P., (ed.) et al., (2002), *SFPE Handbook of Fire Protection Engineering*, Third Edition, National Fire Protection Association, Quincy, MA.

EN 1363–1 (1999), Fire Resistance Tests – Part 1: General Requirements, Brussels.

EN 1363–2 (1999), Fire Resistance Tests – Part 2: Alternative and Additional Procedures, Brussels.

FEMA 403 (2002), *World Trade Center Building Performance Study: Data Collection, Preliminary Observations and Recommendations,* Federal Emergency Management Agency, Washington, DC.

Feng, M. and Wang, Y. (2005), "An Experimental Study of Loaded Full–scale Cold Formed Thin Walled Steel Structural Panels Under Fire Conditions," *Fire Safety Journal*, **40**, pp. 43–63.

Feng, M., Wang, Y., and Davies, J. (2003), "Axial Strength of Cold Formed Thin Walled Steel Channels Under Non–uniform Temperatures in Fire," *Fire Safety Journal*, **38**, pp. 679–707.

Feng, M, Wang, Y., and Davies, J. (2003), "Thermal Performance of Cold Formed Thin Walled Steel Panel Systems in Fire," *Fire Safety Journal*, **38**, pp. 365–394.

Fromy, P. and Curtat, M. (1999), "Application of a Zone Model to the Simulation of Heat-transfer in Fire Resistance Furnaces Piloted with Thermocouples or Plate Thermometers," *Fire Safety Science – Proceedings of the Sixth International Symposium, (IAFSS)*, pp. 531–542.

Gewain, R., and Troup, E. (2001), "Restrained Fire Resistance Ratings in Structural Steel Buildings," *AISC Engineering Journal*, 2001, AISC, Chicago, IL.

Gross, D., and Robertson, A. (1965), "Experimental Fires in Enclosures," Tenth Symposium (International) on Combustion, The Combustion Institute, pp. 931–942.

Grosshandler, W. (2002), *Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings*, NISTIR 6890, National Institute of Standards and Technology, Gaithersburg, MD.

Harada, K., Yabuki, Y., and Terai, T. (1997), "A Theoretical Consideration on Heat-transfer in Fire Resistance Furnaces for Furnace Harmonization," *Fire Safety Science – Proceedings of the Fifth International Symposium (IAFSS)*, pp. 1033–1044.

Harmathy, T. Z. (1967), "Deflection and Failure of Steel-supported Floors and Beams in Fire," ASTM STP 422, pp. 40–62.

Harmathy, T., Sultan, M., and MacLaurin, J. (1987), "Comparison of Severity of Exposure in ASTM E 119 and ISO 834 Fire Resistance Tests," *Journal of Testing and Evaluation*, pp. 371–375.

Henderson J., Tant, M., Moore, G., and Wiebelt, J. (1981), "Determination of Kinetic Parameters for the Thermal Decomposition of Phenolic Ablative Materials by a Multiple Heating Rate Method," *Thermochimica Acta*, **44**, pp. 253–264.

Henderson J., Verma Y., Tant, M., and Moore, G. (1983), "Measurement of the Thermal Conductivity of Polymer Composites to High Temperatures Using the Line Source Technique," *Polymer Composites*; **4** (4), pp. 219–224.

Henderson J., Wiebelt J., Tant M., and Moore, G., (1982), "A Method for the Determination of the Specific Heat and Heat of Decomposition of Composite Materials," *Thermochimica Acta* **57**, pp. 161–171.

ISO 834 (1999), *Fire Resistance Tests – Elements of Building Construction*, International Organization for Standardization, Geneva, Switzerland.

ISO 834-1.1 (1996), *Fire Resistance Tests – Elements of Building Construction – Part 1.1: General Requirements for Fire Resistance Testing*, International Organization for Standardization, Geneva, Switzerland.

Jansson, R. (2004), Measurement of Thermal Properties at Elevated Temperatures – Brandforsk Project 328-031, SP Report 46, Swedish National Testing and Research Institute, Boras, Sweden.

Kobayashi, A. (1987), *Handbook of Experimental Mechanics*, Society for Experimental Mechanics, Inc., Prentice–Hall, Inc, Englewood Cliffs, NJ.

Kodur, V., Sultan, M., and Alfawakhiri, F. (1999), "Fire Resistance Tests on Loadbearing Steel Stud Walls," *Proceedings of Third International Conference on Fire Research and Engineering, Society of Fire Protection Engineers*, Chicago, IL.

Kokkala, M. and Baroudi, D., (1993), A Transient Symmetrical Method for Measurement of Temperature Dependent Thermal Diffusivity, VTT Research Note 1452.

Lane, B. (2003), "Thermal and Structural Analysis Methods and Tools – Gaps in Knowledge and Priority Areas from a Practice Perspective," NIST Workshop, National Institute of Standards and Technology, Gaithersburg, MD.

Lattimer B., and Ouellette J., (2004), "Thermal Properties of Composites for Heat-transfer Modeling during Fires," *Proceedings of SAMPE 04 Conference*, Long Beach, CA.

Lattimer, B., and Ouellette, J. (2006), "Properties of Composite Materials for Thermal Analysis involving Fires," Composites Part A: Applied Science and Manufacturing, **37** (7), pp. 1068–1081.

Lie, T. and Harmathy, T. (1972), A Numerical Procedure to Calculate the Temperature of Protected Steel Columns Exposed to Fire, Fire Study No. 28, NRCC 12535, Div. of Building Research, National Research Council of Canada, Ottawa.

Lim, L., Buchanan, A., and Moss, P. (2004), "Restraint of Fire-exposed Concrete Floor Systems," *Fire and Materials*, **28**, pp. 95–125.

Lonnermark, A. and Ingason, H. (2005), "Gas Temperatures in Heavy Goods Vehicle Fires in Tunnels," *Fire Safety Journal*, **40**, pp. 506–527.

Lundkvist, A., Martensson, U., and Persson, B. (1991), Measurement of Thermal Diffusivity in Materials at High Temperatures – Nordtest Project No. 884–90, SP Report, Swedish National Testing and Research Institute.

Mehaffey, J., Cuerrier, P., and Carisse, G. (1994), "A Model for Predicting Heat-transfer through Gypsum Board/Wood–stud Walls Exposed to Fire," *Fire and Materials*, **18**, pp. 297–305.

NCMA (2002), *NCMA Fires at Gypsum Wall Assemblies and ASTM E 119*, National Concrete and Masonry Association (NCMA), Herndon, VA.

NIST (2005), *Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers,* NCSTAR 1, National Institute of Standards and Technology, Gaithersburg, MD.

NIST (2005), *Mechanical Properties of Structural Steels – Federal Building and Fire Safety Investigation of the World Trade Center Disaster*, NCSTAR 1–3D, National Institute of Standards and Technology, Gaithersburg, MD.

NIST (2005), *Fire Resistance Tests of the Floor Truss Systems – Federal Building and Fire Safety Investigation of the World Trade Center Disaster*, NCSTAR 1–6B, National Institute of Standards and Technology, Gaithersburg, MD.

Nyman, J., (2002) Equivalent Fire Resistance Ratings of Construction Elements Exposed to Realistic Fires, Master Thesis, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Pettersson, O., and Wittenveen, J. (1979), "On the Fire Resistance of Structural Steel Elements Derived from Standard Fire Tests or By Calculation," *Fire Safety Journal*, **2**, pp. 73–87.

Ryan, J. and Robertson, A. (1959), "Proposed Criteria for Defining Load Failure of Beams, Floors, and Roof Constructions During Fire Tests," *Journal of Research of the National Bureau of Standards, C. Engineering and Instrumentation*, **63C** (2).

Bazant, Z. and Chen, E. (1996), *Scaling of Structural Failure*, SAND96–2948, Sandia Report.

Scheffey, J., Williams, F., Durkin, A., and Back, G., (1991) "Interim Evaluation of Navy-approved Fire Insulation Exposed to a Post-flashover Fire (EX-USS SHADWELL)," NRL Ltr Rpt Ser 6180–166, April 11, 1991.

Schwartz, K. and Lie, T. (1985), "Investigating the Unexposed Surface Temperature Criteria of Standard ASTM E 119," *Fire Technology*, **21** (3), pp.169–180.

Sheppard, D., and Gandhi, P., (1993), "Development of a Transient Method for Determining Thermal Properties," *Fire and Materials,* 2nd International Conference, pp. 67–77.

Simitses, G. and Rezaeepazhand, J. (1993), Structural Similitude and Scaling Laws for Laminated Beam Plates, Report to NASA–Langley Research Center, NASA Grant NAG–1–1280.

Simitses, G., and Rezaeepazhand, J. (1993), "Structural Similitude and Scaling Laws for Laminated Beam Plates," Report to NASA-Langley Research Center, NASA Grant NAG-1-1280.

Sultan, M. (1995), "Effect of Insulation in the Wall Cavity on the Fire Resistance Rating of Full-scale Asymmetrical Gypsum Board Protected Wall Assemblies," *Proceedings of the International Conference on Fire Research and Engineering,* Society of Fire Protection Engineers, pp. 545-550.

Sultan, M. (2006), "Fire Resistance Furnace Temperature Measurements: Plate Thermometers vs. Shielded Thermocouples," *Fire Technology,* **42**, pp. 253–267.

Sultan, M., Benichou, N., and Byung, Y. (2003), "Heat Exposure in Fire Resistance Furnaces: Full-scale vs. Intermediate-scale," *Fire and Materials,* National Research Council of Canada, Ottawa, Ontario, pp. 43–54.

Tanaka, T., Nakaya, I., and Yoshida, M. (1985), "Full-scale Experiments for Determining the Burning Conditions to be Applied to Toxicity Tests," *Fire Safety Science – Proceedings of the First International Symposium (IAFSS),* pp. 129–138.

Thomas, P. and Heselden, J. (1972), "Fully-developed Fires in Single Compartments," A Cooperative Research Programme of the Conseil International du Batiment, Fire Research Note 923, Fire Research Station, Borehamwood.

Underwriters Laboratories, Inc. (UL) (2006a), Design No. X795, 2006 *Fire Resistance Directory,* **1**, p. 1095.

Underwriters Laboratories, Inc. (UL) (2006b), Design No. XR711, 2006 *Fire Resistance Directory,* **1**, p. 1124.

University of Edinburgh (numerous co-authors) (2000), *Behaviour of Steel Framed Structures Under Fire Conditions,* Edinburgh, Scotland, UK.

Van de Leur, P., and Twilt, L. (1999), "Thermal Exposure in Fire Resistance Furnaces," *Fire Safety Science – Proceedings of the Sixth International Symposium (IAFSS),* pp. 1087–1098.

Wang, M., (2006), "Scale Modeling of Structural Behavior in Fire," Doctoral Thesis, University of Maryland.

Wickstrom, U. (1997), "The Plate Thermometer – Practical Aspects," SP Report 1997:28, Swedish National Testing and Research Institute, Boras, Sweden.

Wickstrom, U. (1989), "The Plate Thermometer – A Simple Instrument for Reaching Harmonized Fire Resistance Tests," Nordtest Project 609-86, SP Report 1989:03, Swedish National Testing and Research Institute, Boras, Sweden.

http://www.promat-tunnel.com/idprt004.htm#, "Fire Curves," 2007

APPENDIX A – BIBLIOGRAPHY
(Developed by SWRI)

GENERAL

Anchor, R. D., Editor; Malhotra, H. L., Editor; Purkiss, J. A., Editor
Design of Structures Against Fire, Elsevier Applied Science Publishers, New York, Anchor, R. D.; Malhotra, H. L.; Purkiss, J. A., Editors, 258 pp, 1986.

Babrauskas, V.
Fire Endurance in Buildings.
California Univ., Berkeley
National Science Foundation, Washington, DC
Department of Housing and urban Development, Washington, DC
National Fire Prevention and Control Admin., Washington, DC
National Bureau of Standards, Gaithersburg, MD
UCB FRG 76-16; 390 p. November 1976
.

Bushev, V. P.; Pchelintsev, V. A.; Fedorenko, V. S.; Yakovlev, A. I.
Fire Endurance of Structures.
Ministry of Communal Economy, Moscow, USSR
Foreign Literature Study 480; 61 p. 1963.

Harmathy, T. Z.
National Research Council of Canada, Ottawa, Ontario
Fire Safety Design and Concrete, Longman Scientific and Technical, Essex, England, 424 p., 1993.

Lane, B., Thermal and Structural Analysis Methods and Tools: Gaps in Knowledge and Priority Area for Research From a Practice Perspective. White Paper.
NISTIR 7133; White Paper 7; April 20, 2004.
NIST-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: Proceedings. Appendix 9.H: White Papers. October 2-3, 2003, Baltimore, MD, 146-157 pp, 2004.
http://fire.nist.gov/Almand_NIST_SFPE%20_IR%207133.pdf

Lie, T. T., Editor
Structural Fire Protection. American Society of Civil Engineers (ASCE) Manuals and Reports on Engineering Practice No. 78, Am. Soc. of Civil Engineers, New York, NY, Lie, T. T., Editor(s), 256 p., 1992.

FIRE RESISTANCE TESTING

Beitel, J.; Iwankiw, N.
Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing.
Hughes Associates, Inc., Baltimore, MD
NIST GCR 02-843; 92 p. December 2002.

Beitel, J. J.
Current Controversies in Fire Resistance Testing.
Hughes Associates, Inc., Columbia, MD
ASTM STP 1163; PCN-04-011630-31;
American Society for Testing and Materials. Fire Standards in the International Marketplace. ASTM STP 1163. December 5, 1994, Phoenix, AZ, American Society for Testing and Materials, PA, Grand, A. F., Editor, 89-99 pp, 1995.

Berhinig, R. M.
Value of Fire Resistance Testing.
Underwriters Laboratories, Inc., Northbrook, IL
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 86-91 pp, 2003.

Bono, J. A.
New Criteria for Fire Endurance Tests.

Underwriters Laboratories, Inc., Northbrook, IL
Fire Test Performance. Winter Meeting. Proceedings. American Society for Testing and Materials. ASTM STP 464. February 2-7, 1969, Denver, CO, ASTM, Philadelphia, PA, 106-126 pp, 1969.

Buchanan, A. H.
Loading Frame Design for Fire Testing of Walls.
Homes, Wood, Poole and Johnstone
Fire Technology, Vol. 15, No. 2, 107-113, May 1979.

Cooke, G. M. E.
Thermal Bowing and How It Affects the Design of Fire Separating Construction.
Fire Research Station, Borehamwood, England
Fire and Materials, Vol. 13, 1-315, March 1988.
Interflam '88. Research Into Practice. 4th International Fire Conference. Conference Workbook. Organised Jointly by Interflam Conferences Ltd. and the Fire Research Station of the Building Research Establishment, in Association With the Royal Institute of British Architects and With EEC Recognition. March 22-24, 1988., Cambridge, England, John Wiley and Sons, New York, Rogers, S. P. and Quarterman, R. M.,, Editor, 230-236 pp, 1988.

Dekker, J.; Klingelhofer, M.; Vandevelde, P.
Testing and Classification of the Resistance to Fire of Structural Building Components.
TNO Institute for Building Materials and Construction, The Netherlands
North Rhine-Westphalia State Materials Testing Office, Federal Republic of Germany
Laboratory for Fuel Applications and Heat-transfer, Belgium
EUR 8750 EN; CD-NF-84-001-EN-C; 161 p. 1984.

Dougill, J. W.
Relevance of the Established Method of Structural Fire Testing to Reinforced Concrete.
University of London, England
Applied Materials Research, 235-240, October 1966.

Gross, J. L.; Hervey, F.; Izydorek, M.; Mammoser, J.; Treadway, J.
Fire Resistance Tests of the Floor Truss Systems. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
Underwriters Laboratories, Inc., Northbrook, IL
NIST NCSTAR 1-6B; 202 p. September 2005.

Harmathy, T. Z.
Deflection and Failure of Steel-Supported Floors and Beams in Fire.
National Research Council of Canada, Ottawa, Ontario
Research Paper 345; ASTM STP 422; December 1967.
American Society for Testing and Materials. ASTM STP 422, Symposium on Fire Test Methods, Restraint and Smoke, 1966, 40-62 pp, 1966.

Odeen, K.
Standard Fire Endurance Tests: Discussion, Criticism, and Alternatives.
National Institute for Materials Testing, Stockholm, Sweden
Fire Test Performance. Winter Meeting. Proceedings. American Society for Testing and Materials. ASTM STP 464. February 2-7, 1969, Denver, CO, ASTM, Philadelphia, PA, 30-56 pp, 1969.

History

Babrauskas, V.; Williamson, R. B.
Historical Basis of Fire Resistance Testing. Part 1.
California Univ., Berkeley
Fire Technology, Vol. 14, No. 3, 184-194, August 1978.

Babrauskas, V.; Williamson, R. B.
Historical Basis of Fire Resistance Testing. Part 2.

California Univ., Berkeley
Fire Technology, Vol. 14, No. 4, 304-316, November 1978.

Shoub, H.
Early History of Fire Endurance Testing in the United States.
National Bureau of Standards, Washington, DC
American Society for Testing and Materials. Fire Test Methods Symposium. Committee Week, 1961. ASTM Special Technical Publication 301 (ASTM STP 301). February 1, 1961, Cincinnati, OH, Am. Soc. for Testing and Materials, PA, 1-9 pp, 1961.

Fire Resistance Test Procedure

Babrauskas, V.; Williamson, R. B.
Temperature Measurement in Fire Test Furnaces.
California Univ., Berkeley
Fire Technology, Vol. 14, No. 3, 226-238, August 1978.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Determination of the Response Time of Thermocouples to be Used for the Measurement of Air or Gas Phase Temperature in Fire Resistance and Reaction to Fire Testing.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/SM/1; D/1995/6964/1; 7 p. June 1995.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Determination of the Response Time of Electronic Micro-Manometer Transducer Type Pressure Measurement Devices to be Used for the of Differential Pressure.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/SM/2; D/1998/6964/2; 7 p. March 1998.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Method for the Use and Calibration of Radiometers to be Used for the Measurement of Irradiation and/or Total Heat Flux in Fire Resistance and Reaction to Fire Testing.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/SM/4; D/1998/6964/1; 11 p. January 1998.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Fire Resistance Tests for Service Installations: Method for the Measurement of Leakage [Volume Flow Rates] To Indicate Integrity and Smoke Leakage.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/SM/6; D/2000/6964/2; 7 p. April 2000.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Devices and Procedures for Measurement and Control of Pressure in Fire Resistance Furnaces and Their Calibration.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/TR/3; Resolution Number 104; 8 p. March 1998.

European Organisation of Official Laboratories for Fire Testing (EGOLF)
Procedure for the Choice, Use, Checking, Mounting and Replacement of Instrumentation Used for Temperature Measurement in Fire Resistance Tests.
European Organisation of Official Laboratories for Fire Testing, Gent, Belgium
EGOLF/TR/2; Resolution Number 118; D/2000/6964/3; 9 p. April 2000.

Gustaferro, A. H.
Temperature Criteria at Failure.
Portland Cement Association Research and Development Laboratories, Skokie, IL

Fire Test Performance. Winter Meeting. Proceedings. American Society for Testing and Materials. ASTM STP 464. February 2-7, 1969, Denver, CO, ASTM, Philadelphia, PA, 68-84 pp, 1969.

Harmathy, T. Z.
Temperature of the Unexposed Surface of Fire Resistance Test Specimens.
National Research Council of Canada, Ottawa, Ontario
Journal of Testing and Evaluation, Vol. 13, No. 2, 127-131, March 1985.
CIB W14/86/18 (C); DBR Paper 1280; NRCC 24403;

Harmathy, T. Z.
Correction of the Results of Standard Fire Resistance Tests.
National Research Council of Canada, Ottawa, Ontario
Journal of Testing and Evaluation (JTEVA), Vol. 13, No. 4, 303-307, July 1985.

Harmathy, T. Z.
Furnace Pressure in Standard Fire Resistance Tests.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 23, No. 2, 162-163, May 1987.
CIB W14/87/15 (C);

Malhotra, H. L.
Deflection as a Criterion of Failure for Beams and Floors.
Fire Research Station, Borehamwood, England
FR Note 431; 14 p. April 1960.

Malhotra, H. L.
Loading, Restraint and Deformation Criteria in Fire Resistance Tests: A Survey of International Practice.
; 20 p. August 1971.

McGuire, J. H.
Method of Achieving Positive Pressure in a Fire Resistance Furnace.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 14, No. 3, 195-205, August 1978.

McGuire, J. H.
Positive Pressure Fire Resistance Furnace.
National Research Council of Canada, Ottawa, Ontario
Technical Note 570; 7 p. April 1973.

McGuire, J. H.
Scaling of Dimensions in B.S. 476 Fire Resistance Tests.
Fire Research Station, Borehamwood, England
FR Note 95; 7 p. January 1954.

O'Connor, D. J.; Morris, B.; Silcock, G. W. H.
Model Fire Test for Parametric Testing of Half Scale Structural Components.
University of Ulster, N. Ireland
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 997-1008 pp, 1997.

Schwartz, K. J.; Lie, T. T.
Investigating the Unexposed Surface Temperature Criteria of Standard ASTM E 119.
Rolf Jensen & Associates, Inc.
National Research Council of Canada
Fire Technology, Vol. 21, No. 3, 169-180, August 1985.
NRCC 25544; IRC Paper 1359;

Olsson, S.
Probe for Static Pressure Mesurements in Furnaces. Technical Report.

National Testing Institute, Boras, Sweden
TR-SP-RAPP 1985:12; 41 p. 1985.

Persson, H.; Martensson, U.; Hermodsson, T.; Tuovinen, H.
Devices for Measuring the Heat Flux From the Unexposed Side of Objects Duiring Furnace Testing: SMT Project FIRESCAL.
Swedish National Testing and Research Institute, Boras, Sweden
SP Technical Notes 1998:35; SP AR 1998:35; 32 p. 1998.

Rowan, N. T.
Plate Thermometer and Its Use in Fire Resistance Testing.
Fire Safety Engineering, Vol. 6, No. 3, 25-27, June 1999.

Steel, J. S.
Furnace Pressure Probe Investigation.
National Bureau of Standards, Gaithersburg, MD
NBSIR 81-2415; 28 p. December 1981.
Available from National Technical Information Service
PB82-139999

Sultan, M. A.
Correlation of Small- and Full-Scale Fire Resistance on Insulated and Non-Insulated Lightweight Frame Gypsum Board Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. Interflam '96. International Interflam Conference, 7th Proceedings. March 26-28, 1996, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, 933-937 pp, 1996.

Totten, G. E.; Webster, G. M.
Fire Resistance Testing Procedures: A Review and Analysis.
Union Carbide Corp., Tarrytown, NJ
ASTM STP 1284; ASTM PCN 04-012840-12;
American Society for Testing and Materials. Fire Resistance of Industrial Fluids. ASTM STP 1284. Proceedings. June 20, 1995, Indianapolis, IN, ASTM, Philadelphia, PA, Totten, G. E.; Reichel, J., Editors, 42-60 pp, 1996.

Wickstrom, U.
Plate Thermometer: A Simple Instrument for Reaching Harmonized Fire Resistance Tests.
Swedish National Testing Inst., Boras, Sweden
Fire Technology, Vol. 30, No. 2, 195-208, Second Quarter, 1994.
CIB W14/89/01 (S); SP Report 1989:03; NORDTEST Project 609-86; 57 p. 1989.
Available from National Technical Information Service
PB89-224406

Wickstrom, U.
Plate Thermometer: Practical Aspects.
Swedish National Testing and Research Institute, Boras, Sweden
SP Report 1997:28; 23 p. 1997.

Additional Measurements

Brenden, J. J.; Chamberlain, D. L.
Heat Release Rates From Wall Assemblies. Oxygen Consumption and Other Methods Compared.
Forest Products Laboratory, Madison, WI
National Bureau of Standards, Gaithersburg, MD
CIB W14/88/07 (USA); FPL Research Paper 476; 23 p. June 1986.

Tran, H. C.; White, R. H.

Heat Release From Wood Wall Assemblies Using Oxygen Consumption Method.
Department of Agriculture, Madison, WI
Chapter 25; ACS Symposium Series 425;
American Chemical Society. Fire and Polymers--Hazards Identification and Prevention. National Meeting, 197th. ACS Symposium Series 425. April 9-14, 1989, Dallas, TX, American Chemical Society, Washington, DC, Nelson, G. L., Editor, 411-428 pp, 1989.

Comparison of Fire Resistance Test Standards

Cooper, L. Y.; Steckler, K. D.
Methodology for Developing and Implementing Alternative Temperature-Time Curves for Testing the Fire Resistance of Barriers for Nuclear Power Plant Applications.
National Institute of Standards and Technology, Gaithersburg, MD
Nuclear Regulatory Commission, Washington, DC
NISTIR 5842; 116 p. May 1996.

Harmathy, T. Z.; Sultan, M. A.; MacLaurin, J. W.
Comparison of Severity of Exposure in ASTM E 119 and ISO 834 Fire Resistance Tests.
National Research Council of Canada, Ottawa, Ontario
Journal of Testing and Evaluation, Vol. 15, No. 6, 371-375, November 1987.

Harmathy, T. Z.; Sultan, M. A.
Correlation Between the Severities of the ASTM E 119 and ISO 834 Fire Exposures.
National Research Council of Canada, Ottawa, Ontario
Fire Safety Journal, Vol. 13, No. 2-3, 163-168, May 20, 1988.

Lie, T. T.
Fire Temperature--Time Relations.
National Research Council of Canada, Ottawa, Ontario
IRC Paper 1579; NRCC 30108;
Society of Fire Protection Engineers. Handbook of Fire Protection Engineering. Section 3, Chapter 5, 3/81-87 pp, 1988.

Malhotra, H. L.
Harmonization of Fire Tests in Europe for Building Components.
Fire Research Station, Borehamwood, England
Fire Prevention Science and Technology, No. 11, 21-25, April 1975.

Rodak, S. P.
Discussion of Thermal Failure Time Difference Between ISO and ASTM Surface Temperature Measuring Techniques.
National Bureau of Standards, Gaithersburg, MD
NBS 9515; 13 p. September 8, 1967.

Sultan, M.A.
Fire Resistance Furnace Temperature Measurements: Plate Thermometers vs Shielded Thermocouples.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. `42, No. 3, 253-267, July 2006.

Sultan, M. A.
Comparison of Heat Exposure in Fire Resistance Test Furnaces Controlled by Plate Thermometers and by Shielded Thermocouples.
National Research Council of Canada, Ottawa, Ontario
Volume 1;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 1. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 219-229 pp, 2004.

Wickstrom, U.
Revision of ISO 834-1975. Fire Resistance Tests: Elements of Building Construction.
Statens Provningsanstalt, Boras, Sweden
SP-RAPP 1988:02; NORDTEST-PROJECT 552-85; 114 p. December 1987.
Available from National Technical Information Service
PB88-171822

Hose Stream Test

Ingberg, S. H.
Hose-Stream Test as a Part of Fire-Testing Procedure.
Structural and Fire Protection Engineer, Bethesda, MD
ASTM STP 344;
Fire Test Methods Symposium. Fourth (4th) Pacific Area Meeting Papers. Proceedings. American Society for Testing and Materials. ASTM STP 344. 1962, ASTM, Philadelphia, PA, 57-68 p., 1962.

Specimen Conditioning

Abrams, M. S.; Orals, D. L.
Concrete Drying Methods and Their Effect on Fire Resistance.
Portland Cement Assn., Skokie, IL
ASTM STP 385;
American Society for Testing and Materials. Moisture in Materials in Relation to Fire Tests. Annual Meeting, 67th. June 24, 1965, Chicago, IL, American Society for Testing and Materials, PA, 52-73 pp, 1965

Harmathy, T. Z.; Porteous, E. O.
Sampling Method for Measuring the Moisture Distribution in Fire Test Specimens.
National Research Council of Canada, Ottawa, Ontario
NRCC 42; 8 p. July 1963.

Harmathy, T. Z.
Effect of Moisture on the Fire Endurance of Building Elements.
National Research Council of Canada, Ottawa, Ontario
Research Paper No. 270; NRC 8626; August 1965.
American Society for Testing and Materials. Moisture in Materials in Relation to Fire Tests. Annual Meeting, 67th. ASTM STP 385. June 24, 1965, Chicago, IL, American Society for Testing and Materials, PA, 74-94 pp, 1965.

Harmathy, T. Z.; Lie, T. T.
Experimental Verification of the Rule of Moisture Moment.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 7, No. 1, 17-24, February 1971.
NRCC 11947; Research Paper No. 484.

Lie, T. T.
Feasibility of Determining the Equilibrium Moisture Condition in Fire Resistance Test Specimens by Measuring Their Electrical Resistance.
National Research Council of Canada, Ottawa, Ontario
Building Research Note No. 75; 12 p. March 1971.

Ryan, J. V.
Some Experience Gained from the Use of Humidity Sensing Elements to Indicate the Drying of Fire Test Specimens.
National Bureau of Standards, Gaithersburg, MD
NBS 6116; 6 p. August 12, 1958.

Specimen Restraint

Abrams, M. S.; Lin, T. D.
Simulation of Realistic Thermal Restraint During Fire Tests of Floor and Roof Assemblies. Appendices. Final Report.

Fire Research Station, Borehamwood, England
Portland Cement Assoc., Skokie, IL
National Bureau of Standards, Gaithersburg, MD
; 334 p. January 1974.

Ashton, L. A.
Effect of Restraint in Fire Resistance Tests.
Fire Research Station, Borehamwood, England
FR Note 359; 8 p. June 1958.

Bennetts, I. D.; Goh, C. C.; O'Meagher, A. J.; Thomas, I. R.
Restraint of Compression Members in Fire.
Melbourne Research Labs., Victoria, Australia
MRL/PS65/89/002; 38 p. September 1989.

Bletzacker, R. W.
Effect of Structural Restraint, Stiffness and Composite Action on the Fire Resistance of Steel Constructions.
Ohio State Univ., Columbus
American Iron and Steel Institute, Washington, DC
; 7 p. December 23, 1963.

Bletzacker, R. W.
Effect of the Building Frame on the Fire Resistance of Floor and Ceiling Assemblies.
Ohio State Univ., Columbus
Methods and Applications of Fire Testing Symposium. Proceedings. Armstrong Cork Co. June 24-25, 1965, H/1-9 pp, 1965.

Carlson, C. C.; Selvaggio, S. L.; Gustaferro, A. H.
Review of Studies of the Effect of Restraint on the Fire Resistance of Prestressed Concrete.
Portland Cement Assoc., San Ramon, CA
Fire Resistance of Prestressed Concrete Symposium. Proceedings. June 1965, Braunschweig, Germany, 32-42 pp, 1965.

Issen, L. A.; Gustaferro, A. H.; Carlson, C. C.
Fire Tests of Concrete Members: An Improved Method for Estimating Thermal Restraint Forces.
National Bureau of Standards, Gaithersburg, MD
Portland Cement Assoication, Skokie, IL
ASTM SP 464; 34 p. 1969.
American Society for Testing and Materials. Fire Test Performance. Winter Meeting. Proceedings. ASTM STP 464. February 2-7, 1969, American Society for Testing and Materials, Philadelphia, PA, 153-185 pp, 1969.

Lim, L.; Buchanan, A. H.; Moss, P. J.
Restraint of Fire-Exposed Concrete Floor Systems.
Canterbury Univ., Christchurch, New Zealand
Fire and Materials, Vol. 28, No. 2/4, 95-125, March/August 2004.

Lin, T. D.; Abrams, M. S.
Simulation of Realistic Thermal Restraint During Fire Tests of Floors and Roofs.
Portland Cement Assoc., Skokie, IL
NBS GCR 81-317;
Fire Safety of Concrete Structures. ACI Committee 216. Abrams, M. S., editor. September 1980, San Juan, Puerto Rico, 1-68 pp, 1983.
Available from National Technical Information Service
PB81-179657

Malhotra, H. L.
First Programe of Tests on Effect of Restraint on Fire Resistance of Floors.
Fire Research Station, Borehamwood, England
FR Note 435; 7 p. April 1960.

Selvaggio, S. L.; Carlson, C. C.
Effect of Restraing on Fire Resistance of Prestressed Concrete.
Portland Cement Assoc., Skokie, IL
Bulletin 164;
Fire Test Methods Symposium. Proceedings. American Society for Testing and Materials. ASTM STP No. 344. 1963, 1-25 pp, 1963.

Selvaggio, S. L.; Carlson, C. C.
Restraint in Fire Tests of Concrete Floors and Roofs.
Portland Cement Assoc., Skokie, IL
Fire Test Methods: Restraint and Smoke Proceedings spronsored by American Society for Testing and Materials. ASTM STP 422. Annual Meeting, 69th. June 26-July 1, 1966, Atlantic City, NJ, ASTM, Philadelphia, PA, 21-39 pp, 1967.

Shoub, H.; Gross, D.
Effect of the Building Frame on the Fire Resistance of Floor and Ceiling Assemblies.
Ohio State Univ., Columbus
Methods and Applications of Fire Testing Symposium. Proceedings. Armstrong Cork Co. June 24-25, 1965, H/1-9 pp, 1965.

Fire Resistance Test Furnaces

Babrauskas, V.
Harmonizing Fire-Resistance Furnaces Utilizing the Plate Thermometer.
Fire Science and Technology Inc., Issaquah, WA
Building Standards, Vol. 66, No. 5, 11-14, September/October 1997.

Bohm, B.; Hadvig, S.
Calculation of Heat-transfer in Fire Test Furnaces With Specific Interest in the Exposure of Steel Structures. A Technical Note.
Technical Univ. of Denmark, Lyngby
Fire Safety Journal, Vol. 5, 281-286, 1983.
CIB W14/83/02 (DK);

Bressloff, N.; Rubini, P.; Cox, G.
CFD Modelling of a Fire Resistance Furnace.
Fire Research Station, Garston, England
Session III; Structures 3;
European Symposium on Fire Safety Science, First (1st). **ABSTRACTS**. Proceedings. Session III. Structures 3. August 21-23, 1995, Zurich, Switzerland, III-14/141-142 pp, 1995.

Carlson, C. C.; Hubbell, J. B.
Design and Operation of the PCA Floor Furnace.
Portland Cement Assoc., San Ramon, CA
RR001.02B; 34 p. 1969.

Cooke, G. M. E.
Can Harmonisation of Fire Resistance Furnaces be Achieved by Plate Thermometer Control?
Fire Research Station, Borehamwood, England
International Association for Fire Safety Science. Fire Safety Science. Proceedings. 4th International Symposium. July 13-17, 1994, Ottawa, Ontario, Canada, Intl. Assoc. for Fire Safety Science, Boston, MA, Kashiwagi, T., Editor, 1195-1207 pp, 1994.

Cooke, G. M. E.
Use of Plate Thermometers for Standardising Fire Resistance Furnaces.
Fire Research Station, Borehamwood, England
BRE OP 58; 146 p. March 1994.

Davies, J. M.; Dewhurst, D.; McNicholas, J.

Furnace Characterisation and the Harmonisation of Fire Resistance Testing.
University of Manchester, England
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. Interflam '96. International Interflam Conference, 7th Proceedings. March 26-28, 1996, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, 921-925 pp, 1996.

Fang, J. B.; Scott, J. T.
Heat-transfer in Furnaces for CIB Cooperative Program and Heat Balance Analysis of Wall Furnace. Final Report.
National Bureau of Standards, Gaithersburg, MD
NBSIR 75-794; 47 p. November 1975.
Available from National Technical Information Service
PB-247203

Fromy, P.; Curtat, M.
Application of a Zone Model to the Simulation of Heat-transfer in Fire Resistance Furnaces Piloted With Thermocouples or Plate Thermometers.
CSTB, Cedex, France
Fire Safety Science. Proceedings. Sixth (6th) International Symposium. International Association for Fire Safety Science (IAFSS). July 5-9, 1999, Poitiers, France, Intl. Assoc. for Fire Safety Science, Boston, MA, Curtat, M., Editor, 531-542 pp, 2000.

Gross, D.; Bailey, W. H.; Bender, E. W.; Robertson, A. F.
Central Furnance Control and Recording Facility.
National Bureau of Standards, Gaithersburg, MD
NBS 7015; 29 p. November 21, 1960.

Harada, K.; Yabuki, Y.; Terai, T.
Theoretical Consideration on Heat-transfer in Fire Resistance Furnaces for Furnace Harmonization.
Building Research Inst., Tsukuba, Japan
Hazama Corp., Tokyo, Japan
Kinki Univ., Higashi-Hiroshima, Japan
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 1033-1044 pp, 1997.

Harada, K.; Masuda, H.; Yoshida, M.; Motegi, T.; Sudo, M.
Heat-transfer in Fire Resistance Furnaces: Experimental Investigation of the Variation of Heat Impact Due to furnace Construction and Control Thermocouples.
Building Research Institute, Tsukuba, Japan
Tsukuba Testing Center, Japan
Bulletin of Japan Association for Fire Science and Engineering, Vol. 48, No. 2, 9-17, 1998.

Holm, C.; Loikkanen, P.
Joint Investigation of Vertical Furnaces in Nordic Countries.
Technical Research Centre of Finland, Espoo
VTT Research Report 56/1981; CIB W14/82/51; 61 p. 1981.

Holve, D.
Theoretical Analysis of the ASTM E 119 Standard Fire Test.
Stanford Research Institute, Menlo Park, CA
CIB W14/149/75 (USA); 19 p. 1975.

Hsiung, K. H.; Oppenheim, P.; Chang, W. P.; Rinker, M.E.
Furnace for the Evaluation of the Fire Resistance of Concrete Slabs.
Florida Univ., Gainesville
American Technologies International. Fire Safety '91 Conference. Volume 4. November 4-7, 1991, St. Petersburg, FL, Am. Technologies Intl., Pinellas Park, FL, 265-275 pp, 1991.

Kanury, A. M.; Holve, D. J.

Theoretical Analysis of the ASTM E 119 Standard Fire Test of Building Construction and Materials. Final Report.
Stanford Research Inst., Menlo Park, CA
National Bureau of Standards, Gaithersburg, MD
NBS GCR 76-50; 141 p. August 1975.
Available from National Technical Information Service
PB-247939

Keltner, N.; Nash, L.; Beitel, J.; Parker, A.; Welsh, S.; Gilda, B.
Fire Safety Test Furnace Characterization Unit.
University of Nevada, Reno
Sandia National Laboratories, Albuquerque, NM
ASTM STP 1427; ASTM Stock Number: STP 1427;
Thermal Measurements: The Foundation of Fire Standards. American Society for Testing and Materials (ASTM). Proceedings. ASTM STP 1427. December 3, 2001, Dallas, TX, American Society for Testing and Materials, West, Gritzo, L. A.; Alvares, N. J., Editors, 128-146 pp, 2003.

Paulsen, O.
On the Heat-transfer in Fire Test Furnaces.
Technical University of Denmark
; 251 p. 1979.

Paulsen, O. R.; Hadvig, S.
Heat-transfer in Fire Test Furnaces.
Technical University of Denmark, Lyngby
Journal of Fire and Flammability, Vol. 8, 423-442, October 1977.

Rodak, S. P.
Furnace Temperature Control Tests in a Horizontal Slab Furnace.
National Bureau of Standards, Gaithersburg, MD
Coast Guard, Washington, DC
NBS 10 007; 13 p. March 11, 1969.

Ryan, J. V.
Examination of the Temperature Distribution Within the N.B.S. Floor Test Furnace.
National Bureau of Standards, Gaithersburg, MD
NBS 5994; 15 p. July 25, 1958.

Schriever, R.; Muller, R.; Rudolphi, R.
Calibration Element for Fire Resistance Furnaces, Testing Specimens Totally Engulfed in Fire.
Federal Institute for materials Research and Testing, Berlin
British Steel, England
Volume 2;
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. **Interflam 1999. (Interflam '99).** International Interflam Conference, 8th Proceedings. Volume 2. June 29-July 1, 1999, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1057-1068 pp, 1999.

Shorter, G. W.; Harmathy, T. Z.
Fire Research furnaces at the National Research Council.
National Research Council of Canada, Ottawa, Ontario
Fire Study No. 1; NRC 5732; 18 p. July 1960.

Sterner, E.; Wickstrom, U.
Calibration of Fire Resistance Test Furnaces NORDTEST Project No. 785-88.
Building Research Association of New Zealand, Judgeford
CIB W14/1/90 (S); SP REPORT 1989:36; BRANZ 91; 34 p. 1989.
Pacific Timber Engineering Conference, 2nd. August 28-31, 1989, Auckland, Australia, 119-124 pp, 1989.
Available from National Technical Information Service
PB90-189416

Sultan, M. A.; Harmathy, T. Z.; Mehaffey, J. R.
Heat Transmission in Fire Test Furnaces.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 10, No. 2, 47-55, June 1986.
CIB W14/86/23 (C); IRC Paper 1451; NRCC 27636; 34 p. November 1985

Sultan, M. A.
Effect of the Furnace Lining Materials and Fuels on the Fire Severity in Fire Test Furnaces.
National Research Council of Canada, Ottawa, Ontario
Interscience Communications Limited. Fire and Materials. International Conference, 2nd. September 23-24, 1993, Arlington, VA, 111-119 pp, 1993.

Sultan, M. A.
Effect of Furnace Parameters on Fire Severity in Standard Fire Resistance Tests.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 20, No. 5, 245-252, September/October 1996.

Sultan, M. A.; Denham, M.; Torvl, D. A.
Fire Exposure in Standard Fire Resistance Test-Furnaces.
National Research Council of Canada, Ottawa, Ontario
National Heat-transfer Conference. Volume 3. HTD-Vol. 341. American Society of Mechanical Engineers (ASME). Proceedings. August 1997, Baltimore, MD, 37-49 pp, 1997.

Sultan, M. A.; Denham, M.
Harmonization of the Fire Severity in Standard Fire Resistance Test Furnaces.
National Research Council of Canada, Ottawa, Ontario
NRCC-40102;
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 1045-1056 pp, 1997.

Sultan, M. A.; Benichou, N.
Heat Exposure Measurements in Fire Resistance Wall and Floor Test Furnaces.
National Research Council of Canada, Ottawa, Ontario
NRCC-46893;
Structures in Fire, 3rd International Workshop. Proceedings. May 10-11, 2004, Ontario, Canada, 1-9 pp, 2004.
http://irc.nrc-cnrc.gc.ca/fulltext/nrcc46893/nrcc46893.pdf

Sultan, M. A.; Benichou, N.; Min, B. Y.
Heat Exposure in Fire Resistance Furnaces: Full-Scale VS Intermediate-Scale.
National Research Council of Canada, Ottawa, Ontario
Korea Institute of Construction Technology, Kyunggi, Republic of Korea
NRCC-46106;
Fire and Materials 2003. 8th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 27-28, 2003, San Francisco, CA, 43-53 pp, 2003.

Tatman, P. J.
Centralized Control of Test Furnaces in the PCA Fire Research Laboratory.
Portland Cement Assoc., San Ramon, CA
Journal of the PCA Research and Development Laboratories, Vol. 3, No. 2, 22-26, May 1961.
Bulletin 132;

vandeLeur, P. H. E.; Twilt, L.
Thermal Exposure in fire Resistance Furnaces.
TNO Institute for Building Materials and Construction, Delft, The Netherlands

Fire Safety Science. Proceedings. Sixth (6th) International Symposium. International Association for Fire Safety Science (IAFSS). July 5-9, 1999, Poitiers, France, Intl. Assoc. for Fire Safety Science, Boston, MA, Curtat, M., Editor, 1087-1098 pp, 2000.

Welch, S.; Rubini, P.
Three-Dimensional Simulation of a Fire-Resistance Furnace.
Cranfield Univ., Bedfordshire, UK
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 1009-1020 pp, 1997.

Zabawsky, Z.
Construction of an ASTM E 119 Furnace.
Armstrong Cork Co., Lancaster, PA
Methods and Applications of Fire Testing Symposium. Proceedings. Armstrong Cork Co. June 24-25, 1965, F/1-8 pp, 1965.

Relationship between the Standard Fire Resistance Test and Real Fires

Ashton, L. A.
Use in Building Codes of the Insulation Requirement of Fire Resistance Tests.
Fire Research Station, Borehamwood, England
FR Note 430; 3 p. April 1960.

Bellman, R. F.
Significance of ASTM E 119 Floor-Furnace Tests.
Underwriters Laboratories, Inc., Northbrook, IL
Methods and Applications of Fire Testing Symposium. Proceedings. Armstrong Cork Co. June 24-25, 1965, G/1-9 pp, 1965.

Butcher, E. G.; Law, M.
Comparison Between Furnace Tests and Experimental Fires.
Fire Research Station, Borehamwood, England
Paper 4;
Behavior of Structural Steel in Fires. Symposium No. 2. Proceedings. January 24, 1967, Borehamwood, England, 44-55 pp, 1967.
Available from National Technical Information Service
AD-835937

Dexter, R. J.; Gilvary, K. R.
Evaluation of Alternative Methods for Fire Rating Structural Elements.
Department of Civil Engineering, Minneapolis, MN
Walter P. Moore and Associates, Inc., Tampa, FL
International Conference on Fire Research and Engineering (ICFRE2), Second (2nd). Proceedings. National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE). August 3-8, 1997, Gaithersburg, MD, Society of Fire Protection Engineers, Boston, MA, 428-437 pp, 1998.

Gerlich, H.
Furnace Testing Or 'Real' Building Fires?
Winstone Wallboards
Build, 30, April/May 2002.

Gerlich, H. J. T.; Nyman, J. F.; Buchanan, A. H.; Wade, C.
Equivalent Fire Resistance of Drywall Construction Exposed to Compartment Fires.
Winstone Wallboards, New Zealand
Cosgrove Major Consultants, New Zealand
University of Canterbury, Christchurch, New Zealand
Building Research Association of New Zealand, Judgeford
Fire and Materials 2003. 8th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 27-28, 2003, San Francisco, CA, 21-32 pp, 2003.

Gross, D.
To the Editor. RE: Viewpoint by T. Z. Harmathy--Thermal Inertia or Thermal Absorptivity?
National Bureau of Standards, Gaithersburg, MD
Fire Technology, Vol. 21, No. 4, 324-326, November 1985.

Harada, K.; Kogure, R.; Matsuyama, K.; Wakamatsu, T.
Equivalent Fire Duration Based on Time-Heat Flux Area.
Science University of Tokyo, Chiba
Kyoto Univ., Japan
Asia-Oceania Symposium on Fire Science and Technology, 4th Proceedings. Co-Organized by Asia-Oceania Association for Fire Science and Technology (AOAFST) and Japan Association for Fire Science and Engineering (JAFSE). May 24-26, 2000, Tokyo, Japan, 513-524 pp, 2000.

Harmathy, T. Z.
Treatise on Theoretical Fire Endurance Rating.
National Research Council of Canada, Ottawa, Ontario
NRC 6305; DBR Paper 153; 1961.
American Society for Testing and Materials (ASTM). Special Technical Publication (STP) 301. 1961, ASTM, Philadelphia, PA, 10-40 pp, 1961.

Harmathy, T. Z.
Relationship Between Fire Resistance and Fire Tolerance.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 2, No. 4, 154-163, 1978.
CIB W14/79/19 (C); DBR Paper 817; NRCC 17136;

Harmathy, T. Z.
On the Equivalent Fire Exposure.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 11, No. 2, 95-104, June 1987.
CIB W14/87/17 (C); NRCC 28721; IRC Paper 1514;

Harmathy, T. Z.; Mehaffey, J. R.
Normalized Heat Load: A Key Parameter in Fire Safety Design.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 6, No. 1, 27-31, March 1982.
CIB W14/82/32 (C);

Harmathy, T. Z.
Fire Resistance Test and Its Relation to Real-World Fires.
Fire Research Station, Borehamwood, England
Fire and Materials, Vol. 5, No. 3, 112-122, September 1981.
CIB W14/79/04 (C); NRCC 20009; DBR Paper 1022;

Harmathy, T. Z.
Design to Cope With Fully Developed Fires.
National Research Council of Canada, Ottawa, Ontario
ASTM STP 685; DBR Paper 854; NRCC 17644;
American Society for Testing Materials. Design of Buildings for Fire Safety. Symposium Sponsored by ASTM Committee E05 on Fire Standards. ASTM STP 685. June 27, 1978, Boston, MA, American Society for Testing and Materials, PA, Smith, E. E.; Harmathy, T. Z., Editors, 198-276 pp, 1978.

Harmathy, T. Z.
How Much Fire Resistance is Really Needed?
National Research Council of Canada, Ottawa, Ontario
Concrete International--Design and Construction, Vol. 10, No. 12, 40-44, December 1988.
CIB W14/77/03 (C);

Hertz, K.
Equivalent Time of Fire Exposure for Concrete Structures.
Technical Univ. of Denmark, Lyngby
Report 163; CIB W14/83/03 (DK); 28 p. February 1983.

Ingberg, S. H.
Fire Tests of Office Occupancies.
National Bureau of Standards, Gaithersburg, MD
NFPA Quarterly, Vol. 20, No. 3, 243-252, January 1927.

Ingberg, S. H.
Tests of the Severity of Building Fires.
National Fire Protection Assoc., Quincy, MA
NFPA Quarterly, Vol. 22, No. 1, 43-61, July 1928.

Ingberg, S. H.
Fire Resistance Requirements in Building Codes.
National Bureau of Standards, Washington, DC
National Fire Protection Association Quarterly, Vol. 23, No. 2, 153-162, October 1929.

International Organization for Standardization
Principles of Structural Fire-Engineering Design With Special Regard to the Connection Between Real Fire Exposure and the Heating Conditions of the Standard Fire-Resistance Test (ISO 834).
International Organization for Standardization
ISO TR 3956-1975 (E); 8 p. November 1, 1975.

International Organization for Standardization
Principles of Structural Fire-Engineering Design With Special Regard to the Connection Between Real Fire Exposure and the Heating Conditions of the Standard Fire-Resistance Test (ISO 834).
International Organization for Standardization
ISO TR 3956-1975 (E); 8 p. November 1, 1975.

Jackman, P.
All Fire-Resisting Building Elements Should be Equal, But Some Are More Equal Than Others.
International Consultants Ltd.
Fire Prevention, No. 193, 32-35, October 1986.

Johannesson, P.
Real Fire as a Full Scale Fire Test.
Technical Bulletin 12; 4 p. 1961.

Law, M.
Review of Formulae for T-Equivalent.
Arup Fire, Ove Arup and Partners, London, England
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 985-996 pp, 1997.

Malhotra, H. L.
Fire Resistance Versus Fire Behavior.
Fire Research Station, Borehamwood, England
Fire Prevention, No. 134, 21-27, January 1980.
Conseil International du Batiment (CIB). Systems Approach to Fire Safety in Buildings. Volume 2. Session 3. Active Systems Performance and Criteria: Smoke Control, Detection, Sprinklers. Session 4. Passive Systems Performance and Criteria: Combustibles, Fire Resistance. August 29-30, 1979, Tsukuba, Japan, IV/121-36 pp, 1980.

Mehaffey, J. R.; Harmathy, T. Z.
Assessment of Fire Resistance Requirements.

National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 17, No. 4, 221-237, November 1981.
CIB W14/82/31 (C);

Nyman, J.
Equivalent Fire Resistance Ratings of Construction Elements Exposed to Realistic Fires.
University of Canterbury, Christchurch, New Zealand
Fire Engineering Research Report 02/13; 221 p. May 2002

Robertson, A. F.; Gross, D.
Fire Load, Fire Severity and Fire Endurance.
National Bureau of Standards, Gaithersburg, MD
ASTM STP 464;
American Society for Testing and Materials. Fire Test Performance. Winter Meeting. Proceedings. ASTM STP 464. February 2-7, 1969, Denver, CO, 3-29 pp, 1969.

Sfintesco, D.
Furnace Tests and Fire Resistance.
Centre Technique Industriel de la Construction Metallique, Puteaux, France
Paper 9;
Behavior of Structural Steel in Fires. Symposium No. 2. Proceedings. January 24, 1967, Borehamwood, England, 111-115 pp, 1967.
Available from National Technical Information Service
AD-835937

Shields, T. J.; Silcock, G. W.; Dunlop, K. E.
Time Based Approach to Building Code Equivalency.
Ulster Univ., Jordanstown, Northern Ireland
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers. **Interflam 1990. (Interflam '90).** Fire Safety. International Fire Conference, 5th. September 3-6, 1990, Canterbury, England, Interscience Communications Ltd., London, England, Franks, C. A., Editor, 77-84 pp, 1990.

Simms, D. L.; Smith, P. G.
On the Fire Resistance Requirements of Structures.
Fire Research Station, Borehamwood, England
FR Note 447; 11 p. October 1960.

Thomas, P. H.
Some Notes on Fires in Compartments.
Lund Univ., Sweden
CIB W14/88/52 (S); LUTVDG/TVBB-3033; 35 p. 1988.

Wickstrom, U.
Application of the Standard Fire Curve for Expressing Natural Fires for Design Puposes.
National Testing Inst., Boras, Sweden
ASTM STP 882;
American Society for Testing and Materials. Fire Safety: Science and Engineering. ASTM STP 882. June 26-17, 1984, Denver, CO, Harmathy, T. Z., Editor, 145-159 pp, 1984.

Williamson, R. B.
Relationship Between Fire Severity and Fire Endurance.
California Univ., Berkeley
University of California, Berkeley. Fire Safety in Urban Housing. January 30-31, 1975, Berkeley, CA, 1-4 pp, 1975.

Gilvary, K. R.; Dexter, R. J.
Evaluation of Alternative Methods for Fire Rating Structural Elements.
Lehigh Univ., Bethelhem, PA
National Institute of Standards and Technology, Gaithersburg, MD
NIST GCR 97-718; ATLSS Report No. 97-05; 102 p. June 1997.

AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB97-184055

Schulz-Forberg, B.
Furnace Test by the Standard Fire Curve as an Alternate Method to Meet the Thermal Test Requirements.
Bundesanstalt fur Materialprufung, Federal Republic of Germany
Union Carbide Corporation and U.S. Atomic Energy Commission. Packaging and Transportaiton of Radioactive Materials. International Symposium, 4th. September 22-27, 1974, Miami Beach, FL, 659-667 pp, 1974.
Available from National Technical Information Service
CONF-740901

TEST DATA

Schwartz, K. J.
Effects of Thermal Insulation on Fire Resistive Assemblies.
Portland Cement Association, Skokie, IL
SFPE TR 81-07; 21 p. 1981.

Przetak, L.
Standard Details for Fire-Resistive Building Construction, McGraw-Hill Book Co., New York, 373 p., 1977.

Composite Floor Slabs

Abdel-Halim, M. A. H.; Hakmi, M. R.; O'Leary, D. C.
Fire Resistance of Composite Floor Slabs Using a Model Fire Test Facility.
Jordan University of Science and Technolgoy, Irbid, Jordan
University of Salford, UK
Engineering Structures, Vol. 21, No. 2, 176-172, February 1999.

Abrams, M. S.; Gustaferro, A. H.
Fire Endurance of Concrete Slabs as Influenced by Thickness, Aggregate Type, and Moisture.
Portland Cement Assoc., San Ramon, CA
Journal of the PCA Research and Development Laboratories, Vol. 10, No. 2, 9-24, May 1968

Adams, F. C.; Day, T. V.
Thermal Movement of Concrete Floor Units Under Fire Conditions.
Fire Research Station, Borehamwood, England
FR Note 816; 27 p. April 1970.
CANNOT BE REFERENCED
AVAILABLE FROM: BRE, Fire Information Services, BRE Library, Garston, Watford, Herts WD2 7JR, UNITED KINGDOM. Telephone: 44-1923-664069, Fax: 44-1923-664910, Email: library@bre.co.uk Website: http://www.bre.co.uk

Bletzacker, R. W.
Fire Resistance of Protected Steel Beam Floor and Roof Assemblies as Affected by Structural Restraint.
Ohio State Univ., Columbus
Fire Test Methods: Restraint and Smoke Proceedings spronsored by American Society for Testing and Materials. ASTM STP 422. Annual Meeting, 69th. June 26-July 1, 1966, Atlantic City, NJ, ASTM, Philadelphia, PA, 63-90 pp, 1967.

Cooke, G. M. E.; Lawson, R. M.; Newman, G. M.
Fire Resistance of Composite Deck Slabs.
Fire Research Station, Borehamwood, England
Steel Construction Institute, England
Structural Engineer, Vol. 66, No. 16, 253-261, August 16, 1988.

Fellinger, J. H. H.; Twilt, L.
Fire Behavior of Long Span Composite Floor.
TNO Institute for Building Materials and Construction, Delft, The Netherlands
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 1093-1104 pp, 1997.

Kodur, V. K. R.
Fire Performance of High-Strength Concrete Structural Members.
National Research Council of Canada, Ottawa, Ontario
Construction Technology Update, No. 31, 1-4, 1999.
FOR MORE INFORMATION CONTACT: National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, K1A 0R6, Telephone (613) 993-2607, Fax: (613) 952-7673, Email: Irc.Client-Services@nrc.ca **Website: http://www.nrc.ca/irc/ircpubs --OR-- http://irc.nrc-cnrc.gc.ca/catalogue/ctu.html**
DOWNLOAD THE FULLTEXT (Construction Technology Update No. 31): http://irc.nrc-cnrc.gc.ca/ctus/31.html

Pearce, N. S.; Stanzak, W. W.
Load and Fire Test Data on Steel-Supported Floor Assemblies.
Underwriters Laboratories of Canada, Scarborough
National Research Council of Canada, Ottawa, Ontario
Fire Test Methods: Restraint and Smoke Proceedings sponsored by American Society for Testing and Materials. ASTM STP 422. Annual Meeting, 69th. June 26-July 1, 1966, Atlantic City, NJ, ASTM, Philadelphia, PA, 5-20 pp, 1967.

Wade, C. A.
Performance of Concrete Floors Exposed to Real Fires.
Building Research Association of New Zealand, Poriua
Journal of Fire Protection Engineering, Vol. 6, No. 3, 113-124, 1994.

Woodside, A.; deRuiter, J. J.; Wade, C. A.
Fire Resistance of New Zealand Concretes. Part 1. Study Report.
Building Research Association of New Zealand, Judgeford
BRANZ Study Report SR34; 70 p. February 1991.

Gypsum-Protected Steel Stud Walls

Alfawakhiri, F.; Sultan, M. A.
Fire Resistance of Load-Bearing Steel-Stud Walls Protected With Gypsum Board.
Canadian Steel Construction Council, Canada
National Research Council of Canada, Ottawa, Ontario
Fire and Materials. 6th International Conference and Exhibition. Proceedings. Interscience Communications Limited. February 22-23, 1999, San Antonio, TX, 235-246 pp, 1999.

Alfawakhiri, F.; Sultan, M. A.; MacKinnon, D. H.
Fire Resistance of Loadbearing Steel-Stud Walls Protected With Gypsum Board: A Review.
Canadian Steel Construction Council, Ontario, Canada
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 35, No. 4, 308-335, 4th Quarter, November 1999.

Alfawakhiri, F.; Sultan, M. A.; Kodur, V. K. R.
Loadbearing LSF Walls Exposed to Standard Fire.
Canadian Steel Construction Council, Toronto, Canada
National Research Council of Canada, Ottawa, Ontario
NRCC-43707;
Structural Speciality Conference of the Canadian Society for Civil Engineering (CSCE), 3rd.
Proceedings. June 7-10, 2000, London, Ontario, 114-121 pp, 2000.

American Iron and Steel Institute
Fire-Resistance Ratings of Load-Bearing Steel Stud Walls With Gypsum Wallboard Protection With or Without Cavity Insulation.
American Iron and Steel Inst., Washington, DC
AISI FT-901-0481-16M-R1; 4 p. 1981.

Andersson, L.
Fire Resistance of Partition Walls. Modified Addition-Method. [Avskiljande vaggars brandmotstand. Additionsmetod.
LA 90:02; 32 p. May 1990.

Clancy, P.
Parametric Study on the Time-to-Failure of Wood Framed Walls in Fire.
Victoria University of Technology, Australia
Fire Technology, Vol. 38, No. 3, 243-269, 3rd Quarter/July 2002.

Jones, B.
Performance of Gypsum Plasterboard Assemblies Exposed to Real Building Fires.
University of Canterbury, Christchurch, New Zealand

Fire Engineering Research Report 01/4; 174 p. March 2001.
For more information contact: School of Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand. Telephone: 643-364-2250, Fax: 643-364-2758, Website: http://www.civil.canterbury.ac.nz
http://www.civil.canterbury.ac.nz

Kodur, V. K. R.; Benichou, N.; Sultan, M. A.
Behavior of Load-Bearing Wood-Stud Shear Walls Exposed to Fire.
National Research Council of Canada, Ottawa, Ontario
NRCC 44519;
Interscience Communications Ltd.; Building Research Establishment; National Fire Protection Association; National Institute of Standards and Technology; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute. **Interflam '2001.** International Interflam Conference, 9th Proceedings. Volume 2. September 17-19, 2001, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1369-1374 pp, 2001.
For more information contact: National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, K1A 0R6, Telephone (613) 993-2607, Fax: (613) 952-7673, Email: Irc.Client-Services@nrc.ca, Website: http://www.nrc.ca/irc/fulltext/prac/nrcc44519

Kodur, V. K. R.; Sultan, M. A.
Factors Influencing Fire Resistance of Load-bearing Steel Stud Walls.
Michigan State Univ., East Lansing, MI
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 42, No. 1/1st Quarter, 5-26, January 2006.

Kodur, V. R.; Sultan, M. A.
Factors Governing Fire Resistance of Loadbearing Steel Stud Walls.
National Research Council of Canada, Ottawa, Ontario
NRCC 45211;
FOR MORE INFORMATION CONTACT: National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, K1A 0R6, Telephone (613) 993-2607, Fax: (613) 952-7673, Email: Irc.Client-Services@nrc.ca **Full Document in PDF - Website: http://irc.nrc-cnrc.gc.ca/fulltext/nrcc45211/**

Kodur, V.
Results of Fire-Resistance Testing on Wall Assemblies Will Provide Housing Industry With Important New Information.
Construction Innovation, Vol. 7, No. 2, 6-7, June 2002.
FOR MORE INFORMATION CONTACT: National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, K1A 0R6, Telephone (613) 993-2607, Fax: (613) 952-7673, Email: Irc.Client-Services@nrc.ca **Website: http://irc.nrc-cnrc.gc.ca/newsletter/v7no2/ resistance[underscore]e.html**
FOR MORE INFORMATION CONTACT: Dr. Venkatesh Kodur, Telephone 613-993-9729, Fax: 613-954-0483, Email: venkatesh.kodur@nrc.ca
Kodur, V. K. R.; Sultan, M. A.; Alfawakhiri, F.
Fire Resistance Tests on Loadbearing Steel Stud Walls.
National Research Council of Canada, Ottawa, Ontario
Canadian Steel Construction Council, Toronto, Canada
International Conference on Fire Research and Engineering (ICFRE3), Third (3rd). Proceedings. Society of Fire Protection Engineers (SFPE), National Institute of Standards and Technology (NIST) and International Association of Fire Safety Science (IAFSS). October 4-8, 1999, Chicago, IL, Society of Fire Protection Engineers, Boston, MA, 275-286 pp, 1999.

Konig, J.
Fire Tests of Load Carrying Timber Frame Assemblies Exposed to Standard and Parametric Fires.
Tratek-Swedish Institute for Wood Technology Research, Stockholm, Sweden
Fire and Materials '98 International Conference, 5th. Proceedings. Interscience Communications Ltd. February 23-24, 1998, San Antonio, TX, Interscience Communications Ltd., London, England, 65-76 pp, 1998.

Manzello, S. L.; Gann, R. G.; Kukuck, S. R.; Prasad, K.; Jones, W. W.
Real Fire Performance of Partition Assemblies.
National Institute of Standards and Technology, Gaithersburg, MD
Fire and Materials, Vol. 29, No. 6, 351-366, November/December 2005.
http://fire.nist.gov/bfrlpubs/fire05/PDF/f05112.pdf

Mehaffey, J. R.; Sultan, M. A.
Heat-transfer Through Wood-Stud Wall Assemblies Exposed to Fire.
Forintex Canada Corp.
National Research Council of Canada, Ottawa, Ontario
Wisconsin-Madison Univ., Madison, WI
Interscience Communications Limited. Fire and Materials. International Conference, 1st. September 24-25, 1992, Arlington, VA, 247-251 pp, 1992.

Ostman, B.; Konig, J.; Noren, J.
Contribution to Fire Resistance of Timber Frame Assemblies by Means of Fire Protective Boards.
Swedish Institute for Wood Technology Research, Sweden
Interscience Communications Limited. Fire and Materials. 3rd International Conference and Exhibition. October 27-28, 1994, Arlington, VA, 1-10 pp, 1994.

Richardson, L. R.; Batista, M.
Revisting the Component Additive Method for Light-Frame Walls Protected by Gypsum Board.
Forintek Canada Corp., Ottawa
Fire and Materials, Vol. 21, No. 3, 107-114, May/June 1997.

Richardson, L. R.
Thoughts and Observations on Fire-endurance Tests of Wood-Frame Assemblies Protected by Gypsum Board.
Forintek Canada Corp., Sainte-Foy, Canada
Fire and Materials, Vol. 25, No. 6, 223-239, November/December 2001.

Son, B. C.; Shoub, H.
Fire Endurance Tests of Double Module Walls of Gypsum Board and Steel Studs. Final Report.
National Bureau of Standards, Gaithersburg, MD
Department of Housing and Urban Development, Washington, DC
NBSIR 73-173; 32 p. April 1973.
Available from National Technical Information Service
COM-73-10844

Sultan, M. A.
Fire Resistance Tests on Full-Scale, Insulated and Non-Insulated, Gypsum-Board-Protected Wall Assemblies.
Fire Research News, No. 73, 1-3, Summer 1994.

Sultan, M. A.; Lougheed, G. D.
Effect of Insulation on the Fire Resistance of Small-Scale Gypsum Board Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
Interscience Communications Limited. Fire and Materials. 3rd International Conference and Exhibition. October 27-28, 1994, Arlington, VA, 11-20 pp, 1994.

Sultan, M. A.; Lougheed, G. D.; Denham, E. M. A.
Temperature Measurements in Fire Resistance Tests on Small-Scale Gypsum Wallboard Assemblies
With and Without Resilient Channels.
National Research Council of Canada, Ottawa, Ontario
Internal Report No. 655; 79 p. December 1993.

Sultan, M. A.; Lougheed, G. D.; Monette, R. C.; MacLaurin, J. W.; Denham, M.
Temperature Measurements in Full-Scale Insulated Gypsum Board-Protected Wall Assemblies With
Resilient Channels.

National Research Council of Canada, Ottawa, Ontario
Internal Report No. 676; IRC-IR-676; 119 p. December 1994.

Sultan, M. A.; MacLaurin, J. W.; Denham, M.; Monette, R. C.
Temperature Measurements in Full-Scale Insulated and Non-Insulated (1x2) Gypsum Board Protected Wall Assemblies With Steel Studs.
National Research Council of Canada, Ottawa, Ontario
Internal Report No. 675; IRC-IR-675; 66 p. December 1994.

Sultan, M. A.; Lougheed, G. D.; Denham, M.; Monette, R. C.; MacLaurin, J. W.
Temperature Measurements in Full-Scale Fire Resistance Tests on Non-Insulated Regular GypsumBoard Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
Internal Report No. 674; IRC-IR-674; 112 p. December 1994.

Sultan, M. A.
Effect of Gypsum Board Density and Glass Fibre in Gypsum Board Core on the Fire Resistance of Lightweight Frame Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
Interscience Communications Limited. Fire and Materials. 4th International Conference and Exhibition. Proceedings. November 15-16, 1995, Crystal City, VA, 115-123 pp, 1995.

Sultan, M. A.; Kodur, V. K. R.; Richardson, L. R.; McPhee, R. A.
Fire Resistance of Lightweight Frame Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
Forintek Canada Corp., Sainte-Foy, Canada
Canadian Wood Council, Canada
NRCC 41363;
Japan/Canada Housing R&D Workshop, 4th. Proceedings. 1997, Sapporo, Japan, III/50-56 pp, 1997.

Thomas, R.; Sultan, M.; Latour, J.
Impact of The Variability of Type X Gypsum Board.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials 2005. 9th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 31-February 1, 2005, San Francisco, CA, Interscience Communications Limited, London, England, 131-137 pp, 2005.

MODELING

Franssen, J. M.; Schleich, J. B.; Cajot, L. G.; Talamona, D.; Zhao, B.; Twilt, L.; Both, K.
Comparison Between Five Structural Fire Codes Applied to Steel Elements.
University of Liege, Belgium
ProfilARBED-Recherches, Luxembourg
CTICM, St. Remy-Les-Chevreuse
T.N.O., Rijkswijk, Netherland
International Association for Fire Safety Science. Fire Safety Science. Proceedings. 4th International Symposium. July 13-17, 1994, Ottawa, Ontario, Canada, Intl. Assoc. for Fire Safety Science, Boston, MA, Kashiwagi, T., Editor, 1125-1136 pp, 1994.

Mason, J. E.
Heat-transfer Progrms for the Design of Structures Exposed to Fire.
University of Canterbury, Christchurch, New Zealand
Fire Engineering Research Report 00/9; 86 p. March 2000.
For more information contact: School of Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand. Telephone: 643-364-2250, Fax: 643-364-2758, Website: http://www.civil.canterbury.ac.nz
http://www.civil.canterbury.ac.nz

Material Properties

Abrams, M. A.; Cruz, C. R.
Behavior at High Temperature of Steel Strand for Prestressed Concrete.
Portland Cement Assoc., Skokie, IL
Journal of the PCA Research and Development Laboratories, Vol. 3, No. 3, 8-19, September 1961.

Abrams, M. S.
Compressive Strength of Concrete at Temperatures to 1,600 F. PCA Research and Development Bulletin.
Portland Cement Association, Skokie, IL
Bulletin RD016.01T; PCA R/D Ser. 1387-1; ACI SP-25; 11 p. 1973.

Abrams, M. S.
Behavior of Inorganic Materials in Fire.
ASTM STP 464; ASTM STP 685;
National Fire Protection Association. Fire Protection Structure and Systems Design. Open Learning Fire Service Program. 65-115 pp, 1982 **AND** American Society for Testing and Materials. Fire Test Performance. ASTM STP 464. Smith, E. E. and Harmathy, T. Z. Editor(s), 14-75 pp, 1970 **AND** American Society for Testing and Materials. Design of Buildings for Fire Safety. Symposium Sponsored by ASTM Committee E05 on Fire Standards. ASTM STP 685. June 27, 1978, TH1092.S95 1979, Boston, MA, ASTM, Philadelphia, PA, Smith, E. E. and Harmathy, T. Z. Editor(s), 14-75, 1979, 1982.

Anderberg, Y.
Properties of Materials at High Temperatures Steel.
Lund Institute of Technology, Sweden
CIB W14/88/27 (S); LUTVDG/TVBB-3008; 171 p. February 1983.

Anderberg, Y.
Behavior of Steel at High Temperatures.
Lund Institute of Technology, Sweden
RILEM-COMMITTEE 44-PHT; CIB W14/82/44 (S); 104 p. February 1983.

Anderberg, Y.
Mechanical Behavior at Fire of Concrete and Hyperstatic Concrete Structures.
Lund Institute of Technology, Sweden
Bulletin 56; 9 p. September 1976.

Anderberg, Y.; Thelanderson, S.

Constitutive Law for Concrete at Transient High Temperature Conditions.
Lund Institute of Technology, Sweden
CIB W14/79/35 (S); ACI Publication SP 55-8; Bulletin 65;
American Concrete Institute. Analytical Design of Fire Exposed Concrete Structures. Douglas McHenry International Symposium. ACI Publication SP-55. Bulletin 65. October 1976, Mexico City, Mexico, American Concrete Institute, Detroit, MI, 187-205 pp, 1976.

Anderberg, Y.; Thelandersson, S.
Stress and Deformation Characteristics of Concrete at High Temperatures. Part 2. Experimental Investigation and Material Behavior Model.
Lund Institute of Technology, Sweden
Bulletin 54; 84 p. August 1976.

Aschl, H.
Mechanical Properties of Mass-Concrete at Elevated Temperatures.
Aschl-Consult, Federal Republic of Germany
3rd International Conference on Mechanical Behavior of Materials. August 20-24, 1979, Cambridge, England, 1-10 pp, 1979.

Ashton, L. A.
Prestressed Concrete and High Temperatures.
Fire Research Station, Borehamwood, England
FR Note 72; 5 p. June 1953.

Baldwin, R.; North, M. A.
Stress-Strain Relationship for Concrete at High Temperatures.
Fire Research Station, Borehamwood, England
Magazine of Concrete Research, Vol. 25, No. 85, 208-212, December 1973.

Baldwin, R.; North, M. A.
Stress-Strain Curves of Concrete at High Temperature: A Review.
Fire Research Station, Borehamwood, England
FR Note 785; 11 p. October 1969.

Balendran, R. V.; Nadeem, A.; Maqsood, T.; Leung, H. Y.
Flexural and Split Cylinder Strengths of HSC at Elevated Temperatures.
City University of Hong Kong
Fire Technology, Vol. 39, No. 1 (1st Quarter), 47-61, January 2003.

Banovic, S. W.; McCowan, C. N.; Luecke, W. E.
Physical Properties of Structural Steels. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-3E; 162 p. September 2005.

Bankvall, C. G.
Heat-transfer in Fibrous Materials.
National Swedish Building Research, Stockholm
D4:1972; 69 p. 1972.

Becker, J.; Bizri, H.; Bresler, B.
FIRES-T: A Computer Program for the Fire Response of Structures-Thermal.
California Univ., Berkeley
National Science Foundation, Washington, DC
UCB FRG-74-1; 76 p. January 1974.

Benichou, N.; Sultan, M. A.
Thermal Properties of Components of Lightweight Wood-Framed Assemblies at Elevated Temperatures.
National Research Council of Canada, Ottawa, Ontario

Fire and Materials 2001. 7th International Conference and Exhibition. Proceedings. Interscience Communications Limited. January 22-24, 2001, San Antonio, TX, 447-458 pp, 2001.

Benichou, N.; Sultan, M. A.
Thermal Properties of Lightweight-Framed Construction Components at Elevated Temperatures.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 29, No. 3, 165-179, May/June 2005.

Bessey, G. E.
Investigations on Building Fires. Part 2. The Visible Changes in Concrete or Mortar Exposed to High Temperatures.
Fire Research Station, Borehamwood, England
Technical Paper 4; 16 p. 1950.

Cammerer, J. S.
Thermal Conductivity of Light-Weight Concretes Especially of Aerated and Foam Concretes.
Fortschritte und Forschungen im Bauwesen, Vol. B, No. 2, 74-79, 1942.
TT-319; 15 p. 1952.

Chang, W. T.; Wang, C. T.; Huang, C. W.
Concrete at Temperatures Above 100 deg C.
Yuan Christian Univ., Taiwan, Republic of China
Central Police Univ., Taiwan, Republic of China
national Science Council, Republic of China
Fire Safety Journal, Vol. 23, 223-243, 1994.

Concrete Construction
Designing Concrete Mixes for Increased Fire or Heat Resistance.
Concrete Construction, 403-405,407, August 1974

Cramer, S. M.; Friday, O. M.; White, R. H.; Sriprutkiat, G.
Mechanical Properties of Gypsum Board at Elevated Temperatures.
University of Wisconsin-Madison, WI
Forest Products Lab., Madison, WI
Fire and Materials 2003. 8th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 27-28, 2003, San Francisco, CA, 33-42 pp, 2003.
FOR MORE INFORMATION CONTACT: Interscience Communications Limited, West Yard House, Guildford Grove, Greenwich London, SE10 8JT, England. Telephone: +44 (0)20 8692 5050, Fax: +44 (0)20 8692 5155, Email: intercomm@dial.pipex.com, Website: http://www.intercomm.dial.pipex.com

Cramer, S. M.; Sriprutkiat, G.; White, R. H.
Engineering Analysis of Gypsum Board Ceiling Membranes at Elevated Temperatures.
University of Wisconsin-Madison, WI
USDA Forest Service Forest Products Laboratory, Madison, WI
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 173-182 pp, 2003.

Clifton, J. R.
Nondestructive Tests to Determine Concrete Strength: A Status Report. Final Report.
National Bureau of Standards, Washington, DC
NBSIR 75-729; July 1975.
Available from National Technical Information Service
PB-246858/5

Cooke, G. M. E.
Introduction to the Mechanical Properties of Structural Steel at Elevated Temperatures.
Fire Research Station, Borehamwood, England
Fire Safety Journal, Vol. 13, No. 1, 45-54, April 1988.

Cornish, R. C.; Stevens, A. G.; Skinner, D.

Short Term Creep and Tensile Data On AS A82 Wire. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/6; 49 p. January 19721.

Cruz, C. R.
Elastic Properties of Concrete at High Temperatures.
Portland Cement Assoc., Skokie, IL
Journal of the PCA Research and Development Laboratories, Vol. 8, No. 1, 37-45, January 1966.
Bulletin 191;

Cruz, C. R.
Apparatus for Measuring Creep of Concrete at High Temperatures.
Portland Cement Assoc., Skokie, IL
Journal of the PCA Research and Development Laboratories, Vol. 10, No. 3, 36-42, September 1968.
Bulletin 225;

Cruz, C. R.
Optical Method for Determining the Elastic Constants of Concrete.
Portland Cement Assoc., Skokie, IL
Journal of the PCA Research and Development Laboratories, Vol. 4, No. 2, 24-32, May 1962.
Bulletin 144;

Cruz, C. R.; Gillen, M.
Thermal Expansion of Portland Cement Paste, Mortar and Concrete at High Temperatures.
Portland Cement Assoc., Skokie, IL
Fire and Materials, Vol. 4, No. 2, 66-70, June 1980.

Dias, W. P. S.
Some Properties of Hardened Cement Paste and Reinforcing Bars Upon Cooling From Elevated Temperatures.
Moratuwa Univ., Sri Lanka
Fire and Materials, Vol. 16, No. 1, 29-35, January/March 1992.

Dotreppe, J. C.
Mechanical Properties of Quenched and Self-Tempered Reinforcing Steel at Elevated Temperatures Compared With Recommendations of Eurocode 2 - Part 1-2.
Universite de Liege, Belgium
Materials and Structures, Vol. 30, 430-438, August/September 1997.

Elmroth, A.
Thermal Conductivity of Very Thick Loose Fill Mineral Wool Insulation--Result of Field Measurements.
Royal Institute of Technology, Stockholm, Sweden
Swedish Council for Building Research and Building Materials and Building Technoloy. Building Physics in the Nordic Countries. Symposium and Day of Building Physics. August 24-27, 1987, Lund, Sweden, Swedish Council for Building Research, Stockholm, Kronvall, J., Editor, 43-50 pp, 1987.

Felicetti, R.; Gambarova, P. G.
Mechanical Properties of Siliceous HSC Subjected to High-Temperature Cycles.
Milan University of Technology, Italy
NIST SP 919; September 1997.
International Workshop on Fire Performance of High-Strength Concrete. Proceedings. Appendix B: Workshop Papers. B9. February 13-14, 1997, Gaithersburg, MD, Phan, L. T.; Carino, N. J.; Duthinh, D.; Garboczi, E., Editors, 149-153 pp, 1997.

Flynn, D. R.
Response of High Performance Concrete to Fire Conditions: Review of Thermal Property Data and Measurement Techniques.
MetSys Corp., Millwood, VA
National Institute of Standards and Technology, Gaithersburg, MD
NIST GCR 99-767; MetSys Report No. 98-01-101; 139 p. March 1999.

Gillen, M.
Short-Term Creep of Concrete at Elevated Temperatures.
Construction Technology Laboratories, Skokie, IL
National Bureau of Standards, Gaithersburg, MD
NBS GCR 82-407; 112 p. September 1982.
Available from National Technical Information Service
PB83-118117

Gillen, M.
Short-Term Creep of Concrete at Elevated Temperatures.
Portland Cement Assoc., Skokie, IL
Fire and Materials, Vol. 5, No. 4, 142-148, December 1981.

Groenhout, R.; Knight, D.; Skinner, D. H.
Steel Properties for Fire Resistance.
Melbourne Research Labs., Clayton, Australia
MRL 6/1; 84 p. 1969.

Guenther, D. A.; Goodwin, L. G.; Brininger, F. L.
Temperature Determination of a Fire From Mechanical Properties.
Ohio State Univ., Columbus
Fire Technology, Vol. 14, No. 1, 61-66, February 1978.

Guenther, D. A.; McGarry, D. L.; Shearer, R. P.; MacDleary, R. C.
Fire Analyses From Mechanical Properties.
Ohio State Univ., Columbus
Fire Technology, Vol. 12, No. 3, 173-185, August 1976.

Harada, T.
Thermal Expansion of Concrete at High Temperature.
Tokyo Institute of Technology, Meguro-ku
CIB CTF/67/26 (J); 26 p. 1967.

Harmathy, T. Z.; Berndt, J. E.
Hydrated Portland Cement and Lightweight Concrete at Elevated Temperatures.
National Research of Canada, Ottawa, Ontario
American Concrete Institute Journal, Vol. 63, No. 1, 93-112, January 1966.
Research Paper 280; NRC 8847;

Harmathy, T. Z.
Properties of Building Materials--Rapporteur's Report to the Meeting of CIB W14, Athens, Greece, May 1980.
National Research Council of Canada, Ottawa, Ontario
CIB W14/81/18 (C); 13 p. 1981.

Harmathy, T. Z.
Properties of Building Materials at Elevated Temperatures.
National Research Council of Canada, Ottawa, Ontario
CIB W14/82/07 (C); DBR Paper 1080; NRCC 20956; 67 p. March 1983.

Harmathy, T. Z.
Variable-State Methods of Measuring the Thermal Properties of Solids.
National Research Council of Canada, Ottawa, Ontario
Journal of Applied Physics, Vol. 35, No. 4, 1190-1200, April 1964.
NRC 8086; DBR Paper 221;

Harmathy, T. Z.; Allen, L. W.
Thermal Properties of Selected Masonry Unit Concretes.

National Research Council of Canada, Ottawa, Ontario
Journal of the American Concrete Institute, Vol. 70, 132-142, February 1973.
NRCC 13209; RP 562; April 1973.

Hertz, K. D.
Residual Properties of Concrete Heated Rapidly.
Technical Univ. of Denmark
ACI SP-92-8;
Evaluation and Repair of Fire Damage to Concrete, American Concrete Inst., Detroit, MI, Harmathy, T. Z., Editor, 143-152 pp, 1986.

Hertz, K. D.
Application of Idealized Materials Data for Calculation of Fire Exposed Concrete Constructions.
Technical University of Denmark
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 147-153 pp, 2003.

Houser, J. L.
Development of a Bench Test for Type X Core Gypsum Board. Final Report.
National Bureau of Standards, Gaithersburg, MD
NBSIR 74-588; 22 p. December 1974.

Houser, J. L.
Method and Apparatus for Fire Testing Gypsum Boards and the Like.
Department of Commerce, Washington, DC
Serial 503,129; 16 p. September 4, 1974.
Available from National Technical Information Service
COM-75-10153

Husem, M.
Effects of High Temperature on Compressive and Flexural Strengths of Ordinary and High-Performance Concrete.
Karadeniz Technical Univ., 61080 Trabzon, Turkey
Fire Safety Journal, Vol. 41, No. 2, 155-163, March 2006.

Jansson, R.
Measurement of the Thermal Properties at High Temperature.
SP Swedish National Testing and Research Institute, Boras, Sweden
Volume 1;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 1. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 181-187 pp, 2004.

Jensen, J. J.; Hammer, T. A.; Hansen, P. A.
Fire Resistance and Residual Strength of HSC Exposed to Hydrocarbon Fire.
SINTEF, Trondheim, Norway
NIST SP 919; September 1997.
International Workshop on Fire Performance of High-Strength Concrete. Proceedings. Appendix B: Workshop Papers. B2. February 13-14, 1997, Gaithersburg, MD, Phan, L. T.; Carino, N. J.; Duthinh, D.; Garboczi, E., Editors, 59-67 pp, 1997.

Jumppanen, U. M.; Diederichs, U.; Hinrichsmeyer, K.
Material Properties of F-Concrete at High Temperatures.
Technical Research Centre of Finland, Espoo
VTT Research Report 452; 60 p. November 1986.

Khoury, G. A.; Grainger, B. N.; Sullivan, P. J. E.
Strain of Concrete During First Cooling From 600 Deg. C Under Load. Transient Thermal Strain of Concrete During First Heating Cycle to 600 Deg. C.

Imperial College of Science and Technology, London, England
Central Electricity Research Labs., Surrey, England
Magazine of Concrete Research, Vol. 38, No. 134, 1-12, March 1986.
CIB W14/86/45 (UK);

Khoury, G. A.; Sullivan, P. J. E.
Research at Imperial College on the Effect of Elevated Temperatures on Concrete.
London Univ., England
Fire Safety Journal, Vol. 13, No. 1, 69-72, April 1988.

Kang, S. W.; Hong, S. G.
Behavior of Concrete Members at Elevated Temperatures Considering Inelastic Deformation.
Institute of Construction Technology
Seoul National Univ.
Fire Technology, Vol. 39, No. 1 (1st Quarter), 9-22, January 2003.

Kim, H.; Seo, C.; Shin, H.
Experimental Study on the Physical Properties by Compressive Strength Areas of Concrete at High Temperature.
KICT, Korea
Poster Session 32; PS 32;
Tall Buildings in Historical Cities: Culture and Technology for Sustainable Cities. Volume 2. Proceedings. Council on Tall Buildings and Urban Habitat (CTBUH) 2004 Seoul Conference. October 10-13, 2004, Seoul, Korea, Lee, L. H.; Klemencic, R.; Kim, S. D., Editors, 1096-1103 pp, 2004.

Kwon, Y. J.; Kim, M. H.; Kim, Y. R.; Jang, J. B.
Experimental Study on the Engineering Properties of Deteriorated Concrete by Fire Damage.
Hoseo Univ., Korea
Chungman National Univ.
TS 3-7-5 Fire Engineering (1);
Tall Buildings in Historical Cities: Culture and Technology for Sustainable Cities. Volume 1. Proceedings. Council on Tall Buildings and Urban Habitat (CTBUH) 2004 Seoul Conference. October 10-13, 2004, Seoul, Korea, Lee, L. H.; Klemencic, R.; Kim, S. D., Editors, 588-595 pp, 2004.

Kishitani, K.; Fujii, J.; Mori, M.
Study on the Physical Behavior of Cement Mortars Containing Organic Materials Under Heat.
Tokyo Univ., Japan
Paper 39;
[proceedings unknown], 136-140 pp, 1976.

Knight, D.; Skinner, D. H.; Lay, M. G.
Prediction of a Creep Equation of State From Isothermal Tests.
Melbourne Research Labs., Clayton, Australia
MRL 18/1; 43 p. July 1973.

Knight, D.; Skinner, D. H.; Lay, M. G.
Prediction of Isothermal Creep. Project 18. Fire Resistance of Steels--Engineering Aspects.
Melbourne Research Labs., Clayton, Australia
MRL 18/2; 57 p. April 1971.

Knight, D.
Anisothermal Behavior of a Tension Member. Project 18. Fire Resistance of Steels--Engineering Aspects.
Melbourne Research Labs., Clayton, Australia
MRL 18/4; 38 p. September 1971.

Kodur, V. K. R.; Sultan, M. A.
Effect of Temperature on Thermal Properties of High-Strength Concrete.
National Research Council of Canada, Ottawa, Ontario
Journal of Materials in Civil Engineering, Vol. 15, No. 2, 101-107, March/April 2003.

NRCC-44002;
http://irc.nrc-cnrc.gc.ca/fulltext/nrcc44002/
http://dx.doi.org/10.1061/(ASCE)0899-1561(2003)15:2(101)

Kokkala, M.; Baroudi, D.
Transient Symmetrical Method for the Measurement of Temperature Dependent Thermal Diffusivity.
VTT-Technical Research Center of Finland, Espoo
VTT Research Notes 1452; 26 p. 1993.

Lawson, J. R.; Phan, L. T.; Davis, F. L.
Mechanical Properties of High Performance Concrete After Exposure to Elevated Temperatures.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6475; 39 p. March 2000.

Lie, T. T.; Kodur, V. K. R.
Thermal and Mechanical Properties of Steel-Fibre-Reinforced Concrete at Elevated Temperatures.
National Research Council of Canada, Ottawa, Ontario
Canadian Journal of Civil Engineering, Vol. 23, No. 4, 511-517, 1996.
NRCC 39025;

Li, L.; Purkiss, J.
Stress-Strain Constitutive Equations of Concrete Material at Elevated Temperatures.
Aston Univ., Birmingham B4 7ET, UK
Fire Safety Journal, Vol. 40, No. 7, 669-686, October 2005.

Luecke, W. E.; McColskey, J. D.; McCowan, C. N.; Banovic, S. W.; Fields, R. J.; Foecke, T.; Siewert, T. A.; Gayle, F. W.
Mechanical Properties of Structural Steels. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-3D; 322 p. September 2005.

Lundkvist, A.; Martensson, U.; Persson, B.
Measurement of Thermal Diffusivity in Materials at High Temperatures. Nordtest Project No. 884-90.
Swedish National Testing and Research Institute, Boras, Sweden
SP REPORT 1991:53; CIB W14/92/15 (S); 30 p. 1991.

Malhotra, H. L.
Fire Behavior of Building Materials (2.3).
Fire Research Station, Borehamwood, England
BUILD International, 275-279, September/October 1971.

Malhotra, H. L.
Effect of Temperature on the Crushing Strength of Concrete.
Fire Research Station, Borehamwood, England
FR Note 130; 28 p. November 1954.

Malhotra, H. L.
Effect of Temperature on the Compressive Strength of Concrete.
Magazine of Concrete Research, Vol. 8, No. 23, 85-94, August 1956.

Menzel, C. A.
Tests of the Fire Resistance and Thermal Properties of Solid Concrete Slabs and Their Significance.
Portland Cement Assoc., San Ramon, CA
American Society for Testing Materials Proceedings. Volume 43. 1943, Philadelphia, PA, 1099-1153 pp, 1943.

Mori, M.
Study on High-Temperature Properties of Building Materials During Fire.
Tokyo Univ., Japan
; 1976.

Morita, T.; Schneider, U.; Franssen, J. M.
Influence of Stress History Function in the Schneider-Concrete-Model Under Fire Attack.
Shimizu Corp., Tokyo, Japan
Technical University of Vienna, Austria
University of Liege, Belgium
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 1057-1068 pp, 1997.

Nug, C. N.
Calcination of Gypsum Plasterboard Under Fire Exposure.
University of Canterbury, Christchurch, New Zealand
Fire Engineering Research Report 04/6; 127 p. May 2004.
http://www.civil.canterbury.ac.nz/fire/pdfreports/Chu04.pdf
http://www.civil.canterbury.ac.nz/fire/fe_resrch_reps.html

Outinen, J.; Makelainen, P.
Mechanical Properties of Structural Steel at Elevated Temperatures and After Cooling Down.
Constructional Steelwork Association FCSA, Finland
Helsinki University of Technology, Espoo, Finland
Fire and Materials, Vol. 28, No. 2/4, 237-251, March/August 2004.

Pettersson, O.
Practical Need of Scientific Material Models for Structural Fire Design--General Review.
Lund Univ., Sweden
Fire Safety Journal, Vol. 13, No. 1, 1-8, April 1988.
CIB W14/88/56 (S); LUTVDG/TVBB-3036;

Phan, L. T.
Fire Performance of High-Strength Concrete: A Report of the State-of-the-Art.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 5934; 115 p. December 1996.
Available from National Technical Information Service
PB97-132153

Phan, L. T.; Carino, N. J.
Review of Mechanical Properties of HSC at Elevated Temperature.
National Institute of Standards and Technology, Gaithersburg, MD
Journal of Materials in Civil Engineering, Vol. 10, No. 1, 58-64, February 1998.

Phan, L. T.; Peacock, R. D.
Experimental Plan for Testing the Mechanical Properties of High-Strength Concrete at Elevated Temperatures.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6210; 29 p. May 1999.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB98-156458

Phan, L. T.; Carino, N. J.
Fire Performance of High Strength Concrete: Research Needs.
National Institute of Standards and Technology, Gaithersburg, MD
Advanced Technology in Structural Engineering. ASCE/SEI Structures Congress 2000. Proceedings. May 8-10, 2000, Philadelphia, PA, Elgaaly, M., Editor, 2000.

Phan, L. T.; Lawson, J. R.; Davis, F. L.
Effects of Elevated Temperature Exposure on Heating Characteristics, Spalling, and Residual Properties of High Performance Concrete.
National Institute of Standards and Technology, Gaithersburg, MD

Materials and Structures, Vol. 34, 83-91, March 2001.

Phan, L. T.; Carino, N. J.
Mechanical Properties of High-Strength Concrete at Elevated Temperatures.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6726; 102 p. March 2001.

Phan, L. T.; Carino, N. J.
Effects of Test Conditions and Mixture Proportions on Behavior of High-Strength Concrete Exposed to High Temperature.
National Institute of Standards and Technology, Gaithersburg, MD
ACI Materials Journal, Vol. 99, No. 1, 54-66, January/February 2002.

Phan, L. T.
High-Strength Concrete at High Temperature: An Overview.
National Institute of Standards and Technology, Gaithersburg, MD
Utilization of High Strength/High Performance Concrete, 6th International Symposium. Proceedings. Volume 1. June 2002, Leipzig, Germany, Konig, G.; Dehn, F.; Faust, T., Editors, 501-518 pp, 2002.

Philleo, R.
Some Physical Properties of Concrete at High Temperatures.
Portland Cement Assoc., Skokie, IL
Journal of the American Concrete Institute Proceedings Volume 54, Vol. 29, No. 10, 857-865, April 1958.
Bulletin 97; Title No. 54-47;

Purkiss, J. A.
High Temperature Effects.
Aston Univ., Birmingham, England
Design of Structures Against Fire, Elsevier Applied Science Publishers, New York, Anchor, R. D.; Malhotra, H. L.; Purkiss, J. A., Editors, 41-51 pp, 1986.

Reichard, T. W.
Creep and Drying Shrinkage of Lightweight and Normal-Weight Concretes.
National Bureau of Standards, Washington, DC
NBS Monograph 074; March 4, 1964.
Available from National Technical Information Service
PB-195213

Ryan, J. V.
Study of Gypsum Plasters Exposed to Fire.
National Bureau of Standards, Washington, DC
Journal of Research of the National Bureau of Standards. C. Engineering and Instrumentation., Vol. 66C, No. 4, 373-387, October-December 1962.
Paper 66C4-113;

Schneider, U.
Concrete at High Temperatures--A General Review.
Kassel Univ., West Germany
Fire Safety Journal, Vol. 13, No. 1, 55-68, April 1988.

Schneider, U.
Modeling of Concrete Behavior at High Temperatures.
Kassel Univ., Germany
Design of Structures Against Fire, Elsevier Applied Science Publishers, New York, Anchor, R. D.; Malhotra, H. L.; Purkiss, J. A., Editors, 53-69 pp, 1986.

Schneider, U.
Properties of Materials at High Temperatures Concrete.
Bauingenieurwesen Universitat Gesamthochschule, Kassel, West Germany
CIB W14/85/25 (FRG); 131 p. 1985.

Schneider, U.
Behavior of Concrete Under Thermal Steady State and Non-Steady State Conditions.
Universitat Braunschweig, West Germany
Fire and Materials, Vol. 1, No. 3, 103-115, September 1976.

Schneider, U.; Schwesinger, P.; Debicki, G.; Diederichs, U.; Felicetti, R.; Franssen, J. M.; Furumura, F.; Jumppanen, U. M.; Khoury, G. A.; Millard, A.; Morris, W. A.; Phan, L. T.
Recommendations of TC 129-MHT: Test Methods for Mechanical Properties of Concrete at High Temperatures. Part 4. Tensile Strength for Service and Accident Conditions.
National Institute of Standards and Technology, Gaithersburg, MD
Materials and Structures, Vol. 33, No. 228, 219-223, May 2000.

Schneider, U.; Schwesinger, P.; Debicki, G.; Diederichs, U.; Felicetti, R.; Franssen, J. M.; Furumura, F.; Jumppanen, U. M.; Khoury, G. A.; Millard, A.; Morris, W. A.; Phan, L. T.
Recommendations of TC 129-MHT: Test Methods for Mechanical Properties of Concrete at High Temperatures. Part 9. Shrinkage for Service and Accident Conditions.
National Institute of Standards and Technology, Gaithersburg, MD
Materials and Structures, Vol. 33, No. 228, 224-228, May 2000.

Sheppard, D. T.
Test Method for the Determination of Temperature Dependent Thermal Properties of Fire Insulation Materials.
Worcester Polytechnic Inst., MA
Thesis; 183 p. November 1992.

Sheppard, D. T.; Gandhi, P. D.
Development of a Transient Method of Determining Thermal Properties.
Underwriters Laboratories, Inc., Northbrook, IL
Interscience Communications Limited. Fire and Materials. International Conference, 2nd. September 23-24, 1993, Arlington, VA, 67-77 pp, 1993.

Skinner, D. H.; Stevens, A. G.; Marks, G. L.
Fire Resistance Properties of Three Steels. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/9; 40 p. March 1973.

Skinner, D. H.; Knight, D. C.
Elevated Temperature Tensile Properties of AS A151. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/7; 21 p. October 1971.

Skinner, D. H.
Measurement of High Temperature Properties of Steel. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/10; 63 p. May 1972.

Skinner, D. H.
Mechanical Behavior of Steel During Fires. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 006/75/013; 161 p. November 1974.

Skinner, D. H.; Cornish, R. C.; Toyama, M.
Parameters for Short-Term and Anisothermal Creep. Project 6. Fire Resistance of Steels--High

Temperature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/12; 98 p. April 1973.

Spacek, L.; Toman, J.
Determination of Coefficients of Thermal Conductivity of Building Materials in Dependence on the Temperature to 1000 Deg Centigrate.
Czechoslovak Technical Univ., Praha
CIB W14/81/17 (CZ); 12 p. 1981.

Steel Construction Institute
Experimental Data Relating to the Performance of Steel Components at Elevated Temperatures. Work Package No. FR1.
Steel Construction Inst., UK
FR1; 81 p. April 1991.

Stevens, A. G.; Cornish, R. C.; Skinner, D.
Tensile Data on Four Structural Steels. Project 6. Fire Resistance of Steels--High Temeprature Mechanical Properties.
Melbourne Research Labs., Clayton, Australia
MRL 6/5; 56 p. November 1971.

Sullivan, P. J. E.; Thiruchelvam, C.
High Strength Plastic Concrete at Elevated Temperature.
City Univ., London, England
Journal of Applied Fire Science, Vol. 9, No. 2, 113-12, 1999-2000.

Sullivan, P. J. E.; Sharshar, R.
Performance of Concrete at Elevated Temperatures (As Measured by the Reduction in Compressive Strength).
Sullivan and Associates, Richmansworth, England
Imperial College, London, England
Fire Technology, Vol. 28, No. 3, 240-250, August 1992.

Sullivan, P. J. E.; Khoury, G. A.
Fire Performance of Various Concretes Deduced From Strain Measurements During First Heating.
Imperial College
ACI SP-92-10;
Evaluation and Repair of Fire Damage to Concrete, American Concrete Inst., Detroit, MI, Harmathy, T. Z., Editor, 175-196 pp, 1986.

Suter, G. T.
Can Extremely Green Concrete Withstand Fire With Minor Damange?
Carleton Univ., Ottawa, Canada
Fire Safety of Concrete Structures. ACI Committee 216. September 1980, San Juan, Pureto Rico, Abrams, M. S., Editor, 255-268 pp, 1983.

Thelandersson, S.
Mechanical Behavior of Concrete Under Torsional Loading at Transient, High-Temperature Conditions.
Lund Institute of Technology, Sweden
Bulletin 46; 81 p. November 1974.

Thomas, G.
Thermal Properties of Gypsum Plasterboard at High Temperatures.
Victoria University of Wellington, Wellington, New Zealand
Fire and Materials, Vol. 26, No. 1, 37-45, January/February 2002.

Tomasson, B.
High Performance Concrete Exposed to Fire Material Properties and Design Guide Lines.
Fire Safety Design AB, Lund, Sweden
Volume 2;

Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. **Interflam 1999. (Interflam '99).** International Interflam Conference, 8th Proceedings. Volume 2. June 29-July 1, 1999, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 915-926 pp, 1999.

Wang, Y. C.; Wong, P. M. H.; Kodur, V.
Mechanical Properties of Fibre Reinforced Polymer Reinforcing Bars at Elevated Temperatures.
University of Manchester, UK
National Research Council of Canada, Ottawa, Ontario
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 183-192 pp, 2003.

Williams-Leir, G.
Creep of Structural Steel in Fire: Analytical Expressions.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 7, No. 2, 73-78, June 1983.
NRCC 22572; DBR Paper 1121;

Williamson, R. B.; Rashed, A. I.
High Strength Concrete and Mortars in High Temperature Environments.
California Univ., Berkeley
Energy Department, Washington, DC
CIB W14/86/28 (USA);
Materials Research Society Symposium Proceedings, Vol. 42, 1985, 295-303 pp, 1985.

Xiao, J.; Koning, G.
Study on concrete at High Temperature in China: An Overview.
Tongji University, Shanghai 200092, China
Leipzig University, Leipzig 04109, Germany
Fire Safety Journal, Vol. 39, No. 1, 89-103, February 2004.

Xiao, J.; Xie, M.; Zhang, C.
Residual Compressive Behavior of Pre-Heated High-Performance Concrete With Blast-Furnace-Slag.
Tongji Univ., Shanghai 200092, PR China
Siegen Univ., Germany
Fire Safety Journal, Vol. 41, No. 2, 91-98, March 2006.

Xiao, J.; Falkner, H.
On Residual Strength of High-Performance Concrete With and Without Polypropylene Fibers at Elevated Temperatures.
Tongji Univ., Shanghai 200092, PR China
Institute of Building Materials, 38106 Braunschweig, Germany
Fire Safety Journal, Vol. 41, No. 2, 115-121, March 2006.

Zhukov, V. V.; Gusev, A. A.
Mechanical and Structural Characteristics of Concrete After Exposure of Load and High Temperature.
CIB W14/86/36 (USSR); 8 p. 1986.

Spalling of Concrete

Ahmed, G. N.; Hurst, J. P.
Analytical Approach for Investigating the Causes of Spalling of High-Strength Concrete at Elevated Temperatures.
Portland Cement Assoc., Skokie, IL
NIST SP 919; September 1997.
International Workshop on Fire Performance of High-Strength Concrete. Proceedings. Appendix B: Workshop Papers. B6. February 13-14, 1997, Gaithersburg, MD, Phan, L. T.; Carino, N. J.; Duthinh, D.; Garboczi, E., Editors, 95-108 pp, 1997

Akhtaruzzaman, A. A.; Sullivan, P. J. E.
Explosive Spalling of Concrete Exposed to High Temperature.
Imperial College of Science and Technology, London, England
CSTR 70/2; 34 p. December 1970.

Ali, F.
Is High Strength Concrete More Susceptible to Explosive Spalling than Normal Strength Concrete in Fire?
University of Ulster, Jordanstown, UK
Fire and Materials, Vol. 26, No. 3, 127-130, May/June 2002.

Ali, F. A.; Connolly, R.; Sullivan, P. J. E.
Spalling of High Strength Concrete at Elevated Temperatures.
Ulster Univ., Jordanstown, Northern Ireland
Late Building Research Establishment, Garston, UK
City Univ., London, England
Journal of Applied Fire Science, Vol. 6, No. 1, 3-14, 1996/1997.

Ali, F. A.; Connolly, R.; Sullivan, P. J. E.
Spalling of High Strength Concrete at Elevated Temperatures.
Chapter 10;
Behavior of Glass and Other Materials Exposed to Fire. Volume 1. Chapter 10. Applied Fire Science in Transition Series, Baywood Publishing Co. Inc., Amityville, NY, DeCicco, P. R., Editor(s), 153-163 p., 2002.

Anderberg, Y.
Spalling Phenomena of HPC and OC.
NIST SP 919; September 1997.
International Workshop on Fire Performance of High-Strength Concrete. Proceedings. Appendix B: Workshop Papers. B3. February 13-14, 1997, Gaithersburg, MD, Phan, L. T.; Carino, N. J.; Duthinh, D.; Garboczi, E., Editors, 69-73 pp, 1997.

Beland, B.
Spalling of Concrete.
Sherbrooke Univ., Canada
Fire and Arson Investigator, Vol. 44, No. 1, 26-31, September 1993

Bilodeau, A.; Kodur, V. K. R.; Hoff, G. C.
Optimization of the Type and Amount of Polypropylele Fibers for Preventing the Spalling of Lightweight Concrete Subjected to Hydrocarbon Fire.
National Research Council of Canada, Ottawa, Ontario
Cement and Concrete Composites, Vol. 26, No. 2, 163-174, February 2004.
NRCC-45687;

Bostrom, L.
Methodology For Measurement Of Spalling Of Concrete.
SP Swedish National Testing and Research Institute, Boras, Sweden
Fire and Materials 2005. 9th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 31-February 1, 2005, San Francisco, CA, Interscience Communications Limited, London, England, 121-129 pp, 2005.

Bostrom, L.
Spalling of Concrete When Exposed to Fire.
SP Swedish National Testing and Research Institute, Boras, Sweden
Strategies for Performance in the Aftermath of the World Trade Center. CIB-CTBUH Conference on Tall Buildings. Proceedings. Task Group on Tall Buildings: CIB TG50. CIB Publication No. 290. October 20-23, 2003, Kuala Lumpur, Malaysia, Shafii, F.; Bukowski, R.; Klemencic, R., Editors, 631-638 pp, 2003.

Canfield, D. V.
Causes of Spalling Concrete at Elevated Temperatures.
University of Southern Mississippi, Hattisburg

Fire and Arson Investigator, Vol. 34, No. 4, 22-23, June 1984.

Connolly, R.
Spalling of Concrete.
Fire Engineers Journal, Vol. 57, No. 186, 38-40, January 1997.
European Symposium on Fire Safety Science, First (1st). **ABSTRACTS**. Proceedings. Session III. Structures 3. ETH Institute for Structural Engineering. August 21-23, 1995, Zurich, Switzerland, III-12/137-138 pp, 1997.

Copier, W. J.
Spalling of Normal Weight and Lightweight Concrete Exposed to Fire.
IBBC-Instituto T.N.O. for Building Materials and Building Structures, Rijswijk (ZH), The Netherlands
Fire Safety of Concrete Structures. ACI Committee 216. September 1980, San Juan, Puerto Rico, Abrams, M. S., Editor, 219-236 pp, 1983.

Copier, W. J.
Spalling of Normalweight and Lightweight Concrete on Exposure to Fire.
Instituut TNO Voor Bouwmaterialen en Bouwconstructies, Delft, The Netherlands
; 94 p. 1979.

Diederichs, U.; Jumppanen, U. M.; Schneider, U.
High Temperature Properties and Spalling Behavior of High Strength Concrete.
Institut fur Baustoffe, Braunschweig
VTT-Technical Research Center of Finland, Espoo
Institut fur Baustofflehre, Wien
High Performance Concrete: Material Properties and Design, 4th Weimar Workshop. Proceedings. October 4-5, 1995, Weimar, Germany, Wittmann, F. H.; Schwesinger, P., Editors, 219-235 pp, 1995.

Hertz, K. D.
Limits of Spalling of Fire-Exposed Concrete.
Technical University of Denmark, Lyngby
Fire Safety Journal, Vol. 38, No. 2, 103-116, March 2003.

Hertz, K. K.; Sorensen, L. S.
Test Method for Spalling of Fire Exposed Concrete.
Technical University of Denmark, DK-2800 Kgs. Lyngby
Fire Safety Journal, Vol. 40, No. 5, 466-476, July 2005.

Harada, K.; Negishi, K.
Spalling of Cement Mortar During Fire.
Building Research Institute, Ibaraki, Japan
Kyoto Univ., Japan
Modeling of Deterioration in Composite Building Components Due to Heat and Mass Transfer Workshop. Proceedings. Building Research Institute (BRI) Proceedings No. 6. January 22-23, 1998, Tsukuba, Japan, 171-185 pp, 1998.

Inwood, M.
Review of the New Zealand Standard for Concrete Structures (NZS 3101) for High Strength and Lightweight Concrete Exposed to Fire.
University of Canterbury, Christchurch, New Zealand
Fire Engineering Research Report 99/10; 78 p. March 1999.

Kishitani, K.; Mori, M.
Study on Influence of Popping of Aggregates on Fire Resistance of Concrete.
Tokyo Univ., Japan
Journal of the Faculty of Engineering, The University of Tokyo (B), Vol. 33, No. 1, 45-103, 1975.

Kodur, V. K. R.
Spalling in High Strength Concrete Exposed to Fire: Concerns, Causes, Critical Parameters and Cures.
National Research Council of Canada, Ottawa, Ontario

NRCC 43412;
ASCE Structures Congress 2000. 2000, Philadelphia, PA, 1-9 pp, 2000.

Lima, R. C. A.; Silva, F.; Gastal, F. P. S. L.
Investigation of Spalling in High Performance Concrete.
Federal University of Brazil, Rio Grande do Sul
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 154-162 pp, 2003.

Malhotra, H. L.
Spalling of Concrete in Fires. Technical Note 118.
Fire Research Station, Borehamwood, England
Construction Industry Research and Information Assoc., London, England
Technical Note 118; 36 p. 1984.

Meyer-Ottens, C.
On the Problem of Spalling of Concrete Structural Components Under Fire-Induced Stress.
Foreign Technology Div., Wright-Patterson AFB, OH
FTD-ID(RS)T-0392-90; 89 p. June 1990.
Available from National Technical Information Service
AD/B-146777

Meyer-Ottens, C.
Behavior of Concrete Structural Elements in Fires, Spalling of Normal Concrete Elements Under Fire Stress; Causes and Preventive Measures.
Building Research Establishment, Watford, England
Library Translation 2058; 15 p. December 1977.

Midkiff, C. R., Jr.
Spalling of Concrete as an Indicator of Arson--Let's Look at the Concrete Before We Decide.
Fire and Arson Investigator, Vol. 41, No. 2, 42-44, December 1990.

Morita, T.; Nishida, A.; Yamazaki, N.; Schneider, U.; Diederichs, U.
Experimental Study on Spalling of High Strength Concrete Elements Under Fire Attack.
Shimizu Corp., Tokyo, Japan
Vienna University of Technology, Austria
University of Rostock, Wismar, Germany
Fire Safety Science. Proceedings. Sixth (6th) International Symposium. International Association for Fire Safety Science (IAFSS). July 5-9, 1999, Poitiers, France, Intl. Assoc. for Fire Safety Science, Boston, MA, Curtat, M., Editor, 855-866 pp, 2000.

Nasri, V.; Fauvel, P.
Numerical Simulation of Concrete Spalling in Tunnel Liner Due To Fire.
STV Incorporated
SNCF, USA
Tunnel Fires and Escape From Tunnels, 3rd International Conference. Organised and Sponsored by Tunnel Management International. Proceedings. October 9-11, 2001, Washington, DC, 167-176 pp, 2001.

Noumowe, N. A.; Clastres, P.
Experimental and Numerical Contributions to Explanation of Concrete Spalling.
INSA de Lyo, France
Modeling of Deterioration in Composite Building Components Due to Heat and Mass Transfer Workshop. Proceedings. Building Research Institute (BRI) Proceedings No. 6. January 22-23, 1998, Tsukuba, Japan, 151-167 pp, 1998.

Phan, L. T.; Lawson, J. R.; Davis, F. L.
Heating, Spalling Characteristics and Residual Properties of High Performance Concrete.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6588; November 2000.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 15th Joint Panel Meeting. Volume 2. Proceedings. March 1-7, 2000, San Antonio, TX, Bryner, S. L., Editor, 389-398 pp, 2000.

Saito, H.
Explosive Spalling of Prestressed Concrete in Fire.
Building Research Inst., Tokyo, Japan
BRI Occasional Report No. 22; 18 p. June 1965.

Sarvaranta, L.; Elomaa, M.; Jarvela
Study of Spalling Behavior of PAN Fiber-Reinforced Concrete by Thermal Analysis.
VTT-Technical Research Center of Finland, Espoo
Helsinki Univ., Finland
Jyväskylä Univ., Finland
Fire and Materials, Vol. 17, No. 5, 225-230, September/October 1993.

Shamalta, M.; Breunese, A.; Peelen, W.; Fellinger, J.
Numerical Modeling and Experimental Assessment of Concrete Spalling in Fire.
TNO Centre for Fire Research, Delft, The Netherlands
TNO Civil Infrastructure, Delft, The Netherlands
Fire Safety (Special Issue), Vol. 50, No. 4, 303-319, 2005.

Smith, F. P.
Concrete Spalling Under Controlled Conditions.
Alabama Univ., Birmingham
Fire and Arson Investigator, Vol. 32, No. 2, 38-39, October/December 1981.

Tovey, A. K.
Evidence to Support Calculation Methods for Predicting the Fire Resistance of Concrete Structures.
Cement and Concrete Assoc., Wexham Springs, England
Fire Research Station. International Seminar on Three Decades of Structural Fire Safety. Organized by Bill Malhotra on the Occasion of His Retirement. February 22-23, 1983., Borehamwood, England, 299-312 pp, 1983.

Modeling Studies

Ahmed, G. N.; Hurst, J. P.
Modeling the Thermal Behavior of Concrete Slabs Subjected to the ASTM E 119 Standard Fire Condition.
Portland Cement Assoc., Skokie, IL
Journal of Fire Protection Engineering, Vol. 7, No. 4, 125-132, 1995.

Ahmed, G. N.; Hurst, J. P.
Coupled Heat and Mass Transport Phenomena in Siliceous Aggregate Concrete Slabs Subjected to Fire.
Portland Cement Assoc., Skokie, IL
Fire and Materials, Vol. 21, No. 4, 161-168, July/August 1997.

Anderberg, Y.
Fire Engineering Design of Structures Based on Design Guides.
Fire Safety Design, Lund, Sweden
Pacific Rim Conference and Second (2nd) International Conference on Performance-Based Codes and Fire Safety Design Methods. Proceedings. International Code Council and the Society of Fire Protection Engineers (SFPE). May 3-9, 1998, Maui, HI, International Code Council, Birmingham, AL, 357-369 pp, 1998.

Benichou, N.; Mehaffey, J. R.; Sultan, M. A.; Takeda, H.
Modeling the Fire Resistance of Loadbearing Wood-Stud Wall Assemblies.

National Research Council of Canada, Ottawa, Ontario
Forintek Canada Corp., Sainte-Foy, Canada
NRCC 43148;
Wood and Fire Safety International Scientific Conference, 4th. Proceedings. May 4-19, 2000, Svolen, Slovakia, 33-43 pp, 2000.

Benichou, N.; Kodur, V. R.; Sultan, M. A.
Experimental Study and Numerical Modelling of the Fire Resistance of Wood-Stud Wall Assemblies.
National Research Council of Canada, Ottawa, Ontario
NRCC-45166;
4th Structural Speciality Conference. Canadian Society for Civil Engineering. June 5-8, 2002, Montreal, Canada, 1-10 pp, 2002.
FOR MORE INFORMATION CONTACT: National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, K1A 0R6, Telephone (613) 993-2607, Fax: (613) 952-7673, Email: Irc.Client-Services@nrc.ca, Website: http://www.nrc.ca/irc/ircpubs

Benichou, N.; Sultan, M. A.; Kodur, V. R.
Fire Resistance Performance of Lightweight Framed Wall Assemblies: Effects of Various Parameters, Key Design considerations and Numerical Modelling.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials 2003. 8th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 27-28, 2003, San Francisco, CA, 9-20 pp, 2003.
FOR MORE INFORMATION CONTACT: Interscience Communications Limited, West Yard House, Guildford Grove, Greenwich London, SE10 8JT, England. Telephone: +44 (0)20 8692 5050, Fax: +44 (0)20 8692 5155, Email: intercomm@dial.pipex.com, Website: http://www.intercomm.dial.pipex.com

Cameron, N. J. K.; Usmani, A. S.
Ultimate Capacity of Composite Floor Slabs at the Fire Limit State.
University of Edinburgh, UK
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 217-226 pp, 2003.

Cooke, G. M. E.
Can Integrity in Fire Resistance Tests Be Predicted?
Fire Research Station, Borehamwood, England
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers. **Interflam 1993. (Interflam '93).** Fire Safety. International Fire Conference, 6th. March 30-April 1, 1993, Oxford, England, Interscience Communications Ltd., London, England, Franks, C. A., Editor, 321-330 pp, 1993.

Cooper, L. Y.
Thermal Response of Gypsum-Panel/Steel-Stud Wall Systems Explosed to Fire Environments - A Simulation for Use in Zone-Type Fire Models.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6027; 54 p. June 1997.

Cooper, L. Y.; Franssen, J. M.
Basis for Using Fire Modeling With 1-D Thermal Analyses of Barriers/Partitions to Simulate 2-D and 3-D Barrier/Partition Structural Performance in Real Fires.
National Institute of Standards and Technology, Gaithersburg, MD
University of Liege, Belgium
Fire Safety Journal, Vol. 33, No. 2, 115-128, September 1999.
NISTIR 6170; 22 p. September 1998.

Cooper, L. Y.; Reneke, P. A.
Prototype Model for Simulating Barrier Fire Performance: CFAST.GYPST - For Evaluating the Thermal Response of Gypsum-Panel/Steel-Stud Wall Systems.

National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6482; 70 p. February 2000.

Fung, F. C.
Computer Program for the Thermal Analysis of the Fire Endurance of Construction Walls.
National Bureau of Standards, Gaithersburg, MD
NBSIR 77-1260; 61 p. June 1977.
Available from National Technical Information Service
PB-268112

Fung, F. C. W.
Fire Endurance Thermal Analysis of Construction Walls.
National Bureau of Standards, Gaithersburg, MD
NBS 10 494; 35 p. September 29, 1971.
AVAILABLE FROM: National Archives, Civilian Records, Room 2800, 8601 Adelphia Road, College, Park, MD 20740-6001, Telephone: 301-713-7230

Elghazouli, A. Y.; Izzuddin, B. A.
Analytical Assessment of the Structural Performance of Composite Floors Subject to Compartment Fires.
Imperial College of Science, London, England
Fire Safety Journal, Vol. 36, No. 8, 769-793, November 2001.

Huang, Z.; Burgess, I. W.; Plank, R. J.
Three-Dimensional Modelling of Two Full-Scale Fire Tests on a Composite Building.
University of Sheffield, UK
Proceedings of the Institution of Civil Engineers, Structures and Buildings, Vol. 134, No. 3, 243-255, August 1999.
Paper 11884;

Hurst, J. P.; Ahmed, G. N.
Modeling the Thermal Response of Gypsum Wallboard and Stud Assemblies Subjected to Standard Fire Testing.
Portland Cement Assoc., San Ramon, CA
National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE). International Conference on Fire Research and Engineering (ICFRE). Proceedings. September 10-15, 1995, Orlando, FL, SFPE, Boston, MA, Lund, D. P.; Angell, E. A., Editors, 557-562 pp, 1995.

Gerlich, H. J. T.; Barnett, C. R.; McLellan, D. L.; Buchanan, A. H.
Predicting the Performance of Drywall Construction Exposed to Design Fires.
Winstone Wallboards, New Zealand
Macdonald Barnett Partners Ltd., New Zealand
University of Canterbury, Christchurch, New Zealand
Volume 1;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 1. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 257-267 pp, 2004.

Iding, R.; Bresler, B.; Nizamuddin, Z.
FIRES-T3: A Computer Program for the Fire Response of Structure-Thermal (Three-Dimensional Version).
California Univ., Berkeley
National Science Foundation, Washington, DC
National Bureau of Standards, Gaithersburg, MD
NIST GCR 95-682; UCB FRG 77-15; 178 p. June 1996.
Available from National Technical Information Service
PB96-195300

Jones, B.; Gerlich, H.; buchanan, A.
Modelling the Performance of Gypsum Plasterboard Assemblies Exposed to Real Building Fires and Stanard Furnace Tests.
Holmes Fire and Safety Limited, Sydney, Australia

Winstone Wallboards Limited, Lower Hutt, New Zealand
University of Canterbury, Christchurch, New Zealand
Performance-Based Codes and Fire Safety Design Methods, 4th International Conference. Proceedings. March 20-22, 2002, Melbourne, Australia, Almand, K.; Coate, C.; England, P.; Gordon, J., Editors, 276-287 pp, 2002.

Lamont, S.; Usmani, A. S.; Drysdale, D. D.
Heat-transfer Analysis of the Composite Slab in the Cardington Frame Fire Tests.
Edinburgh Univ., Scotland
Fire Safety Journal, Vol. 36, No. 8, 815-839, November 2001.

Lamont, S.
Structural Behavior in Fire and Real Design.
Arup Fire, London, England
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 267-277 pp, 2003.

Lennon, T.; Moore, D.
Natural Fire Safety Concept: Full-Scale Tests at Cardington.
Building Research Establishment, Watford, England
Fire Safety Journal, Vol. 38, No. 7, 623-643, November 2003.

Lie, T. T.
Calculation of the Fire Resistance of Composite Concrete Floor and Roof Slabs.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 14, No. 1, 28-45, February 1978.
DBR Paper 722; NRCC 16658;

Maddox, J. A.; Gemeny, D. F.
Computer Modeling and Fire Tests Used to Verify Fire Resistance of Various Wall Assemblies.
Rolf Jensen and Associates, Inc., CA
Volume 1;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 1. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 199-206 pp, 2004.

Mehaffey, J. R.; Sultan, M. A.
Heat-transfer Through Wood-Stud Wall Assemblies Exposed to Fire.
Forintex Canada Corp.
National Research Council of Canada, Ottawa, Ontario
Wisconsin-Madison Univ., Madison, WI
Interscience Communications Limited. Fire and Materials. International Conference, 1st. September 24-25, 1992, Arlington, VA, 247-251 pp, 1992.

Mehaffey, J. R.
Model for Predicting Heat-transfer Through Gypsum-Board/Wood-Stud Walls Exposed to Fire.
Forintek Canada Corp., Ottawa, Canada
Society of Fire Protection Engineers and Worcester Polytechnic Institute. Computer Applications in Fire Protection. Proceedings. June 28-29, 1993, Worcester, MA, 63-68 pp, 1993.

Mehaffey, J. R.; Takeda, H.
Predicting Heat-transfer Through Wood Stud Walls Exposed to Fire.
Forintek Canada Corp., Vancouver, Canada
Forintek Canada Corp., Ontario, Canada
National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE). International Conference on Fire Research and Engineering (ICFRE). Proceedings. September 10-15, 1995, Orlando, FL, SFPE, Boston, MA, Lund, D. P.; Angell, E. A., Editors, 568-573 pp, 1995.

Lin, E. C. Y.; Mahaffey, J. R.
Modeling the Fire Resistance of Wood-Frame Office Buildings.
Forintek Canada Corp., Sainte-Foy, Canada
Journal of Fire Sciences, Vol. 15, No. 4, 308-338, July/August 1997.

Persson, B.
Measurement of Thermal Properties at High Temperatures.
Swedish National Testing and Research Institute, Boras, Sweden
TNO Building and Construction Research. CIB/W14 Workshop, 3rd. Fire Engineering Workshop on Modelling. Proceedings. January 25-26, 1993, Delft, The Netherlands, Twilt, L., Editor, 182-186 pp, 1993.

Quintiere, J. G.; Chang, P. C.
How To Use a Scale Model to Simulate Fire and Structural Failure.
Maryland Univ., College Park
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 124-133 pp, 2003.

Ranby, A.
Temperaturberakningar i brandutsatta stralregelvaggar. [Temperature Calculations of a Steel Framed Wall in Case of Fire.]
Swedish Institute of Steel Construction, Stockholm, Sweden
Report 188:2; 36 p. Feburary 1997.

Sahota, M. S.
Heat and Mass Transfer in Porous Concrete Structures Subject to Fire.
California Univ., Berkeley
UCB FRG 76-15; 165 p. September 1976.

Sand, A. M.; Rotter, J. M.; Usmani, A. S.; O'Connor, M. A.
Finite Element Modelling of Fire Tests on the Cardington Composite Building.
Edinburgh Univ., Scotland
British Steel, England
Volume 2;
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. **Interflam 1999. (Interflam '99).** International Interflam Conference, 8th Proceedings. Volume 2. June 29-July 1, 1999, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1045-1056 pp, 1999.

Schleich, J. B.
ISO: Fire Resistance Tests on Full Scale Building Elements. Future Developments by Numerical Simulation.
Arbed Recherche Centre, Luxembourg
ITSEMAP. International Meeting of Fire Research and Test Centers. Papers. October 7-9, 1986, Avila, Spain, 481-501 pp, 1986.

Takeda, H.; Mehaffey, J. R.
WALL2D: A Model for Predicting Heat-transfer Through Wood-Stud Walls Exposed to Fire.
Forintek Canada Corp., Sainte-Foy, Canada
Fire and Materials, Vol. 22, No. 4, 133-140, July/August 1998.

Takeda, H.
Model to Predict Fire Resistance of Non-Load Bearing Wood-Stud Walls.
Fire and Materials, Vol. 27, No. 1, 19-39, January/February 2003.

Takeda, H.
Fire Resistance of Exterior Walls: Model and Full-Scale Test.
Fire Research Canada (LGS), Orleans, Ontario, Canada
Fire Safety Science. Proceedings. Eighth (8th) International Symposium. International Association for Fire Safety Science (IAFSS). September 18-23, 2005, Beijing, China, Intl. Assoc. for Fire Safety Science, Boston, MA, Gottuk, D. T.; Lattimer, B. Y., Editors, 291-302 pp, 2005.

Takeda, H.
Model to Predict Fire Resistance of Wood-Stud Walls: The Effect of Shrinkage of Gypsum Board.
Forintek Canada Corp., Sainte-Foy, Canada
Fire and Materials. 6th International Conference and Exhibition. Proceedings. Interscience Communications Limited. February 22-23, 1999, San Antonio, TX, 247-256 pp, 1999.

Wade, C. A.
Summary Report on a Finite Element Program for Modelling the Thermal Response of Building Components Exposed to Fire.
Building Research Association of New Zealand, Judgeford
Study Report 51; 48 p. 1993.

Wozniak, G.; Lukomski, M.; Kosiorek, M.
Calculation Methods of Fire Resistance Assessment of Light Steel Frame Partition Walls With Gypsum Board Cladding.
Building Research Institute, Warsaw, Poland
Performance-Based Codes and Fire Safety Design Methods, 5th International Conference. Proceedings. October 6-8, 2004, Luxembourg, Almand, K.; Attlan, J. M.; D'Hoop, J. M.; Gordon, J., Editors, 315-326 pp, 2004.

Cameron, N. J. K.; Usmani, A. S.
Ultimate Capacity of Composite Floor Slabs at the Fire Limit State.
University of Edinburgh, UK
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 217-226 pp, 2003.

Zhao, B.
Prediction of Interaction in a Composite Beam (Concrete Slab and Steel Section) by Taking Into Account Fire Behavior of Shear Connectors.
CTICM, France
TNO Building and Construction Research. CIB/W14 Workshop, 3rd. Fire Engineering Workshop on Modelling. Proceedings. January 25-26, 1993, Delft, The Netherlands, Twilt, L., Editor, 176-181 pp, 1993.

Wozniak, G.; Lukomski, M.; Kosiorek, M.
Calculation Methods of Fire Resistance Assessment of Light Steel Frame Partition Walls With Gypsum Board Cladding.
Building Research Institute, Warsaw, Poland
Performance-Based Codes and Fire Safety Design Methods, 5th International Conference. Proceedings. October 6-8, 2004, Luxembourg, Almand, K.; Attlan, J. M.; D'Hoop, J. M.; Gordon, J., Editors, 315-326 pp, 2004.

Composite Floors

Bailey, C.
Steel Structures Supporting Composite Floor Slabs: Design for Fire.
Building Research Establishment, Garston, England
Digest 462; 12 p. December 2001.
For more information contact: CRC Limited, 151 Rosebery Avenue, London EC1R 4GB, England, Telephone: 020 7505 6622, Fax: 020 7505 6606, Email: crc@construction.emap.co.uk, Website: http://www.bre.co.uk

Cameron, N. J. K.; Usmani, A. S.
Ultimate Capacity of Composite Floor Slabs at the Fire Limit State.
University of Edinburgh, UK
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 217-226 pp, 2003.

Elghazouli, A. Y.; Izzuddin, B. A.

Analytical Assessment of the Structural Performance of Composite Floors Subject to Compartment Fires.
Imperial College of Science, London, England
Fire Safety Journal, Vol. 36, No. 8, 769-793, November 2001.

Gillie, M.; Usmani, A.; Rotter, M.; O'Connor, M.
Modelling of Heated Composite Floor Slabs With Reference to the Cardington Experiments.
Edinburgh Univ., Scotland
CORUS plc, Rotherham, UK
Fire Safety Journal, Vol. 36, No. 8, 745-767, November 2001.

Huang, Z.; Burgess, I.; Plank, R.; Bailey, C.
Comparison of BRE Simple Design Method for Composite Floor Slabs in Fire With Non-Linear FE Modelling.
Sheffield Univ., UK
Building Research Establishment, Watford, England
Fire and Materials, Vol. 28, No. 2/4, 127-138, March/August 2004.

PERFORMANCE-BASED STRUCTURAL FIRE DESIGN AND CODE COMPLIANCE

American Concrete Institute
Guide for Determining the Fire Endurance of Concrete Elements. ACI Committee 216.
American Concrete Inst., Detroit, MI
; 139 p. September 1980.

Almand, K. H.; Hurley, M. J.
Current Developments in the Structural Fire Protection Engineering Profession.
Society of Fire Protection Engineers, Bethesda, MD
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 134-143 pp, 2003.

Boring, D. F.; Spence, J. C.; Wells, W. G.
American Iron and Steel Institute, New York, NY
Fire Protection Through Modern Building Codes. 5th Edition, American Iron and Steel Inst., New York, NY, 252 p., 1981.

PBD Process

Albano, L. D.; Fitzgerald, R. W.
Design Fires for Structural Performance.
Worcester Polytechnic Institute, MA
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 53-64 pp, 2003.

Anderberg, Y.
Analytical Fire Engineering Design of Reinforced Concrete Structures Based on Real Fire Characteristics.
Lund Institute of Technology, Sweden
Federation Internationale de la Precontrainte. Proceedings of the 8th Congress. Part 1. April 30, 1978-May 5, 1978, London, England, 112-123 pp, 1978.

Anderberg, Y.; Magnusson, S. E.; Pettersson, O.; Thelanderson, S.; Wickstrom, U.
Analytical Approach to Fire Engineering Design of Concrete Structure.
Lund Institute of Technology, Sweden
CIB W14/79/35 (S); ACI Publication SP 55-16; Bulletin 65;
American Concrete Institute. Analytical Design of Fire Exposed Concrete Structures. Douglas McHenry International Symposium. ACI Publication SP-55. Bulletin. October 1976, Mexico City, Mexico, American Concrete Institute, Detroit, MI, 409-438 pp, 1976.

Anderberg, Y.
Fire-Exposed Hyperstatic Concrete Structures: An Experimental and Theoretical Study.
Lund Institute of Technology, Sweden
CIB W14/79/35 (S); ACI Publication SP 55-17; Bulletin 65;
American Concrete Institute. Analytical Design of Fire Exposed Concrete Structures. Douglas McHenry International Symposium. ACI Publication SP-55. Bulletin 65. October 1976, Mexico City, Mexico, American Concrete Institute, Detroit, MI, 439-459 pp, 1976.

Anderberg, Y.
Fire Exposed Hyperstatic Concrete Structures--An Experimental and Theoretical Study.
Lund Institute of Technology, Sweden
Bulletin 55; 186 p. August 1976.

Anderberg, Y.
Mechanical Behavior at Fire of Concrete and Hyperstatic Concrete Structures.
Lund Institute of Technology, Sweden
Bulletin 56; 9 p. September 1976.

Babrauskas, V.
Closed-Form Approximation for Post-Flashover Compartment Fire Temperatures.

National Bureau of Standards, Gaithersburg, MD
Fire Safety Journal, Vol. 4, No. 1, 63-73, August 1981.

Babrauskas, V.; Williamson, R. B.
Post-Flashover Compartment Fires.
California Univ., Berkeley
National Science Foundation, Washington, DC
Department of Housing and Urban Development, Washington, DC
National Bureau of Standards, Gaithersburg, MD
UCB FRG 75-1; CIB W14/145/75 (USA); 94 p. Decmeber 1975.

Babrauskas, V.; Williamson, R. B.
Post-Flashover Compartment Fires--Application of a Theoretical Model.
National Institute of Standards and Technology, Gaithersburg, MD
California Univ., Berkeley
Fire and Materials, Vol. 3, No. 1, 1-7, March 1979.

Babrauskas, V.; Williamson, R. B.
Post-Flashover Compartment Fires: Basis of a Theoretical Model.
National Bureau of Standards, Gaithersburg, MD
California Univ., Berkeley
Fire and Materials, Vol. 2, No. 2, 39-53, April 1978.

Babrauskas, V.
Performance-Based Fire Safety Engineering Design: The Role of Fire Models and Fire Tests.
Fire Science and Technology Inc., Issaquah, WA
Volume 2; NIST SP 995; Volume 2; March 2003.
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. **Interflam 1999. (Interflam '99).** International Interflam Conference, 8th Proceedings. Volume 2. June 29-July 1, 1999, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 799-807 pp, 1999.

Baum, H. R.
Simulating Fire Effects on Complex Building Structures.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Safety Science. Proceedings. Eighth (8th) International Symposium. International Association for Fire Safety Science (IAFSS). September 18-23, 2005, Beijing, China, Intl. Assoc. for Fire Safety Science, Boston, MA, Gottuk, D. T.; Lattimer, B. Y., Editors, 3-18 pp, 2005.

Beyler, C. L.; DiNenno, P. D.
Overview of Designing Buildings for Fire Resistance.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6890; September 2002.
Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings. Appendix III. Presentations: C. February 19-20, 2002, Gaithersburg, MD, Grosshandler, W. L., Editor, 44-50 pp, 2002.

Bohm, B.
Fire Resistance Tests and Differentiated Design Procedures--The Building Code: Aims and Means.
Technological Institute, Copenhagen, Denmark
Fire Technology, Vol. 14, No. 3, 239-246, August 1978.

Baldwin, R.; Heselden, A. J. M.; Thomas, P. H.
Analysis of the C.I.B. Experiments on Fully-Developed Compartment Fires.
Fire Research Station, Borehamwood, England
Internal Note 241; 50 p. October 1965.

Bohm, B.
Fully Developed Compartment Fires: The Effect of Thermal Inertia of Bounding Walls on the Thermal Exposure.
Technical Univ. of Denmark, Lyngby

International Association for Fire Safety Science. Fire Safety Science. Proceedings. 1st International Symposium October 7-11, 1985, Gaithersburg, MD, Hemisphere Publishing Corp., NY, Grant, C. E.; Pagni, P. J., Editors, 119-127 pp, 1986.

Bohm, B.
Non-Uniform Compartment Fires. Report No. 1. Preliminary Investigation of Fully Developed Fires.
Technical University of Denmark, Lyngby
CIB W14/83/01 (DK); 63 p. January 1983.

Bohm, B.; Hadvig, S.
Rebuttal to Comments by S. E. Magnusson on "Nonconventional Fully Developed Polyethylene and Wood Compartment Fires", Combustion and Flame, Volume 44, Page 201).
Technical Univ. of Denmark, Lyngby
Combustion and Flame, Vol. 52, No. 3, 317-318, October 1983.

Bohm, B.; Hadvig, S.
Nonconventional Fully Developed Polyethylene and Wood Compartment Fires.
Technical Univ. of Denmark, Lyngby
Combustion and Flame, Vol. 44, No. 1-3, 201-221, January 1982.

Bohm, B.
Fully Developed Polyethylene and Wood Compartment Fires With Application to Structural Design.
Technical University of Denmark
Thesis; 303 p. 1977.

Bub, H.
Structural Fire Protection. Model Code. Draft.
CIB W14/79/45 (D); 84 p. December 1979.

Buchanan, A. H.
Fire Engineering for a Performance-based Code.
Canterbury Univ., Christchurch, New Zealand
Fire Safety Journal, Vol. 23, No. 1, 1-16, 1994.
Tyne and Wear Metropolitan Fire Department and The Institution of Fire Engineers, Northern Branch. Fire Risk Assessment: Opportunity or Problem? Joint Conference. March 26, 1993, 1-12 pp, 1993 **AND** Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers. Interflam '93. Fire Safety. International Fire Conference, 6th. March 30-April 1, 1993, Oxford, England, Interscience Communications Ltd., London, England, Franks, C. A., Editor, 457- 468 pp, 1993, 1993.

Buchanan, A. H.
Performance-based Structural Design for Fire.
University of Canterbury, Christchurch, New Zealand
Pacific Rim Conference and Second (2nd) International Conference on Performance-Based Codes and Fire Safety Design Methods. Proceedings. International Code Council and the Society of Fire Protection Engineers (SFPE). May 3-9, 1998, Maui, HI, International Code Council, Birmingham, AL, 371-382 pp, 1998.

Bullen, M. L.; Thomas, P. H.
Compartment Fires With Non-Cellulosic Fuels.
Fire Research Station, Borehamwood, England
Combustion Institute, Symposium (International) on Combustion, 17th. August 20-25, 1978, Leeds, England, Combustion Inst., Pittsburgh, PA, 1139-1147 pp, 1979.

Cadorin, J. F.; Franssen, J. M.
Tool to Design Steel Elements Submitted to Compartment Fires - OZone V2. Part 1: Pre- and Post-Flashover Compartment Fire Model.
Universit de Lige, Belgium
Fire Safety Journal, Vol. 38, No. 5, 395-427, September 2003.

Cadorin, J. F.; Pintea, D.; Dotreppe, J. C.; Franssen, J. M.

Tool to Design Steel Elements Submitted to Compartment Fires - OZone V2. Part 2: Methodology and Application.
Universit de Lige, Belgium
Fire Safety Journal, Vol. 38, No. 5, 429-451, September 2003.

Cooke, G. M. E.; Morgan, P. B. E.
Thermal Bowing in Fire and How It Affects Building Design.
Fire Research Station, Borehamwood, England
BRE IP 21/88; 4 p. December 1988.

Coward, S. K. D.
Simulation Method for Estimating the Distribution of Fire Severities In Office Rooms.
Fire Research Station, Borehamwood, England
CP 31/75; 7 p. April 1975.

Deierlein, G. G.; Hamilton, S.
Framework for Structural Fire Engineering and Design Methods. White Paper.
NISTIR 7133; White Paper 3; April 20, 2004.
NIST-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: Proceedings. Appendix 9.H: White Papers. October 2-3, 2003, Baltimore, MD, 75-99 pp, 2004.

Drysdale, D. D.
Flashover and the Fully Developed Compartment Fire.
Edinburgh Univ., Scotland
Paper 4;
University of Edinburgh. Fire Science and Investigation. September 10-11, 1987, Edinburgh, Scotland, 16 pp, 1987.

Ellingwood, B. R.
Load Combination Requirements for Fire-Resistant Structural Design.
Georgia Institute of Technology, Atlanta
Journal of Fire Protection Engineering, Vol. 15, No. 1, 43-61, February 2005.

Faller, G.
Performance-Based Design Approach to Fire Resistance Grading of Buildings.
Arup Consulting Engineers, Dublin, Ireland
Fire Engineers Journal, Vol. 60, No. 205, 23-27, March 2000.

Fang, J. B.
Repeatability of Large-Scale Room Fire Tests.
National Bureau of Standards, Gaithersburg, MD
Fire Technology, Vol. 17, No. 1, 5-15, February 1981.
CIB W14/82/23 (USA);

Ferreira, M. J.
Barrier Performance Utilizing Normalized Heat Load, as Part of an Engineering Based Building Fire Protection Analysis Method.
Worcester Polytechnic Inst., MA
Thesis; 133 p. December 1993.

Feasey, R.; Buchanan, A.
Post-Flashover Fires for Structural Design.
Opus International Consultants, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
Fire Safety Journal, Vol. 37, No. 1, 83-105, February 2002.

Feasey, R.
Post-Flashover Design Fires.
University of Canterbury, Christchurch, New Zealand
Fire Engineering Research Report 99/6; 241 p. March 1999
http://www.civil.canterbury.ac.nz

Fitzgerald, R. W.
Selection of Fire Endurance Requirements for Building Design. [Integration of Fire Science Into Building Requirements.]
Worcester Polytechnic Institute, MA
Fire Safety Journal, Vol. 17, No. 2, 159-163, 1991.
Lund University. Science of Building Fire Safety. Symposium to Honor Professor Ove Pettersson on His Retirement. May 2-4, 1989, Lund, Sweden, 1-3 pp, 1989.

Franssen, J. M.
Time History Versus Ultimate State Design in Structures Submitted to the Fire.
University of Liege, Belgium
TNO Building and Construction Research. CIB/W14 Workshop, 3rd. Fire Engineering Workshop on Modelling. Proceedings. January 25-26, 1993, Delft, The Netherlands, Twilt, L., Editor, 113-118 pp, 1993.

Gandhi, P. D.
How a Computer Program Can Predict Fire Performance: FIRES-T3.
Underwriters Labs., Northbrook, IL
Lab Data, Vol. 17, No. 2, 9-13, 1986.

Gerlich, J. T.; Collier, P. C. R.; Buchanan, A. H.
Design of Light Steel-Framed Walls for Fire Resistance.
Winstone Wallboards Ltd., Lower Hutt, New Zealand
Building Research Association of New Zealand, Judgeford
University of Canterbury, Christchurch, New Zealand
Fire and Materials, Vol. 20, No. 2, 79-96, March/April 1996.

Gosselin, G. C.
Fire Compartmentation and Fire Resistance.
Institute for Research in Construction, Ottawa, Canada
NRCC 28277;
National Research Council of Canada. Designing for Fire Safety. Science and Its Application to Building Codes. Building Science Insight '87. Series of One-Day Seminars Held in Ten Cities Across Canada in the Fall of 1987., Canada, 35-44 pp, 1987.

Gosselin, G. C.; Lie, T. T.
Provision of Fire Resistance--Evolution of Design Approaches.
National Research Council of Canada, Ottawa, Ontario
IRC Paper 1529; NRCC 28877;
1987 CSCE Centennial Conference. Volume 1. May 19-22, 1987., Montreal, Quebec, 3-19 pp, 1987.

Hadjisophocleous, G. V.; Cacambouras, M.
Computer Modeling of Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Journal of Fire Protection Engineering, Vol. 5, No. 2, 39-52, April/May/June 1993.

Hagglund, B.
Comparing Fire Models With Experimental Data.
National Defence Research Establishment, Sundbyberg, Sweden
FOA Report C20864-2.4; 39 p. February 1992.

Hamins, A.; Maranghides, A.; McGrattan, K. B.; Johnsson, E. L.; Ohlemiller, T. J.; Donnelly, M. K.; Yang, J. C.; Mulholland, G. W.; Prasad, K. R.; Kukuck, S. R.; Anleitner, R. L.; McAllister, T. P.
Experiments and Modeling of Structural Steel Elements Exposed to Fire. Appendices D-G. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
Army Research Laboratory, Aberdeen Proving Ground, MD
NIST NCSTAR 1-5B; 54 p. September 2005.

Gross, D.
Measurements of Fire Loads and Calculations of Fire Severity.

National Bureau of Standards, Gaithersburg, MD
Wood and Fiber, Vol. 9, No. 1, 72-85, Spring 1977.
Fire Protection Structure and Systems Design: Reader. Open Learning Fire Service Program. 1982, 1977.

Gupta, A. K.; Kumar, R.; Kumar, S.
Compartment Fires: A Simple Mathematical Model.
Central Building Research Institute, Roorkee, India
Indian Institute of Technology Roorkee, India
Journal of Applied Fire Science, Vol. 11, No. 1, 53-74, 2002-2003.

Gupta, A. K.; Kumar, R.; Kumar, S.
Compartment Fires: An Experimental Study.
Central Building Research Institute, Roorkee, India
Indian Institute of Technology Roorkee, India
Journal of Applied Fire Science, Vol. 11, No. 3, 255-277, 2002-2003.

Gustaferro, A. H.
Design Implementation: Concrete Structures.
Consulting Engineers Group, Inc., Glenview, IL
Design of Structures Against Fire, Elsevier Applied Science Publishers, New York, Anchor, R. D.; Malhotra, H. L.; Purkiss, J. A., Editors, 189-211 pp, 1986.

Harada, K.; Takeichi, N.; Sekizawa, A.
Performance Evaluation Methods for Evacuation Safety and for Structural Fire Resistance.
Kyoto Univ., Japan
Building Research Institute, Tsukuba, Japan
National Research Institute of Fire and Disaster, Mitaka, Japan
Performance-Based Codes and Fire Safety Design Methods, 3rd International Conference. Proceedings. June 15-17, 2000, Lund, Sweden, Jonsson, R.; Almand, K.; Maskas, J., Editors, 212-223 pp, 2000.

Harada, K.; Ohmiya, Y.; Natori, A.; Nakamichi, A.
Technical Basis on Structural Fire Resistance Design in Building Standards Law of Japan.
Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
Tokyo University of Science, Yamasaki 2641, Noda 278-8510, Japan
Non-Life Insurance Rating Organization of Japan, Tokyo 101-0054, Japan
4 General Building Research Corporation of Japan, Osaka 540-0024, Japan
Fire and Materials, Vol. 28, No. 2/4, 323-341, March/August 2004.

Harmathy, T. Z.
Fire Severity: Basis of Fire Safety Design.
National Research Council of Canada, Ottawa, Ontario
NRCC 22803; DBR Paper 1148;
Fire Safety of Concrete Structures. ACI Committee 216. Abrams, M. S., editor. September 1980, San Juan, Puerto Rico, 115-149 pp, 1983.

Harmathy, T. Z.; Mehaffey, J. R.
Post-Flashover Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 7, No. 2, 49-61, June 1983.

Harmathy, T. Z.
Effect of the Nature of Fuel on the Characteristics of Fully Developed Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 3, No. 1, 49-60, March 1979.
Interflam '79. International Conference on Flammability. Conference Workbook. Organised Jointly by 'Fire and Materials' and LIRA. March 27-29, 1979, Guildford, England, 19-20 pp, 1979.

Harmathy, T. Z.
Some Overlooked Aspects of the Severity of Compartment Fires.
National Research Council of Canada, Ottawa, Ontario

Fire Safety Journal, Vol. 3, 261-271, 1981.
CIB W14/81/12 (C); DBR Paper 983; NRCC 19541;

Harmathy, T. Z.
Ventilation of Fully-Developed Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Combustion and Flame, Vol. 37, No. 1, 25-39, January 1980.
CIB W14/80/02 (C); DBR Paper 892; NRCC 18068;

Harmathy, T. Z.
Mechanism of Burning of Fully-Developed Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Combustion and Flame, Vol. 31, No. 1, 265-273, 1978.
DBR Paper 777; NRCC 16722;

Harmathy, T. Z.
Role of Thermal Feedback in Compartment Fires.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 11, No. 1, 48-57, February 1975.

Harmathy, T. Z.
Closure to the Discussion of Compartment Fires. A Rebuttal.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 10, No. 3, 247-250, August 1974.

Harmathy, T. Z.
New Look at Compartment Fires. Part 2.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 8, No. 4, 326-351, November 1972.

Harmathy, T. Z.
New Look at Compartment Fires. Part 1.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 8, No. 3, 196-217, 1972.

Heselden, A. J. M.
Parameters Determining the Severity of Fire.
Fire Research Station, Borehamwood, England
Paper 2;
Behavior of Structural Steel in Fires. Symposium No. 2. Proceedings. January 24, 1967, Borehamwood, England, 19-28 pp, 1967.
Available from National Technical Information Service
AD-835937

Heselden, A. J. M.
Some Fires in a Single Compartment With Independent Variation of Fuel Surface Area and Thickness.
Fire Research Station, Borehamwood, England
FR Note 469; 19 p. September 1961.

Heselden, A. J. M.
Supplementary Reports of Work for the C.I.B. International Co-Opperative Research Programe on Fully-Developed Fires.
Fire Research Station, Borehamwood, England
FR Note 923 (Appendix); 252 p. August 1972.

Hertz, K.
Assessment of Performance-Based Requirements for Structural Design.
Technical University of Denmark, Lyngby

Fire Safety Science. Proceedings. Eighth (8th) International Symposium. International Association for Fire Safety Science (IAFSS). September 18-23, 2005, Beijing, China, Intl. Assoc. for Fire Safety Science, Boston, MA, Gottuk, D. T.; Lattimer, B. Y., Editors, 315-325 pp, 2005.

Hosser, D.; Dorn, T.; Richter, E.
Evaluation of Simplified Calculation Methods for Structural Fire Design.
University of Braunschweig, Germany
Fire Safety Journal, Vol. 22, No. 3, 249-304, 1994.
ISO/TC92/SC/WG2 N 227;

Hua, J.; Wang, J.; Kumar, K.; Kumar, S.
Evaluation of the Combustion and Thermal Radiation Modeling Methods for Fuel- and Ventilation-Controlled Compartment fires.
Institute of High Performance Computing, The Capricorn, Singapore
Building Research Establishment, Garston, England
Volume 1;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 1. Posters: Combustion. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 787-794 pp, 2004.

Hurley, M. J.
Predicting Fire Exposures to Structures.
Society of Fire Protection Engineers, Bethesda, MD
Reaching New Horizons. Performance-Based Codes and Fire Safety Design Methods, 6th International Conference. Proceedings. June 14-16, 2006, Tokyo, Japan, Evans, D. D.; Gordon, J.; Hasemi, Y.; Sekizawa, A., Editors, 1-11 pp, 2006.

Johann, M. A.; Albano, L. D.; Fitzgerald, R. W.; Meacham, B. J.
Fire-Robust Structural Design: A Framework for Integration of Structural Engineering and Fire Protection Engineering.
Arup Fire, Westborough, MA
Worcester Polytechnic Institute, MA
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 317-322 pp, 2003.

Johnson, P.; Lovell, T.; Moore, I.
Performance-based Fire Safety Design: Development of the "Fire Engineering Guidelines" in Australia.
Ove Arup and Partners, Melbourne, Australia
Pacific Rim Conference and Second (2nd) International Conference on Performance-Based Codes and Fire Safety Design Methods. Proceedings. International Code Council and the Society of Fire Protection Engineers (SFPE). May 3-9, 1998, Maui, HI, International Code Council, Birmingham, AL, 331-338 pp, 1998.

Kawagoe, K.
Fire Behavior in Rooms.
Building Research Institute, Ibaraki-Ken, Japan
BRI Report 27; 74 p. September 1958.

Kirby, B. R.; Wainman, D. E.; Tomlinson, L. N.; Kay, T. R.; Peacock, B. N.
Natural Fires in Large Scale Compartments.
Swinden Technology Centre, UK
International Journal on Engineering Performance-Based Fire Codes, Vol. 1, No. 2, 45-38, 1999.

Kirby, B. R.; Newman, G. M.; Butterworth, N.; Pagan, J.; English, C.
Development of a Performance-based Approach to Specifying Fire Resistance for Regulatory Purposes.
Swinden Technology Centre, Rotherham, England
Steel Construction Institute, Berkshire, England
Buro Happold (FEDRA), Leeds, England
WFRC Airport House, Surrey, England

WSP Buchanan House, London, England
Performance-Based Codes and Fire Safety Design Methods, 5th International Conference. Proceedings. October 6-8, 2004, Luxembourg, Almand, K.; Attlan, J. M.; D'Hoop, J. M.; Gordon, J., Editors, 183-194 pp, 2004.

Kordina, K.
Natural Fires--Research and Application in Consulting.
Technical University, Braunschweig, Germany
Fire Safety Journal, Vol. 17, No. 2, 113-128, 1991.
Lund University. Science of Building Fire Safety. Symposium to Honor Professor Ove Pettersson on His Retirement. May 2-4, 1989, Lund, Sweden, 1-1 pp, 1989.

Kordina, K.; Haksever, A.; Schneider, U.
Contribution to the Evaluation of Fire Compartment Temperatures on the Basis of Heat Balance Calculations.
Technical Univ., Braunschweig, West Germany
Bauingenieurwesen Universitat-Gasamthochschube Kassel, West Germany
Fire Safety of Concrete Structures. ACI Committee 216. September 1980, San Juan, Puerto Rico, Abrams, M. S., Editor, 237-253 pp, 1983.

Kruppa, J.
Presentation of Parts of Eurocodes on Structural Fire Design.
CTICM-Fire Laboratory, Saint-Remy-Les-Chevreuse, France
ASTM STP 1163; PCN-04-011630-31;
American Society for Testing and Materials. Fire Standards in the International Marketplace. ASTM STP 1163. December 5, 1994, Phoenix, AZ, American Society for Testing and Materials, PA, Grand, A. F., Editor, 72-86 pp, 1995.

Kruppa, J.
Guidance for a Rational Approach toFire Resistance.
CTICM, France
Pacific Rim Conference and Second (2nd) International Conference on Performance-Based Codes and Fire Safety Design Methods. Proceedings. International Code Council and the Society of Fire Protection Engineers (SFPE). May 3-9, 1998, Maui, HI, International Code Council, Birmingham, AL, 383-391 pp, 1998.

Kruppa, J.; Joyeux, D.; Zhao, B.
Scientific Background to the Harmonization of Structural Eurocodes.
CTICM, Paris, France
Fire Safety (Special Issue), Vol. 50, No. 4, 219-235, 2005.

Lamont, S.
Structural Behavior in Fire and Real Design.
Arup Fire, London, England
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 267-277 pp, 2003.

Lamont, S.; Lane, B.; Flint, G.; Usmani, A.
Behavior of Structures in Fire and Real Design: A Case Study.
Arup Fire, Ove Arup and Partners, London, England
Edinburgh Univ., Scotland
Journal of Fire Protection Engineering, Vol. 16, No. 1, 5-35, February 2006.

Lane, B.
Limitations of Fire Resistance Design Methods.
Arup Fire, London, England
Fire Protection Strategies for 21st Century Building and Fire Codes Symposium. **EXTENDED ABSTRACTS.** Proceedings. Society of Fire Protection Engineers and American Institute of Architects. September 17-18, 2002, Baltimore, MD, 65-69 pp, 2002.

Lane, B.
Performance-Based Approach to the Design of Steel Structures in Fire.

ArupFire, New York, NY
Engineered Fire Protection Design...Applying Fire Science to Fire Protection Problems, International Conference. Proceedings. Co-organized by: Society of Fire Protection Engieners (SFPE) and National Institute of Standards and Technology (NIST). June 11-15, 2001, San Francisco, CA, 415-426 pp, 2001.

Lantz, R. V.; Dembsey, N. A.; Barnett, J. R.
Model Validity Defined and Applied to the Problem of Making Legitimate Predictions From Fire Protection Engineering Models.
Worcester Polytechnic Inst., MA
Performance-Based Codes and Fire Safety Design Methods, 3rd International Conference. Proceedings. June 15-17, 2000, Lund, Sweden, Jonsson, R.; Almand, K.; Maskas, J., Editors, 329-340 pp, 2000.

Lennon, T.; Moore, D.
Natural Fire Safety Concept: Full-Scale Tests at Cardington.
Building Research Establishment, Watford, England
Fire Safety Journal, Vol. 38, No. 7, 623-643, November 2003.

Luo, M. C.
Application of Fire Models to Fire Safety Engineering Design.
Ove Arup and Partners Hong Kong Limited, Hong Kong
International Journal on Engineering Performance-Based Fire Codes, Vol. 1, No. 3, 156-161, Winter 1999.
Engineering Performance-Based Fire Codes, 1st International Symposium. Proceedings. Organized and Supported by the Hong Kong Polytechnic University. September 8, 1998, Hong Kong, China, Chow, W. K., Editor, 131-138 pp, 1999.

Ma, Z.; Makelainen, P.
Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design.
Helsinki University of Technology, Finland
Fire Safety Journal, Vol. 34, No. 4, 361-375, 2000.

Magnusson, S. E.
Comments Arising From "Nonconventional Fully Developed Polyethylene and Wood Compartment Fires" by Benny Bohm and Sven Hadvig, (Combustion and Flame, Volume 44, Page 201).
Lund Institute of Technology, Sweden
Combustion and Flame, Vol. 52, No. 3, 315-316, October 1983.

Magnusson, S. E.; Thelandersson, S.
Discussion of Compartment Fires.
Lund Univ., Sweden
Fire Technology, Vol. 10, No. 3, 228-246, August 1974.

Mahoney, J. E.
Development of a Procedure for Construction of Barrier Performance Curves.
Worcester Polytechnic Inst., MA
Thesis; 157 p. September 1995.

Matsuyama, K.; Fujita, T.; Kaneko, H.; Ohmiya, Y.; Tanaka, T.; Wakamatsu, T.
Simple Predictive Method for Room Fire Behavior.
Ataka Fire Safety Design Office, Japan
Shimizu Corp., Japan
NTT Power and Building Facilities, Inc., Japan
Science University of Tokyo, Japan
Kyoto Univ., Japan
Fire Science and Technology, Vol. 18, No. 1, 23-32, 1998.

Mawhinney, J. R.
Evaluating Equivalencies to Building Code Requirements.
National Research Council of Canada, Ottawa, Ontario
Worcester Polytechnic Institute. Firesafety Design in the 21st Century, Conference. Part 1. Conference Report. Part 2. Conference Papers. May 8-10, 1991, Worcester, MA, 265-283 pp, 1991.

McGrattan, K. B.; Bouldin, C.; Forney, G. P.
Computer Simulation of the Fires in the World Trade Center Towers. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-5F; 164 p. September 2005.

Mehaffey, J. R.; Harmathy, T. Z.
Fully Developed Fires: Experimental Findings.
National Research Council of Canada, Ottawa, Ontario
Co-Operating to Fight Fire. 3RD Symposium on Combustibility and Plastics. October 24-25, 1983, Toronto, Ontario, Canada, 1-22 pp, 1983.

Mehaffey, J. R.
Performance-Based Design for Fire Resistance in Wood-Frame Buildings.
Forintek Canada Corp., Sainte-Foy, Canada
Volume 1;
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. **Interflam 1999. (Interflam '99).** International Interflam Conference, 8th Proceedings. Volume 1. June 29-July 1, 1999, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 293-304 pp, 1999.

Ma, Z.; Makelainen, P.
Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design.
Helsinki University of Technology, Finland
Fire Safety Journal, Vol. 34, No. 4, 361-375, 2000.

Milke, J. A.
Performance-Based Design of fire Resistant Assemblies.
Maryland Univ., College Park
Society of Fire Protection Engineers (SFPE). Honors Lecture Series. Proceedings. May 20, 1996. Engineering Seminars: Fire Protection Design for High Challenge or Special Hazard Applications. Proceedings. May 20-22, 1996, Boston, MA, 13-18 pp, 1996.

Milke, J.
ASCE/SFPE Standard on Performance-Based Structural Fire Protection Analyses.
Maryland Univ., College Park
NISTIR 6890; September 2002.
Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings. Appendix III. Presentations: D. February 19-20, 2002, Gaithersburg, MD, Grosshandler, W. L., Editor, 51-53 pp, 2002.

Ministry of Construction, Synthetic Technical Development Project
Development of Fire Safety Design of Buildings. Volume 4. Design Method for Fire Resistance of Building Structures.
Ministry of Construction, Tokyo, Japan
Volume 4 of 4; 190 p. December 1988.

Nakaya, I.; Akita, K.
Simulation Model for Compartment Fires.
Tokyo Univ., Japan
Fire Safety Journal, Vol. 5, No. 2, 157-165, 1983.

Newton, B. A.
Analysis of Common Fire Severity Methods and Barrier Performance.
Worcester Polytechnic Inst., MA
Thesis; 212 p. December 1994.

Nilsson, L.
Time Curve of Heat Release for Compartment Fires With Fuel of Wooden Cribs.
Lund Institute of Technology, Sweden
Bulletin 36; 226 p. 1974.

Pettersson, O.
Structural Fire Safety: As Exemplified by a Swedish Manual for Analytical Design.
Lund Institute of Technology, Sweden
CIB W14/84/14 (S); LUTVDG/TVBB-3006; 11 p. 1982.

Pettersson, O.
Requirements of Fire Resistance Based on Actual Fires (Swedish Approach).
Lund Institute of Technology, Sweden
CIB W14/88/32 (S); LUTVDG/TVBB-3024; 23 p. 1984.

Pope, N. D.; Bailey, C. G.
Quantitative Comparison of FDS and Parametric Fire Curves With Post-Flashover Compartment Fire Test Data.
Manchester Univ., UK
Fire Safety Journal, Vol. 41, No. 2, 99-110, March 2006.

Prasad, K.; Baum, H. R.
Fire Structure Interface and Thermal Response of the World Trade Center Towers. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-5G; 338 p. September 2005.

Raes, H.
Influence of a Building's Construction and Fire Load on the Intensity and Duration of a Fire.
Belgian Fire Protection Assoc.
Fire Prevention Science and Technology, No. 16, 4-16, March 1977.

Ramachandran, G.
Probabilistic Models for Fire Resistance Evaluation.
University of Leeds, UK
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 105-112 pp, 2003.

Robertson, A. F.; Genensky, S. M.
Theoretical Heat-transfer Scaling Relationships for Fire Endurance of Reinforced Concrete.
National Bureau of Standards, Gaithersburg, MD
Department of the Army, Washington, DC
NBS 4854; 28 p. September 21, 1956.

Robertson, D.; Feeney, M.; Velivasakis, E.
Achieving Robustness Through Performance-Based Structural Fire Engineering.
LZA Holmes Fire/Holmes Fire and Safety, New York, NY
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 278-285 pp, 2003.

Seigel, L. G.
Performance Approach to the Design of Fire-Resistive Buildings.
U. S. Steel Corp., Monroeville, PA
Department of Housing and Urban Development, Washington, DC
NBS SP 361;
Joint RILEM-ASTM-CIB Symposium. Performance Concept in Buildings. Volume 1. NBS SP 361. May 2-5, 1972, Philadelphia, PA, 557-566 pp, 1972.

Schneider, U.; Haksever, A.
Energy Balance Equation forBurning with a Vented Compartment. (Warmebilanzberechnungen fur Brandraume mit unterschiedlichen Randbedingungen.)
Universitat Braunschweig, West Germany
CIB W14/80/55 (D); 81 p. 1980.

Schulte, R.

Structural Fire Resistance and Building Code Requirements.
Schulte and Associates, Evanston, IL
Plumbing Engineer, Vol. 33, No. 12, 18,20,22,24-25,58, December 2005.

Siu, J. C.
Challenges Facing Engineered Structural Fire Safety: A Code Official's Perspective.
Fire Protection Engineering, No. 25, 40,42,44,46-49, Winter 2005.

Simms, D. L.; Wraight, H. G. H.
Temperature and Duration of Fires. Part 2. Analysis of Some Full Scale Tests.
Fire Research Station, Borehamwood, England
FR Note 413; 14 p. October 1959.

Simms, D. L.; Hird, D.; Wraight, H. G. H.
Temperature and Duration of Fires. Part 1. Some Experiments With Models With Restricted Ventilation.
Fire Research Station, Borehamwood, England
FR Note 412; 19 p. January 1960.

Thomas, P. H.
Some Problem Aspects of Fully Developed Room Fires.
Fire Research Station, Borehamwood, England
ASTM STP 614;
National Bureau of Standards and the American Society for Testing and Materials. Fire Standards and Safety. ASTM STP 614. April 5-6, 1976, Gaithersburg, MD, American Society for Testing & Materials, PA, Robertson, A. F., Editor, 112-130 pp, 1976.

Thomas, P. H.
On a Relationship Between Certain Zone Models of Two Layer and Uniform Compartment Fires.
Fire Research Station, Borehamwood, England
Fire Science and Technology, Vol. 4, No. 2, 65-73, 1984.

Thomas, P. H.
Specification of Fire Resisting Structures.
Fire Research Station, Borehamwood, England
CIB Congress, 6th. 1974., Budapest, 540-547 pp, 1974.

Thomas, P. H.
Modelling of Compartment Fires.
Fire Research Station, Borehamwood, England
Fire Safety Journal, Vol. 5, No. 3-4, 181-190, 1983.
Vereinigung zur Forderung des Deutschen Brandschutzes e.V. (VFDB). International Fire Protection Seminar, 6th. Volume 1. Topic 1--Methods of Calculation for Ignition, Development and Propagation of a Fire. September 21-24, 1982., Karlsruhe, West Germany, 29-46 pp, 1983.

Thomas, P. H.
Fire Modelling and Fire Behavior in Rooms.
Fire Research Station, Borehamwood, England
CIB W14/80/82 (UK); PD 57/80; 39 p. 1980.

Thomas, P. H.; Bullen, M. L.
Burning of Fuels in Fully-Developed Room Fires.
Fire Research Station, Borehamwood, England
Fire Safety Journal, Vol. 2, No. 4, 275-281, 1979/1980.
CIB W14/80/84 (UK);

Thomas, P. H.; Heselden, A. J.; Law, M.
Fully-Developed Compartment Fires: Two Kinds of Behavior.
Joint Fire Research Organization, Borehamwood, England
Fire Research Technical Paper No. 18; S.O. Code No. 47-162-18; 17 p. 1967.

Wade, C. A.
Fire Engineering Design of Reinforced and Prestressed Concrete Elements. Study Report.
Building Research Association of New Zealand, Judgeford
BRANZ Study Report SR33; 69 p. January 1991.
Webster, C. T.; Wraight, H.; Thomas, P. H.
Burning of Fires in Rooms. Part 3. Effect of the Wood Thickness.
Fire Research Station, Borehamwood, England
FR Note 474; 11 p. September 1961.

Walton, W. D.; Thomas, P. H.
Estimating Temperatures in Compartment Fires.
National Institute of Standards and Technology, Gaithersburg, MD
Lund Univ., Sweden
NFPA SFPE 95; LC Card Number 95-68247;
SFPE Handbook of Fire Protection Engineering. 2nd Edition. Section 3. Chapter 6, National Fire Protection Assoc., Quincy, MA, DiNenno, P. J.; Beyler, C. L.; Custer, R. L. P.; Walton, W. D., Editor(s)(s), 3/134-147 p., 1995.

Wickstrom, U.
Application of the Standard Fire Curve for Expressing Natural Fires for Design Puposes.
National Testing Inst., Boras, Sweden
ASTM STP 882;
American Society for Testing and Materials. Fire Safety: Science and Engineering. ASTM STP 882. June 26-17, 1984, Denver, CO, Harmathy, T. Z., Editor, 145-159 pp, 1984.

Wickstrom, U.
Temperature Analysis of Compartment Fires and Fire-Exposed Structures.
Lund Institute of Technology, Sweden
CIB W14/79/39 (S); Report 79-4; 5 p. 1979.

Wickstom, U.
Use of Eurocodes for Performance-Based Design of Constructions.
Swedish National Testing and Research Institute, Boras, Sweden
Fire Safety Design of Buildings and Fire Safety Engineering. Conference Compendium. Session 2: Fire Safety Building Codes Put Into Practice. Proceedings. August 19-20, 1996, Oslo, Norway, 1-2 pp, 1996.

Yamaguchi, J.; Tanaka, T.
Selection of Design Fire Scenarios in Performance-based Fire Safety Design of Buildings.
Obayashi Corp., Tokyo, Japan
Kyoto Univ., Japan
Reaching New Horizons. Performance-Based Codes and Fire Safety Design Methods, 6th International Conference. Proceedings. June 14-16, 2006, Tokyo, Japan, Evans, D. D.; Gordon, J.; Hasemi, Y.; Sekizawa, A., Editors, 1-9 pp, 2006.

Yamanouchi, H.; Hiraishi, H.; Ohashi, Y.; Fujitani, H.; Okada, T.; Aoki, Y.; Akiyama, H.; Yano, K.; Teshigawara, M.; Gojo, W.; Saito, T.; Fukuyama, H.; Hirano, Y.
Performance-Based engineering for Structural Design of Buildings.
Building Research Inst., Tokyo, Japan
BRI Research Paper 146; 143 p. September 2000.

Yau, R.; Cheng, V.; Yin, R.
Treatment of Fire Source in CFD Models in Performance-based Fire Design.
Ove ARUP and Partners, Hong Kong
International Journal on Engineering Performance-Based Fire Codes, Vol. 5, No. 3, 54-68, 2003.

Yii, E. H.
Modelling the Effects of Fuel Types and Ventilation Openings on Post-Flashover Compartment Fires.
University of Canterbury, Christchurch, New Zealand
Building Research Association of New Zealand, Judgeford
Fire Engineering Research Report 03/1; 336 p. March 2003.

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http://www.civil.canterbury.ac.nz

Yuen, W. W.; Chow, W. K.
New Method of Assessing Uncertainties in Designing Building Fire Safety Provisions.
California Univ., Santa Barbara
Hong Kong Polytechnic Univ., Kowloon
International Journal on Engineering Performance-Based Fire Codes, Vol. 6, No. 2, 78-86, 2004.

Yung, D.
Simplified Model for Postflashover Burning of Thermoplastic Materials.
National Research Council of Canada, Ottawa, Ontario
HTD-Vol. 122;
American Society of Mechanical Engineers (ASME). Heat-transfer in Combustion Systems. Winter Annual Meeting. HTD-Vol. 122. December 10-15, 1989, San Francisco, CA, Ashgriz, N.; Quintiere, J. G.; Semerjian, H. G.; Slezak, S. E., Editors, 45-51 pp, 1989.

Yung, D.; Wade, C.; Fleischmann, C.
Development of Design Fires for Buildings.
Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia
Building Research Association of New Zealand, Judgeford
Canterbury Univ., Christchurch, New Zealand
Fire Safety Engineering International Conference 2004. Issues and Solutions. FSE2004. Proceedings. March 22-24, 2004, Sydney, Australia, 1-12 pp, 2004.

Zhang, W.; Carpenter, D. J.; Roby, R. J.; Viche, D.; Hamer, A.
Prediction of Thermal Loading for Structural Analysis Under Fire Exposure.
Combustion Science and Engineering, Inc., Columbia, MD
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engieners and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 43-52 pp, 2003.

The Role of Standard Fire Resistance Test Data

Ashton, L. A.
Use in Building Codes of the Insulation Requirement of Fire Resistance Tests.
Fire Research Station, Borehamwood, England
FR Note 430; 3 p. April 1960.

Bullock, M.
Generating Fire Engineering Data From fire-Resistance Tests.
Fire Safety Engineering, Vol. 4, No. 3, 16-19, April 1997.

Carlson, R. E.
Problem Areas in the Application of Fire Test Data in the Design of Fire Safe Buildings.
Office of California State Fire Marshall, Sacramento
Methods and Applications of Fire Testing Symposium. Proceedings. Armstrong Cork Co. June 24-25, 1965, C/1-9 pp, 1965.

Cooke, G.
Time Equivalent: Is It a Good Measurement of Compartment Fire Severity?
City Univ., London, England
Fire Safety Engineering, Vol. 6, No. 2, 26-31, April 1999.

Fire Code Reform Centre Ltd.
Project 3: Fire Resistance and Non-Combustibility. Part 1. Objectives and Performance Levels for Fire Resistance.
Fire Code Reform Centre Ltd., NSW Australia

Project 3; Part 1; 195 p. October 1996.

Gerke, L. E.; Pushkin, K. A.
Equivalent Fire Resistance of Public Buildings Constructions.
CIB W14/86/34 (USSR); 5 p. 1986.

Harada, K.; Kogure, R.; Matsuyama, K.; Wakamatsu, T.
Equivalent Fire Duration Based on Time-Heat Flux Area.
Science University of Tokyo, Chiba
Kyoto Univ., Japan
Asia-Oceania Symposium on Fire Science and Technology, 4th Proceedings. Co-Organized by Asia-Oceania Association for Fire Science and Technology (AOAFST) and Japan Association for Fire Science and Engineering (JAFSE). May 24-26, 2000, Tokyo, Japan, 513-524 pp, 2000.

Harmathy, T. Z.
Ten Rules of Fire Endurance Rating.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 1, No. 2, 93, May 1965.

Harmathy, T. Z.
Possibility of Characterizing the Severity of Fires by a Single Parameter.
National Research Council of Canada, Ottawa, Ontario
Fire and Materials, Vol. 4, No. 2, 71-76, June 1980.
CIB W14/80/44 (C); DBR Paper 901; NRCC 18296;

Hui, M. C.; England, J. P.; Young, S. A.
Traditional Fire Resistance Tests in a Performance-Based Code Environment.
Warrington Fire Research (Aust) Pty. Ltd., Victoria, Australia
Engineered Fire Protection Design...Applying Fire Science to Fire Protection Problems, International Conference. Proceedings. Co-organized by: Society of Fire Protection Engieners (SFPE) and National Institute of Standards and Technology (NIST). June 11-15, 2001, San Francisco, CA, 427-436 pp, 2001.
O'Meagher, T.; Lane, B.
Application of Time-Equivalent Analysis in the United Kingdom.
Arup Fire, Melbourne, Australia
Arup Fire, New York, NY
Volume 2;
Interscience Communications Ltd.; Building Research Establishment; National Fire Protection Association; National Institute of Standards and Technology; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute. **Interflam 2001. (Interflam '01).** International Interflam Conference, 9th Proceedings. Volume 2. September 17-19, 2001, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1395-1400 pp, 2001.
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Law, M.
Review of Formulae for T-Equivalent.
Arup Fire, Ove Arup and Partners, London, England
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 985-996 pp, 1997.

O'Meagher, T.; Lane, B.
Application of Time-Equivalent Analysis in the United Kingdom.
Arup Fire, Melbourne, Australia
Arup Fire, New York, NY
Volume 2;
Interscience Communications Ltd.; Building Research Establishment; National Fire Protection Association; National Institute of Standards and Technology; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute. **Interflam 2001. (Interflam '01).** International Interflam Conference, 9th Proceedings. Volume 2.

September 17-19, 2001, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1395-1400 pp, 2001.
For more information contact: Interscience Communications, West Yard House, Guildford Grove, London SE10 8JT, England. Fax: +44(0)208 692 5155, Email: intercomm@dial.pipex.com, Website: http://www.intercomm.dial.pipex.com

Pettersson, O.; Witteveen, J.
On the Fire Resistance of Structural Steel Elements Derived From Standard Fire Tests or By Calculation.
Lund Institute of Technology, Sweden
Institute TNO for Building Materials and Building Structures, Delft, The Netherlands
Fire Safety Journal, Vol. 2, 73-87, 1979/1980.
CIB W14/82/38 (S); Report R80-2;

Pettersson, O.
Possibilities of Predicting the Fire Behavior of Structures on the Basis of Data From Standard Fire Resistance Tests.
Lund Institute of Technology, Sweden
Bulletin 20; 44 p. 1971.
Colloque sur les Principes de la Securite au Feu des Structures. CentreScientifique et Technique du Batiment. June 4, 1971, Paris, France, 1971.

Robertson, A. F.; Gross, D.
Fire Load, Fire Severity and Fire Endurance.
National Bureau of Standards, Gaithersburg, MD
ASTM STP 464;
American Society for Testing and Materials. Fire Test Performance. Winter Meeting. Proceedings. ASTM STP 464. February 2-7, 1969, Denver, CO, 3-29 pp, 1969.

Schaumann, P.; Heise, A.
Performance-Based Design of Office Building Using the Equivalent Time Method.
University of Hannover, Germany
Designing Structures for Fire. Proceedings. Co-Sponsored by: Society of Fire Protection Engineers and Structural Engineering Institute. September 30-October 1, 2003, Baltimore, MD, DEStech Publications, Inc., 113-123 pp, 2003.

Sultan, M. A.; Kodur, V. K. R.
Light-Weight Frame Wall Assemblies: Parameters for Consideration in Fire Resistance Performance-Based Design.
National Research Council of Canada, Ottawa, Ontario
Fire Technology, Vol. 36, No. 2, 75-88, May 2000.

Thomas, G. C.; Buchanan, A. H.; Fleischmann, C. M.
Structural Fire Design: The Role of Time Equivalence.
University of Canterbury, Christchurch, New Zealand
International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, 607-618 pp, 1997.

Thomas, P. H.
Fire Resistance Required to Survive a Burn Out.
Fire Research Station, Borehamwood, England
FR Note 901; 29 p. Novmeber 1970.

Wickstrom, U.
Natural Fires for Design of Steel and Concrete Structures: A Swedish Approach.
Swedish National Testing Inst., Boras, Sweden
SP Report 1990:04;
International Symposium on Fire Engineering for Building Structures and Safety. November 14-15, 1989, Melbourne, Australia, 67-72 pp, 1989.