STANDARD

SFPE Engineering Standard on Calculation Methods to Predict the Thermal Performance of Structural and Fire Resistive Assemblies

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Engineering A Fire Safe World

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CHAPTER 1

Scope and Purpose

1.1 Scope: This standard provides requirements for the development and use of methods to predict the thermal response of structures using listed fire resistive assemblies to time dependent thermal boundary conditions imposed by fires.

1.1.1 The design of structural fire resistance requires three major steps: (1) determination of the thermal exposure to a structure resulting from a fire; (2) determination of the temperature history within the structure, or portion thereof; and (3) determination of the structural response. This standard is limited to the second step in this process.

1.1.2 This standard does not provide design objectives. The design objectives for structural fire resistance shall be determined from the applicable code or as defined by a performance-based design process, subject to the concurrence of the enforcement official, building owner, and other stakeholders.

1.2 Purpose: The purpose of this standard is to provide requirements for calculation methods that provide time-dependent temperature field information resulting from fire exposures required for engineered structural fire design (including structural systems and fire barriers).

1.3 General Requirements

1.3.1 Methods of calculating thermal response of structural and fire resistive assemblies must be demonstrated to be technically sound using the means and methods developed in this standard (see Chapters 4–7).

1.3.2 Technical documentation that demonstrates that the method is technically sound (see Chapters 4–7) and is appropriate for the analysis being conducted (see Chapter 8) shall be developed and submitted to the enforcement official. Such documentation shall include a description of the theoretical basis of the method and comparisons of its predictions to fire test data (see Chapter 9).

CHAPTER 2

Referenced Publications

SFPE. (2011). *SFPE Engineering Standard on Calculating Fire Exposures to Structures*. Bethesda, MD: SFPE.

CHAPTER 3

Definitions

3.1 Definitions

Enforcement official. The enforcement officer or other designated authority charged by the applicable governing body with the duties of administration and enforcement of a code or standard, including duly authorized representatives.

Fire exposure (C)[1]. The thermal conditions due to a fire, environment generated by a fire, or source representing a fire (such as a furnace or heaters) to which a material, product, or assembly is exposed.

Fire resistance. The ability of a building structure or assembly to continue to perform its intended function with respect to load bearing capacity, stability, mechanical integrity, and insulation when exposed to the effects of a fire.

Fire-resistance rating (C). The period of time a building assembly maintains the ability to confine a fire, continues to perform a given structural function, or both, as determined by the tests (e.g., ISO 834, ASTM E 119, UL 263, or EN 1363-1).

Fire resistive assembly. A part of a structure composed of multiple components or elements intended to work together to fulfill the fire resistance of the assembly. Examples include floor-ceiling assemblies, roof-ceiling assemblies, composite floor decks, and light-frame walls with gypsum wallboard.

Listed (C). Equipment, materials, or services included in a list published by an organization that is acceptable to the enforcement official and concerned with evaluation of products or services; that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services; and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

Mechanical integrity (C). Maintaining the geometry and component materials of the assembly in place.

Method. The procedure used to predict the temperatures throughout the assembly, including input data determination, computational method, verification, validation, and documentation of the procedure and its application.

Structure. An arrangement of parts in a building or other construction that serves to carry loads.

Structural assembly. A part of a structure composed of multiple components or elements intended to work together to fulfill the structural purpose of the assembly.

[1]Where the suffix "(C)" is provided following a defined term or paragraph in this standard, additional explanatory commentary is provided in the commentary section at the end of the standard.

Structural element. An individual component of a structure, such as a beam or a column.

Structural response. The mechanical response of a structure, or a portion thereof, to elevated temperatures due to a fire. The effects may include structural deformations and stresses induced by heating and cooling of structural systems during fire exposure, as well as temperature-dependent changes in structural stiffness and strength.

Thermal boundary condition (C). The conditions that describe the heat exchange of the structural assembly surfaces with the fire exposure and other surroundings.

Thermal response. The temperature distribution of a fire resistive assembly or structural element when exposed to thermal boundary conditions.

Validation (C). The process of determining the degree to which a calculation method adequately describes the physical phenomena of interest.

Verification (C). The process of determining the degree of accuracy of the solution of the governing equations.

CHAPTER 4

Method Requirements

4.1 The method developed or used shall include the capabilities and items identified in this chapter.

4.2 (C) The method shall provide time dependent temperatures throughout the structural or fire resistive assembly resulting from a fire exposure. The nature and level of complexity of the method shall be determined based on validation under the Chapter 7 requirements.

4.3 (C) The method shall contain a mathematical description of the thermal model that will be used in the verification, validation, and final application. This description shall include the details of the time and spatial discretization techniques as well as the procedure used to solve the governing equations.

4.4 (C) The method shall provide a description of how material properties are implemented into the modeling framework.

4.5 (C) The method shall include a mathematical description of the thermal boundary conditions in accordance with the requirements of Chapter 5.

4.6 (C) The method shall include the definition of experimental protocols for determination of the required properties of materials included in the structural or fire resistive assembly in accordance with the requirements of Chapter 5.

4.7 (C) The method shall apply only to assembly designs that are listed in accordance with the requirements of the relevant building code or regulation.

4.8 The method shall include a description of all analytical procedures required to perform the prediction of temperatures.

4.9 The method shall include verification of the procedures and their implementation in accordance with the requirements of Chapter 6.

4.10 The method shall include validation of the analytical procedures and their implementation in accordance with the requirements of Chapter 7.

4.11 The method shall include stated limitations of use based on the validation of the method conducted in accordance with the requirements of Chapter 7.

4.12 The method shall include procedures for estimating the uncertainty of its predictions of temperatures in accordance with the requirements of Chapter 7.

4.13 The application of the method shall be in accordance with the requirements of Chapter 8.

4.14 The method shall be documented in accordance with the requirements of Chapter 9.

CHAPTER 5

Model Input Data Definition

5.1 (C) Material Properties

5.1.1 (C) All material properties used in the method shall be determined using documented experimental procedures.

5.1.2 (C) The uncertainty in material properties shall be determined based on the documentation of the experimental procedure and shall be consistent with the findings of the validation performed under Chapter 7 requirements.

5.1.3 (C) Properties of materials are not required if the material as used in the assembly can be demonstrated to have no measurable effect on the predicted temperatures.

5.2 Geometric Definition of the Assembly

5.2.1 Definition of the geometric inputs to the method shall be consistent with the level of detail utilized in the validation performed under Chapter 7 requirements.

5.2.2 Materials or layers may be ignored if they can be demonstrated to have no measurable effect on the predicted temperatures or where ignoring the material is demonstrated to provide conservative predictions.

5.3 (C) Thermal Boundary Conditions

5.3.1 Thermal boundary conditions shall be determined using the *SFPE Engineering Standard on Calculating Fire Exposures to Structures*.

CHAPTER 6

Verification

6.1 (C) If the method produces a solution of the discretized form of the governing equations, the solution shall be shown to converge to the exact solution with increasing temporal or spatial resolution using the same solution approach planned for the application.

6.2 Verification shall be performed for the particular version of the model planned for use in an application, and shall be repeated when a different model version is planned for use. If a finite element method is used, then the same spatial discretization and element type that is used in the validation and verification study shall also be used in the final application.

6.3 (C) Verification of the algorithms shall be performed using the relevant verification cases in Annex A which include some or all of the physics of the method that will be used in the final application.

6.4 (C) Where Annex A does not address the physics contained in the method, additional verification cases, produced and documented by the user, the developer, or others shall be used that are capable of exercising all aspects of the method.

6.5 (C) Grid resolution requirements for a grid-independent solution shall be determined and reported based on grid resolution studies using the verification cases.

6.6 All verification work shall be documented fully in a verification report, to include a full description of all cases verified, all comparisons against the verification cases, description of model discretization or elements used, grid resolution studies, and all findings, conclusions, and limitations identified in the verification process.

6.7 Justification of the sufficiency of the verification cases used shall be provided in the verification report (see Chapter 9).

CHAPTER 7

Method Validation

7.1 (C) The method shall be validated against measurements from experiments that are relevant to the given application. The scope of the experiments shall include fire scenarios and types of assemblies under consideration.

7.2 (C) Validation shall be performed for the particular version of the model planned for use in an application, and shall be repeated when a different model version is planned for use. The same discretization or element shall be used in the validation that is planned for use in the final application.

7.3 (C) Validation shall include comparisons with testing comparable to those used to list the assembly.

7.4 The experimental measurements used for validation of the method shall be available and fully documented in a complete and accurate test report produced and documented by the user, the developer, or others.

7.5 An assessment of the measurement uncertainty shall be included in the test report or shall be undertaken as part of the validation process using methods and sources from the scientific literature.

7.6 The uncertainty of the method to predict each validation case shall be determined and reported in a validation report.

7.6.1 The validation report shall list the measured quantities that have been compared to the model predictions.

7.6.2 Assembly surface and interior temperatures, reported as a function of time, shall be compared directly with model predictions considering the uncertainty of the model and experimental data.

7.6.3 The validation report shall justify and document the selection of quantitative metrics used to compare model prediction and experimental measurement.

7.6.4 Comparisons shall express comparative values in terms of a *relative difference*, i.e.:

$$\xi = \frac{\Delta T_{\text{model}} - \Delta T_{\text{exp}}}{\Delta T_{\text{exp}}}$$

where the symbol Δ represents the temperature rise over ambient.

7.6.5 (C) The validation process shall define the conditions under which mechanical integrity of all components of the assembly is assured.

7.7 Reporting

7.7.1 The validation report shall provide sufficient detail about the experiments and the model inputs such that the calculations could be repeated by the reader. At a minimum, the following information should be provided:

7.7.1.1 Person or organization performing the validation study;

7.7.1.2 References to model documentation and reports of experimental measurements;

7.7.1.2.1 Documentation of the experimental determination of input data, model boundary conditions, input and output files, and all other aspects of method application, at a level of detail that would allow the work to be reproduced by others;

7.7.1.3 Description of the fire scenarios which the experiments were designed to address;

7.7.1.4 Quantification of the model accuracy, using the metrics and analysis described in Chapter 7;

7.7.1.5 Conclusion, including limitations of the model and its range of applicability.

CHAPTER 8

Model Application Procedures

8.1 The application of the method shall conform to the requirements of this chapter and the limitations identified in the validation report.

8.2 (C) Only the model version that has been verified through procedures in Chapter 6 and validated as described in Chapter 7 shall be used for predictions in an application. If a finite element method is used, then the same spatial discretization and element type that is used in the validation and verification study shall also be used in the final application.

8.3 (C) Characterization of the assembly and scope of analysis shall be provided.

8.3.1 The type of assembly and thermal exposure to be evaluated using the method shall conform to the limitations identified in the validation report.

8.3.2 The method shall be applied only to assemblies within the limitations of the listed design and the validation cases.

8.3.3 (C) The method shall only be utilized for analyses of fire exposures for which it can be demonstrated that the assembly will maintain mechanical integrity throughout the exposure, consistent with the assumptions of the analysis method.

8.3.4 The fire exposure and thermal boundary condition used in each application shall be documented.

8.3.5 Input data shall be determined and used in accordance with the requirements of Chapter 5 and consistent with the validation of the method described in Chapter 7.

8.3.6 The fire exposure and thermal boundary conditions shall be determined using documented procedures consistent with the validation performed under Chapter 7 requirements.

8.4 Results of the application of the method shall be fully documented.

8.4.1 The uncertainty associated with the model results and the relative level of accuracy of the model and/or calculations used shall be addressed in the analysis via sensitivity or uncertainty analysis to evaluate the impact of the uncertainty associated with the various input values and assumptions.

8.4.2 Documentation associated with the level of uncertainty in the analysis should be submitted with the modeling results, to illustrate the confidence level in the thermal modeling results as well as incorporate the uncertainty with the additional analysis of the structural response of the assemblies, or to allow for the incorporation of this information into additional analysis of the structural or mechanical response of the structural assemblies.

8.5 All documentation of the method and the application of the method shall be provided to the enforcement official and all designated peer reviewers for evaluation.

CHAPTER 9

Verification/Validation Report

9.1 The method and its application shall be fully documented.

9.2 Documentation of the method shall include:

9.2.1 Method report: A complete description of the inputs required, the method for determining inputs, the mathematical model used for predictions, the underlying assumptions in the mathematical model, and the limits of validity;

9.2.2 Verification report: Full documentation of each verification case consistent with the requirements of Chapter 6, and all limitations and requirements for use that arise out of the verification process;

9.2.3 Validation report: Full documentation of each validation case consistent with the requirements of Chapter 7, including the source and uncertainty of the experimental data, the procedures and results of testing used to define material properties, the comparison of the method predictions with experimental data, and all limitations and requirements for use that arise out of the validation process;

9.2.4 Application report: Full documentation of the application of the method to a project consistent with the requirements of Chapter 8, including documentation of the inputs to the method and their source, results and uncertainties, and findings and conclusions resulting from the application of the method.

Annex A: Verification Cases

Verification shall be performed for the particular version of models planned for use in an application. It shall be performed using the relevant verification cases in this annex which include some or all of the physics of the method that will be used in the final application.

Precisely calculated reference temperatures of 16 cases of bodies have been listed, representing a variety of problems that are relevant in fire safety engineering involving a range of complexities:

- **Boundary conditions.** Fire exposures of surfaces consist of two independent components, heat transfer by convection dependent on adjacent gas temperature and by radiation dependent on incident radiation. The boundary condition of a fire-exposed structure is generally highly nonlinear as the radiation emitted from surfaces depends on the temperature to the fourth power.
- **Geometric effects.** In some cases heat transfer to structures can be simplified to 0D (lumped mass) or 1D models, whereas in more complicated cases 2D or 3D models may be needed. Composite assemblies involving multiple materials and voids require special consideration.
- **Material effects.** Thermal conductivity and specific heat capacity are generally dependent on temperature in fire-exposed structures. Hydroscopic materials such as concrete have latent heat effects due to moisture evaporation. Combustible solids undergo thermal decomposition and materials such as timber undergo charring. Intumescent coatings undergo rapid expansion and changes of thermal properties when subjected to elevated temperatures. Some of these complex material effects are not well understood or possible to model at present and are therefore not addressed in the *Standard*.

Case 3 was solved analytically and the other cases were modeled in the finite element codes Abaqus and TASEF. The accuracy of the solutions was within one tenth of a degree Celsius.

GOVERNING EQUATIONS

Heat conduction within an isotropic solid is governed by the following equation (the nomenclature is provided in Table 1):

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \quad (1)$$

In cylindrical coordinates where the temperature varies in the radial coordinate only, Equation 1 can be written:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(r\ k \frac{\partial T}{\partial r}\right) \quad (2)$$

The boundary condition in both Cartesian and cylindrical coordinate systems is typically expressed:

$$-k\frac{\partial T}{\partial n} = \dot{q}'' \qquad (3)$$

where n denotes the normal direction pointing into the solid and $\dot{q}''$ is the heat flux (per Equation 4 or 6) onto the solid surface.

For the problems to follow, the heat flux, $\dot{q}''$, is expressed in one of two ways. For cases where the solid object is completely surrounded by an optically thick gas whose temperature varies only as a function of time, $T_f(t)$, the heat flux is given by:

$$\dot{q}'' = \varepsilon\sigma\left(\overline{T}_f^4 - \overline{T}_s^4\right) + h\left(T_f - T_s\right) \qquad (4)$$

where T_f and $\overline{T}_f$ are the gas temperature in °C and K, respectively, and T_s and $\overline{T}_s$ are the calculated surface temperature in °C and K, respectively. For example, the standard ISO 834 fire is given by the following time-temperature curve:

$$T_f(t) = 20 + 345\ \log\left(\frac{8t}{60} + 1\right) \qquad (5)$$

where T_f is in °C, and t is the time in seconds. For the radiant heater case where the incident radiation is specified, the boundary condition should be expressed in the form of the incident radiative heat flux $\dot{q}''_{inc}$ by

$$\dot{q}'' = \varepsilon\left(\dot{q}''_{inc} - \sigma\overline{T}_s^4\right) + h\left(T_g - T_s\right) \qquad (6)$$

Note that $\overline{T}_s$ is absolute temperature of the surface in Kelvin, K. The convective heat transfer coefficient, *h*, is used to describe convective heat transfer to the sample surface as proportional to the temperature difference between the gas temperature, T_g, and the surface temperature.

Many computer codes do not allow the specification of a radiation boundary condition in the form presented in Equation 6. However, Equation 6 may alternatively be written as

$$\dot{q}'' = \varepsilon\sigma\left(\overline{T}_r^4 - \overline{T}_s^4\right) + h\left(T_g - T_s\right) \qquad (7)$$

where the black body radiation temperature is defined as $\overline{T}_r = \sqrt[4]{\frac{\dot{q}''_{inc}}{\sigma}}$. Equation 7 can be used in place of Equation 6 if necessary.

TABLE 1. NOMENCLATURE

Symbol	Quantity	Units
A/V	surface area to volume ratio	1/m
c	specific heat	J/(kg·K)
h	heat transfer coefficient	W/(m²·K)
k	thermal conductivity	W/(m·K)
$\dot{q}''$	heat flux	W/m² or kW/m²
r	radial coordinate	m
T	temperature	°C
$\overline{T}$	temperature	K
t	time	s
(x, y, z)	Cartesian coordinates	m
σ	Stefan-Boltzmann constant	$5.67x10^{-8}$ W/($m^2 \cdot K^4$)
ρ	density	kg/m³
ε	emissivity	dimensionless

CASE 1—LUMPED MASS SUBJECTED TO STANDARD FIRE

A plate $(\rho = 7850 \text{ kg/m}^3,\ c = 520 \text{ J/(kg}\cdot\text{K)},\ \varepsilon = 0.7)$ that has a thickness of 4 cm and an initial temperature of 20 °C is heated on the top and bottom surfaces according to the standard ISO 834 fire curve, Equation 5. As the thermal conductivity of the material is relatively large, the temperature in the section, T, can be taken as uniform. For the convection heat transfer coefficient, $h = 25 \text{ W/(m}^2\cdot\text{K)}$, calculate the temperature of the plate as a function of time and compare to the values given in Table 2.

TABLE 2. REFERENCE VALUES

Time (s)	Temperature (°C)
0	20.0
300	97.8
600	234.4
900	390.2
1200	539.7
1500	662.9
1800	751.9

CASE 2—LUMPED MASS SUBJECTED TO INCIDENT FLUX

A 1 cm thick horizontal flat plate ($\rho = 7850$ kg/m^3, $c = 560$ J/(kg · K), $\varepsilon = 0.9$) with an initial temperature of 20 °C is exposed from above with a radiant heater set to an incident flux of $\dot{q}''_{inc} = 50$ kW/m^2. The heat flux to the top surface of the plate is given by Equation 6. The gas temperature is 20 °C and $h = 12$ W/$(\mathrm{m}^2 \cdot \mathrm{K})$. Assuming that the bottom and sides of the plate are perfectly insulated, and that the thermal conductivity of the material is sufficiently large to assume a uniform temperature with depth, calculate the temperature of the plate as a function of time and compare to the values given in Table 3.

TABLE 3. REFERENCE VALUES

Time (s)	Temperature (°C)
0	20.0
180	195.0
360	347.3
540	466.2
720	547.5
900	596.6

CASE 3—1D HEAT TRANSFER WITH COOLING BY CONVECTION

A 1 m thick slab of material ($k = 1$ W/$(\mathrm{m} \cdot \mathrm{K})$, $\rho = 1000$ kg/m^3, $c = 1$ J/(kg · K), $\varepsilon = 0$) with an initial temperature of 1000 °C is cooled via convection only. The surrounding air temperature is 0 °C and $h = 1$ W/$(\mathrm{m}^2 \cdot \mathrm{K})$. Assuming that the back and sides of the slab are perfectly insulated, calculate the temperature of the back side of the slab as a function of time and compare to the values given in Table 4.

TABLE 4. REFERENCE VALUES

Time (s)	Temperature (°C)
0	1000.0
60	999.3
300	891.8
600	717.7
900	574.9
1200	460.4
1500	368.7
1800	295.3

CASE 4—1D AXISYMMETRIC HEAT TRANSFER BY CONVECTION

A metal pipe of circular cross section ($k = 50\ \text{W}/(\text{m}\cdot\text{K}), \rho = 5000\ \text{kg/m}^3,\ c = 500\ \text{J/(kg}\cdot\text{K)},\ \varepsilon = 0,$) is coated with an insulation material ($k = 0.05\ \text{W}/(\text{m}\cdot\text{K}),\ \rho = 500\ \text{kg/m}^3,\ c = 1000\ \text{J/(kg}\cdot\text{K)},\ \varepsilon = 0$). The insulation layer is contained within a 1 mm thick metallic cover with the same properties as the pipe. The inner and outer radii of the pipe are 25 mm and 30 mm, and the inner and outer radii of the insulation layer are 30 mm and 80 mm. The surrounding air temperature is 0 °C, and the temperature of the fluid flowing through the pipe is 1000 °C. The inner and outer heat transfer coefficients are 100 W/(m²·K) and 10 W/(m²·K), respectively. Calculate the steady-state temperature at various depths and compare with the values given in Table 5.

TABLE 5. REFERENCE VALUES

Radius (mm)	Temperature (°C)
25	981.2
30	981.0
40	710.3
50	500.3
60	328.8
70	183.7
80	58.1
81	58.1

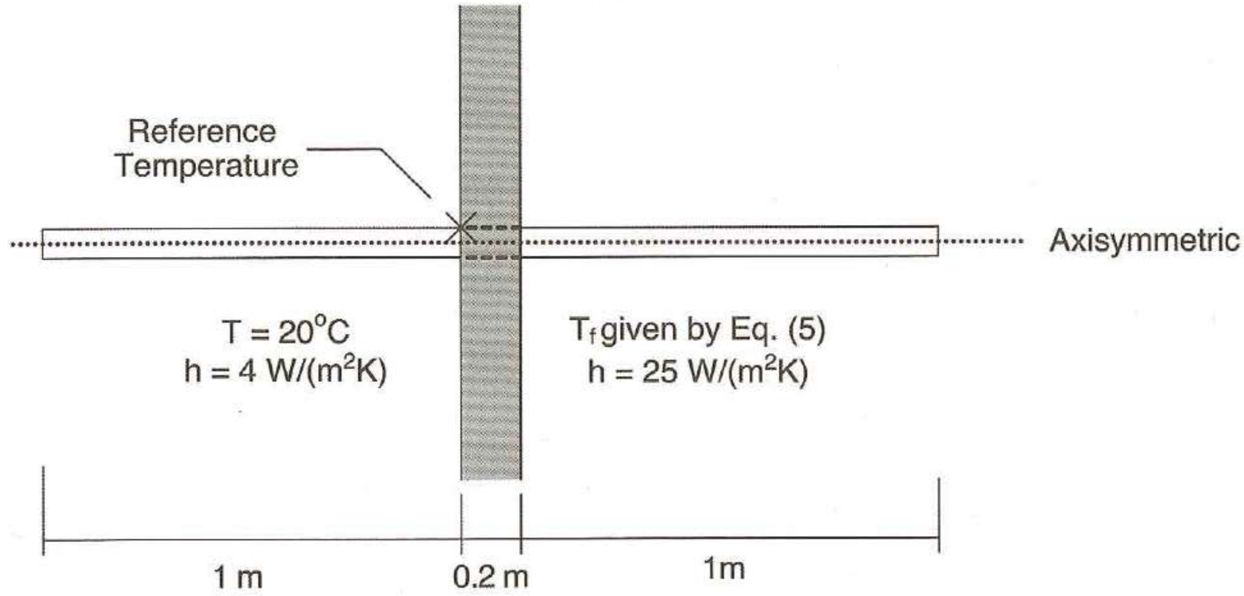
CASE 5—2D AXISYMMETRIC HEAT TRANSFER BY CONVECTION AND RADIATION

A metal pipe of circular cross section ($k = 50\ \text{W}/(\text{m}\cdot\text{K}),\ \rho = 7850\ \text{kg/m}^3,\ c = 500\ \text{J/(kg}\cdot\text{K)},\ \varepsilon = 0.8$) penetrates a 0.2 m thick solid wall ($k = 1.5\ \text{W}/(\text{m}\cdot\text{K}),\ \rho = 2400\ \text{kg/m}^3,\ c = 1000\ \text{J/(kg}\cdot\text{K)},\ \varepsilon = 0.8$), as shown in Figure 1 (page 24). The inner and outer radii of the pipe are 95 mm and 100 mm. The pipe is 2.2 m in length and extends 1 m on each side of the wall. The initial temperature is 20 °C. The inner surface of the pipe is perfectly insulated. The outer surfaces of the pipe and wall are subjected to convection and radiation according to Equation 4. On one side of the wall, the temperature is 20 °C and the heat transfer coefficient is 4 W/(m²·K). On the other side of the wall, the temperature is given by the ISO 834 time-temperature curve, Equation 5, and the heat transfer coefficient is 25 W/(m²·K). Calculate the temperature at the intersection between the pipe and wall on the unheated surface (as shown in Figure 1) and compare with the values given in Table 6.

TABLE 6. REFERENCE VALUES

Time (h)	Temperature (°C)
0.0	20
0.5	49
1.0	107
1.5	158
2.0	201

FIGURE 1. METAL PIPE PENETRATES SOLID WALL



CASE 6—2D HEAT TRANSFER WITH COOLING BY CONVECTION

A 2 m by 2 m square column ($k = 1\ \text{W}/(\text{m}\cdot\text{K})$, $\rho = 1\ \text{kg/m}^3$, $c = 1\ \text{J/(kg}\cdot\text{K)}$, $\varepsilon = 0$) with an initial temperature of 1000 °C cools via convection only. Assuming that $h = 1\ \text{W}/(\text{m}^2\cdot\text{K})$ and the surrounding air temperature is 0 °C, calculate the temperature at the center of the column as a function of time and compare to the values given in Table 7.

TABLE 7. REFERENCE VALUES

Time (s)	Temperature (°C)
0.0	1000.0
0.1	986.4
0.2	903.8
0.4	690.2
0.6	514.7
0.8	382.7
1.0	284.5

CASE 7—2D HEAT TRANSFER BY CONVECTION AND RADIATION

A 0.2 m by 0.2 m square column ($k = 1\ \text{W}/(\text{m}\cdot\text{K})$, $\rho = 2400\ \text{kg/m}^3$, $c = 1000\ \text{J/(kg}\cdot\text{K)}$, $\varepsilon = 0.8$) is heated according to the ISO 834 time-temperature curve, Equation 5. Assuming that $h = 10\ \text{W}/(\text{m}^2\cdot\text{K})$ and that the initial temperature T_∞ is 0 °C, calculate the temperature at the column center, corner, and middle side surface as a function of time and compare to the values given in Table 8.

TABLE 8. REFERENCE VALUES

Time (min)	Temperature (°C)		
	Center	Side	Corner
0	0	0	0
30	9	721	809
60	127	873	921
90	315	952	984
120	492	1005	1028
150	640	1045	1062
180	757	1077	1089

CASE 8—2D HEAT TRANSFER WITH TEMPERATURE-DEPENDENT CONDUCTIVITY

A 0.2 m by 0.2 m square column ($\rho = 2400\ \text{kg/m}^3$, $c = 1000\ \text{J/(kg}\cdot\text{K)}$, $\varepsilon = 0.8$) is heated according to the ISO 834 time-temperature curve, Equation 5. The thermal conductivity of the column material varies linearly with temperature such that its value is 1.5 W/(m·K) at 0 °C, 0.7 W/(m·K) at 200 °C, and 0.5 W/(m·K) at 1000 °C. Assuming that $h = 10\ \text{W}/(\text{m}^2\cdot\text{K})$ and that the initial air temperature is 0 °C, calculate the temperature at the column center, corner, and middle side surface as a function of time and compare to the values given in Table 9.

TABLE 9. REFERENCE VALUES

Time (min)	Temperature (°C)		
	Center	Side	Corner
0	0	0	0
30	18	743	815
60	99	884	923
90	190	958	985
120	300	1008	1028
150	411	1046	1062
180	512	1077	1089

CASE 9—2D HEAT TRANSFER IN A COMPOSITE SECTION WITH TEMPERATURE-DEPENDENT CONDUCTIVITY

A hollow square metal tube ($\rho = 7850$ kg/m^3, $c = 600$ J/(kg · K), $\varepsilon = 0.8$) is filled with an insulation material ($k = 0.05$ W/(m · K), $\rho = 50$ kg/m^3, $c = 1000$ J/(kg · K), $\varepsilon = 0$). The thermal conductivity of the metal tube varies linearly with temperature such that its value is 54.7 W/(m·K) at 0 °C, 27.3 W/(m·K) at 800 °C, and 27.3 W/(m·K) at 1200 °C. The tube walls are 0.5 mm thick, and the exterior width of the assembly is 0.201 m. The surrounding air temperature is 1000 °C, and the initial temperature of the assembly is 0 °C. Assuming that the heating is by convection and radiation, Equation 4, and that the heat transfer coefficient is 10 W/(m^2·K), calculate the temperature at the center of the tube as a function of time and compare with the values given in Table 10.

TABLE 10. REFERENCE VALUES

Time (min)	Temperature (°C)
0	0
30	341
60	723
90	886
120	953
150	981
180	992

CASE 10—2D AXISYMMETRIC HEAT TRANSFER WITH NON-UNIFORM HEAT FLUX

A bar with circular cross section of diameter 20 cm and length 200 cm ($k = 50$ W/(m · K), $\rho = 7850$ kg/m^3, $c = 500$ J/(kg · K), $\varepsilon = 0.8$) is heated uniformly over half of its length by an incident radiant heat flux of 30 kW/m^2 with convection to ambient, Equation 6. The remaining half of the bar's length is cooled by convection and radiation to ambient. The surrounding air temperature over the entire length of the bar is 20 °C, and the initial temperature of the bar is 20 °C. Assuming that the heat transfer coefficient is 10 W/(m^2·K) and that the ends of the bar are perfectly insulated, calculate the temperature along the center of the bar at 60 min for the locations given in Table 11.

TABLE 11. REFERENCE VALUES

Distance (cm)	Temperature (°C)
0	357
25	357
50	353
75	325
100	195
125	59
150	25
175	20
200	20

CASE 11—LUMPED MASS WITH MOISTURE EVAPORATION

A 1 cm by 1 cm square column (dry properties: $\rho = 2400\ \mathrm{kg/m^3}$, $c = 1000\ \mathrm{J/(kg \cdot K)}$, $\varepsilon = 0.8$) is heated according to the ISO 834 time-temperature curve, Equation 5. If the thermal conductivity of the material is relatively large, the temperature in the section, T, can be taken as uniform. The column contains 2.08 % water by mass that evaporates at temperatures between 100 °C and 120 °C. The density of water and specific heat capacity of water can be taken as 1000 kg/m³ and 4187 J/(kg · K), respectively. The latent heat of evaporation (2260 kJ/(kg of water)) is assumed to be in addition to the specific heat of the material. During evaporation, the amount of water is assumed to decrease linearly to zero. Assuming that $h = 10\ \mathrm{W/\left(m^2 \cdot K\right)}$ and that the initial temperature is 20 °C, calculate the temperature of the column as a function of time and compare to the values given in Table 12.

TABLE 12. REFERENCE VALUES

Time (min)	Temperature (°C)
0	20
1	83
2	112
3	148
4	192
5	225
6	249
7	266
8	278
9	285
10	291
15	299

CASE 12—1D HEAT TRANSFER WITH MOISTURE EVAPORATION

A 16 cm thick wall (dry properties: $\rho = 500\ \text{kg/m}^3$, $c = 800\ \text{J/(kg}\cdot\text{K)}$, $k = 0.1\ \text{W/(m}\cdot\text{K)}$, $\varepsilon = 0.8$) is heated on both sides according to the ISO 834 time-temperature curve, Equation 5. The water content of the wall is 10% by mass, and the water is assumed to evaporate between 100 °C and 110 °C. The density of water and specific heat capacity of water can be taken as 1000 kg/m³ and 4187 J/(kg·K), respectively. The latent heat of evaporation (2260 kJ/(kg of water)) is assumed to be in addition to the specific heat of the material. During evaporation, the amount of water is assumed to decrease linearly to zero. Assuming that $h = 25\ \text{W}/\left(\text{m}^2\cdot\text{K}\right)$ and that the initial temperature is 20 °C, calculate the temperature at various depths as a function of time and compare to the values given in Table 13.

TABLE 13. REFERENCE VALUES

Time (min)	Temperature (°C)		
	Surface	4 cm	Center
0	20	20	20
15	717	24	20
30	829	50	20
45	893	83	24
60	938	133	33
75	972	206	46
90	1001	268	62
105	1024	323	80
120	1045	371	94

CASE 13—2D HEAT TRANSFER WITH MOISTURE EVAPORATION

A 0.2 m by 0.2 m square column (dry properties: $\rho = 2400\ \text{kg/m}^3$, $c = 1000\ \text{J/(kg}\cdot\text{K)}$, $\varepsilon = 0.8$) is heated according to the ISO 834 time-temperature curve, Equation 5. The thermal conductivity of the column material varies linearly with temperature such that its value is 1.5 W/(m·K) at 0 °C, 0.7 W/(m·K) at 200 °C, and 0.5 W/(m·K) at 1000 °C. The column contains 2.08 % water by mass that evaporates at temperatures between 100 °C and 120 °C. The density of water and specific heat capacity of water can be taken as 1000 kg/m³ and 4187 J/(kg·K), respectively. The latent heat of evaporation (2260 kJ/(kg of water)) is assumed to be in addition to the specific heat of the material. During evaporation, the amount of water is assumed to decrease linearly to zero. Assuming that $h = 10\ \text{W}/\left(\text{m}^2\cdot\text{K}\right)$ and that the initial temperature is 20 °C, calculate the temperature at the column center, corner, and middle side surface as a function of time and compare to the values given in Table 14.

TABLE 14. REFERENCE VALUES

Time (min)	Temperature (°C)		
	Center	Side	Corner
0	20	20	20
30	31	764	835
60	85	904	943
90	147	978	1005
120	272	1028	1048
150	393	1066	1082
180	500	1097	1109

CASE 14—2D HEAT TRANSFER IN A COMPOSITE SECTION WITH MOISTURE EVAPORATION AND TEMPERATURE-DEPENDENT CONDUCTIVITY

A hollow metal square tube ($\rho = 7850$ kg/m^3, $c = 600$ J/(kg · K), $\varepsilon = 0.8$) is filled with a cementitious material. The tube walls are 10 mm thick, and the exterior dimensions are 220 mm x 220 mm. The thermal conductivity of the tube is 54.7 W/(m·K) at 0 °C and decreases linearly to 27.3 W/(m·K) at 800 °C and remains at this same value for higher temperatures. The cementitious material ($\rho = 2400$ kg/m^3, $c = 1000$ J/(kg · K)) contains 2.08 % water by mass that evaporates between 100 °C and 120 °C. The density of water and specific heat capacity of water can be taken as 1000 kg/m^3 and 4187 J/(kg · K), respectively. The latent heat of evaporation (2260 kJ/(kg of water)) is assumed to be in addition to the specific heat of the material. During evaporation, the amount of water is assumed to decrease linearly to zero. The thermal conductivity of the cementitious material varies linearly with temperature such that its value is 1.5 W/(m·K) at 0 °C, 0.7 W/(m·K) at 200 °C, and 0.5 W/(m·K) at 1000 °C. The surrounding air temperature is 1000 °C, and the initial temperature of the column is 0 °C. Assuming that the heat transfer coefficient is 10 W/(m^2·K), calculate the temperature at the center, side, and corner of the concrete portion of the column as a function of time and compare with the values given in Table 15.

TABLE 15. REFERENCE VALUES

Time (min)	Temperature (°C)		
	Center	Side	Corner
0	0	0	0
30	19	951	981
60	90	971	990
90	177	979	994
120	309	984	995
150	426	988	996
180	524	990	997

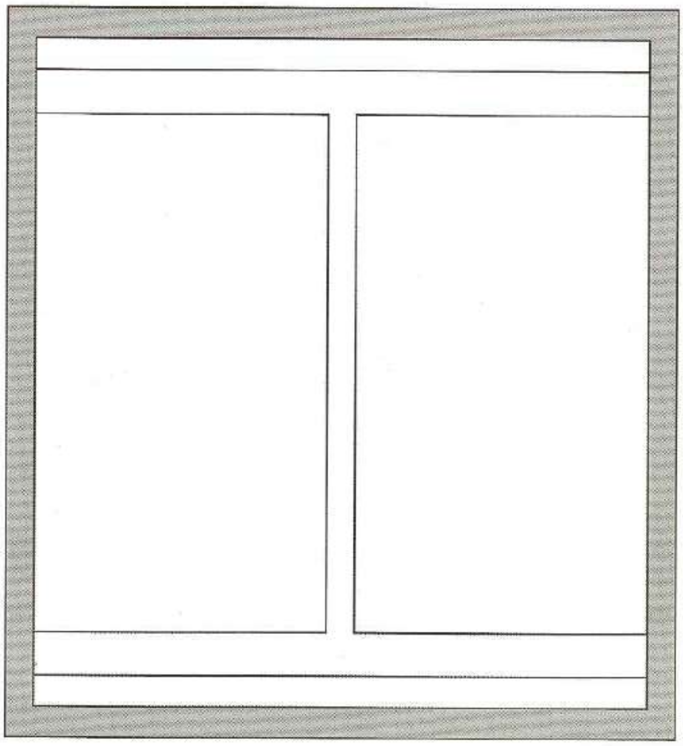
CASE 15—2D HEAT TRANSFER IN A COMPOSITE SECTION WITH CAVITY RADIATION

A metal wide flange column ($\rho = 7850$ kg/m^3, $c = 600$ J/(kg·K), $\varepsilon = 0.8$) is protected by a 1 cm thick insulation board ($\rho = 870$ kg/m^3, $c = 1130$ J/(kg·K), $\varepsilon = 0.8$) as shown in Figure 2. The wide flange column fits within a square area 200 mm by 200 mm, its flanges are 15 mm thick, and its web is 9 mm thick. There is a 10 mm air gap between the boards and the adjacent flanges. The thermal conductivity of the insulation board is 0.174 W/(m·K) at 0 °C and increases linearly to 0.188 W/(m·K) at 250 °C and remains at this same value for higher temperatures. The thermal conductivity of the metal varies linearly with temperature such that its value is 54.0 W/(m·K) at 20 °C, 27.3 W/(m·K) at 800 °C, and 27.3 W/(m·K) at 1200 °C. The fire is represented by the ISO 834 time-temperature curve, Equation 5, with an initial temperature of 20 °C. The convection heat transfer coefficient to the exterior of the insulation board is 10 W/(m^2·K), but it is assumed that there is no convective heat transfer at the interior surfaces of the boards or the wide flange column. Calculate the temperature at the center of either flange as a function of time and compare to the values given in Table 16.

TABLE 16. REFERENCE VALUES

Time (min)	Temperature (°C)
0	20
30	229
60	519
90	736
120	879

FIGURE 2. METAL WIDE FLANGE COLUMN PROTECTED BY INSULATION BOARD



CASE 16—3D HEAT TRANSFER WITH NON-UNIFORM HEAT FLUX

A 1 m by 2 m rectangular metal plate ($k = 50\ \mathrm{W/(m \cdot K)}$, $\rho = 7850\ \mathrm{kg/m^3}$, $c = 500\ \mathrm{J/(kg \cdot K)}$, $\varepsilon = 0.8$) is 100 mm thick. In Cartesian coordinates (x, y), the corners of the plate are (0, 0), (1, 0), (1, 2), and (0, 2). A lower quarter of the plate front surface whose corners are (0, 0), (0.5, 0), (0.5, 1), (0, 1) is heated with an incident radiant heat flux of 30 kW/m^2 with reradiation to the surroundings and convection with surrounding air, Equation 6. The remainder of the front surface and the entire back surface have only reradiation to the surroundings and convection with the surrounding air. The sides of the plate are insulated. The surroundings and air temperature are both at 20°C, while the heat transfer coefficient at the plate surface is 10 W/(m^2·K). Calculate the temperature at the mid-depth along the height of the plate at $x = 0.25$ m and along the width of the plate at $y = 0.5$ m after a 60 minute exposure. Compare the results with the values given in Table 17.

TABLE 17. REFERENCE VALUES

x (m)	y (m)	z (m)	Temperature (°C)
0.25	0.00	0.05	183
0.25	0.25	0.05	182
0.25	0.50	0.05	181
0.25	0.75	0.05	167
0.25	1.00	0.05	102
0.25	1.25	0.05	37
0.25	1.50	0.05	22
0.25	1.75	0.05	20
0.25	2.00	0.05	20
0.00	0.50	0.05	194
0.25	0.50	0.05	181
0.50	0.50	0.05	111
0.75	0.50	0.05	39
1.00	0.50	0.05	25

Commentary

C 3.1 Fire exposure. The fire exposure is the incident radiation onto the surface and the adjacent gas temperature. Note that the incident radiation may be due to radiation from the flames, radiation from hot surfaces, and/or radiation from hot gases.

Fire-resistance rating. Example tests include ASTM E 119, UL 263, UL 1709, EN 1363-1 and ISO 834.

Listed. A listed assembly in the context of this standard is an element of construction that has been tested in a standard fire test (e.g. ASTM E 119, UL 263 UL 1709, EN 1361-1, or ISO 834 or other international test standard) by an organization that is acceptable to the enforcement official to categorize its ability to contain a fire or continue to perform a structural function or both. The listing will give a period of fire resistance for the assembly with respect to the standard fire test defined failure criteria of integrity, insulation, and/or stability.

Mechanical integrity. Falloff of spray-applied fire resistance material (SFRM), loss of gypsum wallboard protection, or spalling of concrete are examples of loss of mechanical integrity.

Thermal Boundary Condition. Thermal boundary conditions include the parameters needed for calculating the convection and radiation heat transfer between structural assembly surfaces and their surroundings. These are the incident radiation, surface temperature, and surface emissivity of the target surface for calculating the heat transfer by radiation, and the adjacent gas temperature, surface temperature, and convection heat transfer coefficient for calculating the heat transfer by convection (for example, see Equation 6 in Annex A).

Validation and Verification. The model evaluation process consists of two main components: verification and validation. *Verification* is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate for the given fire scenario—only that the equations are being solved correctly. *Validation* is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Differences that cannot be explained in terms of numerical errors in the model or uncertainty in the measurements are attributed to the assumptions and simplifications of the model.

C 4.2 Calculation methods may vary in nature and complexity, depending on the nature of the assemblies to be addressed. A lumped mass, one-, two-, or three-dimensional model may be required. This standard does not set any preconditions on the complexity of the heat transfer model.

There are a number of heat transfer models available. These include:

- Nomograms or simple look-up tables
- Analytical expressions/simple numerical methods
- Finite difference and finite element software
- General or fire specific software

C 4.3 The sophistication of the models may vary widely depending on the potential application. Some problems may only require simple lumped capacitance (i.e., with no spatial temperature gradient) models to predict the material temperature rise with time while others may necessitate the use of sophisticated models with one-, two-, or three-dimensional spatial capability. Solvers for transient (and potentially nonlinear) thermal problems vary widely, and time integration schemes for discretization in time exhibit different stability and convergence properties. In all cases, the detailed mathematical description for the model needs to be provided, and the same model used in the verification and validation of the model must be used in the final application. In software for heat transfer analysis, there may be several options for how the model is defined. For example, commercial finite element programs have several choices for element type, element order, and transient solution techniques. These details must be clearly defined in the method and used consistently throughout the process of verification, validation, and final application.

C 4.4 Material properties for thermal analysis may be implemented in different ways depending on the model. Material properties may be constant at all temperatures or vary with temperature. The manner in which the properties are mathematically incorporated into the model should be documented as part of the method to ensure the correct implementation of the material properties. If the material properties vary with temperature, the method by which temperature dependent properties are included in the time and spatial variation needs to be documented.

C 4.5 While they are the responsibility of the user to define, heat transfer boundary conditions at fire exposed surfaces normally take the form of a mixed radiative and convective boundary condition. Eurocode 1 (CEN, EN 1991-1-2, 2002) recommends a value of 25 $W/(m^2K)$. Emissivity of the radiating fire gases is normally taken as 1.0 or some value just less than 1.0. Thus the incident radiation is calculated as the black body radiation temperature equal to the gas temperature.

Heat transfer boundary conditions at non-fire exposed surfaces normally take the form of a convective boundary condition assuming a constant heat transfer coefficient. Eurocode 1 (CEN, EN 1991-1-2, 2002) recommends a value of 9 $W/(m^2K)$ including the effects of radiation. For accurate calculations, Eurocode 1 recommends a convection heat transfer coefficient equal to 4 $W/(m^2K)$ with the effects of radiation then added.

It has been found useful to define the adiabatic surface temperature (AST) as the effective temperature of the exposure for application as the source temperature for both radiation and convection (Wickström 2008, 2009).

References

Pettersson, O., Magnusson, S., & Thor, J. (1976). Fire engineering design of structures. *Swedish Institute of Steel Construction, Publication 50.*

CEN. (2002). *Eurocode 1: Actions on Structures, Part 1-2: General Actions—Actions on Structures Exposed to Fire*, Brussels, Belgium: European Committee for Standardization (CEN).

Wickström, U. (2008). Methods for Predicting Temperatures in Fire-Exposed Structures. In DiNenno et al (Eds.), *SFPE Handbook of Fire Protection Engineering*, 4th Ed. Quincy, MA: National Fire Protection Association.

Wickström,U., Jansson,R., & Tuovinen,H. (2009). Validation fire tests on using the adiabatic surface temperature for predicting heat transfer, *SP Report 2009:19*, Borås, Sweden: SP Technical Research Institute of Sweden.

C 4.6 Several bench scale test methods for determining material properties for use in the prediction of temperatures within a fire resistive assembly have been developed. The method should define the experimental protocol in sufficient detail so as to allow any user to reproduce the results. These methods generally assume that the thermal properties are temperature dependent and energetic of reactions within the material are often reflected in the temperature dependent properties. Most often the heat of reaction is implicitly included in the material heat capacity. Reactions may also be explicitly modeled with the heat of reaction explicitly included in the energy equation.

References

Kodur, V., & Harmathy, T. (2008). Properties of Building Materials. In DiNenno et al (Eds.), *SFPE Handbook of Fire Protection Engineering*, 4th Ed. Quincy, MA: National Fire Protection Association.

Bentz, D., D. R. Flynn, D., Kim, J. & Zarr, R. (2006). A slug calorimeter for evaluating the thermal performance of fire resistive materials. *Fire and Materials* 30: 257–270.

Bentz, D., Prasad, K. & Yang, J. (2006). Towards a methodology for the characterization of fire resistive materials with respect to thermal performance models. *Fire and Materials* 30: 311–321.

Adl-Zarrabin,B., Bostrom, L., & Wickström, U. (2006). Using the TPS method for determining the thermal properties of concrete and wood at elevated temperature. *Fire and Materials* 30: 359–369.

Bentz, D. (2007). Combination of transient plane source and slug calorimeter measurements to estimate the thermal properties of fire resistive materials. *Journal of Testing and Evaluation*, 35(3): 1–5.

C 4.7 The method is limited to listed designs because thermal prediction methodologies inherently assume that the materials will remain in place during the fire exposure (mechanical integrity). Since mechanical integrity cannot be readily predicted, this standard relies on furnace testing to assure that the materials are capable of remaining in place during the exposure. Listings define appropriate extrapolations from test conditions, such as application to heavier steel sections than tested. Use of fire resistive material thicknesses outside the range included in the listing cannot be done without full scale validation testing, as materials are often not as useful at thicknesses outside the range included in the testing. Examples would include a very thin cementitous material that may not maintain mechanical integrity or an intumescent material that will yield little or no additional benefit if a thicker layer is applied. These requirements do not preclude the use of analytical modeling to interpolate thermal performance between available furnace test result data.

The intent of this limitation is to ensure that the testing of a given assembly is performed by a credible unbiased organization that further would ensure the ongoing quality assurance of the product. Accordingly, the standard shall only be applied to thermal response analyses of listed assemblies exposed to natural fire conditions. Implementation of this method represents a greater standard of care than what is currently constituted by building codes, which generally do not require confirmation of the in-situ thermal response of listed assemblies. Hence, this standard primarily supports fire performance analyses of structural systems that utilize listed assemblies for fire resistance purposes.

If modifications to a listed fire resistance assembly are sought for constructability, economy, or others reasons, designers may elect to conduct analyses of such modifications as permitted by the alternative materials, design, and methods of construction provision in the building codes. If deemed acceptable to the enforcement official, analyses of this type are often used to demonstrate that the intent of the code has been met even though the assembly has been modified from that which was tested, and is therefore unlisted. For instance, a designer may analyze a case in which lightweight concrete is substituted for normal weight concrete for a given listed assembly without additional furnace testing. Although this type of approach is commonly employed in practice per the discretion of the enforcement official, this standard is not applicable to such analyses.

C 5.1 A calculation method is specific to a type of structural assembly and to the fire insulating material's physical and chemical response to heat. While heat transfer codes may be applicable to a range of structural and insulating materials, how materials are modeled and how properties are determined depends on the nature (physical and chemical response to heat) of the materials and how the heat transfer model is configured and used. This results from the wide range of material responses that are found for different materials. Material responses may include charring, intumescing, dehydration, phase changes, and chemical reactions, for example. These material responses and associated properties may significantly affect how a model is to be constructed and used.

C 5.1.1 The experimental method of determining material properties is a part of the overall method. For example, a model that is validated for use with mineral fiber insulation cannot be used for gypsum without explicit validation of the method for gypsum containing assemblies. Unlike mineral fiber, gypsum experiences chemical dehydration during heating that is endothermic and contributes significantly to the performance of the gypsum. The material properties must be determined by the application of a defined and documented experimental procedure to the materials to be used. The user may find that the experimental determination of the material properties is available in the technical literature or the user may need to commission testing of materials contained in the assembly. The validation process should include cases that use the materials included in the anticipated application. The validation cases need not include the precise material composition as the application. For instance, if a model is successfully validated for use with concretes made of different aggregates, this validation may be utilized in an application using an aggregate different from the aggregates used in the validation cases. However, it falls to the user to demonstrate that the aggregate anticipated for use follows the material model well and that the physical and chemical processes that occur in the aggregate during heating are the same as the aggregates used in the validation. For proprietary materials it is normally necessary to test the specific proprietary material because the ingredients of the material are not fully known to the user. Validation cases including the proprietary material need to be included in the validation suite.

C 5.1.2 All experimental methods involve uncertainty levels associated with the derived material property. The uncertainties should be well understood and reported. The effect of the material property uncertainties needs to be explored in the validation of the model. Discrepancies between the model results and the experimental results in validation cases arise due to potential errors in the experimental measure and control, from the simplifications of the calculation method, from potential errors in the model inputs employed, from batch to batch variations of the product, and from product changes over the years under the same listing. Manufacturers may change the product formulation in response to the cost or availability of ingredients or to improve some aspect of material performance. The user needs to be cognizant of changes in the material when the validation basis includes testing with an old formulation of the listed product.

C 5.1.3 Typical examples of materials that may not be significant with respect to heat transfer might include kraft paper facing on insulation, paint, or a thin metal sheet on insulation to prevent mechanical damage from impacts or a fabric facing to limit release of insulation fibers to the environment. It may be that the radiative properties of a thin coating need to be considered but the resistance to conduction of heat may not need to be modeled.

C 5.3 The boundary condition in both Cartesian and cylindrical coordinate systems is typically expressed as

$$-k\frac{\partial T}{\partial n} = \dot{q}'' \tag{5.3.1}$$

where n denotes the normal direction pointing into the solid and $\dot{q}''$ is the heat flux onto the solid surface. This includes both radiation and convection heat transfer components.

For cases where the solid object is completely surrounded by an optically thick gas whose temperature varies only as a function of time, $T_f(t)$, the heat flux is given by

$$\dot{q}'' = \varepsilon\sigma\left(\overline{T}_f^4 - \overline{T}_s^4\right) + h\left(T_f - T_s\right) \tag{5.3.2}$$

where T_f and $\overline{T}_f$ are the gas temperature in °C and K, respectively, and T_s and $\overline{T}_s$ are the calculated surface temperature in °C and K, respectively. For example, the standard ISO 834 fire is given by the following time-temperature curve

$$T_f(t) = 20 + 345\ \log\left(\frac{8t}{60} + 1\right) \tag{5.3.3}$$

where T_f is in °C, and t is the time in seconds. In standard furnace tests, this is measured both using thermocouples and plate thermometers. The modeler should consider the impact of the response time of the device and the radiation effects of the sample when using these temperatures and considering their uncertainty on the modeling results.

If the gas is not optically thick, then there can be radiation exchange between two surfaces having different temperature as well as the gases and the surface. Radiation exchange calculations should consider the energy absorbed by the gases and the surface emissivity. In this case, the modeler needs to determine the view factors between different surfaces and surface temperatures to determine the radiation onto a surface. Convection onto a surface will still be determined using the convective heat transfer coefficient multiplied by the temperature difference between the surface and gas temperature.

For the case where the incident radiation onto the surface is specified, the boundary condition should be expressed in the form of the incident radiative heat flux $\dot{q}''_{inc}$ by

$$\dot{q}'' = \varepsilon\left(\dot{q}''_{inc} - \sigma\bar{T}_s^4\right) + h\left(T_g - T_s\right) \quad (5.3.4)$$

Note that $\bar{T}_s$ is absolute temperature of the surface in Kelvin, K. The convective heat transfer coefficient, h, is used to describe convective heat transfer to the sample surface as proportional to the temperature difference between the gas temperature and the surface temperature.

Alternatively Equation 5.3.4 may be written as

$$\dot{q}'' = \varepsilon\sigma\left(\bar{T}_r^4 - \bar{T}_s^4\right) + h\left(T_g - T_s\right) \quad (5.3.5)$$

where the black body radiation temperature is defined as $\bar{T}_r = \sqrt[4]{\frac{\dot{q}''_{inc}}{\sigma}}$.

Water-cooled heat flux gauges are frequently used to measure the fire exposure. The heat flux from a water-cooled heat flux gauge, $\dot{q}''_f$, can be related to the exposure heat flux by

$$\dot{q}'' = \dot{q}''_f - \varepsilon_s\sigma\left(\bar{T}_s^4 - \bar{T}_\infty^4\right) - h\left(T_s - T_\infty\right) \quad (5.3.6)$$

where T_∞ and $\bar{T}_\infty$ are the gas temperature in °C and K, respectively.

References

Lattimer, B.Y. (2008). Heat Fluxes from Fires to Surfaces. In DiNenno et al (Eds.), *The SFPE Handbook of Fire Protection Engineering*, 4th edition, Quincy, MA: National Fire Protection Association.

Wickström, U.. (2008). Methods for Predicting Temperatures in Fire-Exposed Structures. In DiNenno et al (Eds.), *The SFPE Handbook of Fire Protection Engineering*, 4th edition, Quincy, MA: National Fire Protection Association.

C 6.1 The following document provides information concerning the development of the solutions included in Annex A:

Jeffers, A., Wickström, U., and McGrattan, K., Documentation of the Solutions to the SFPE Heat Transfer Verification Cases, Task Group of the SFPE Standards-Making Committee on Calculation Methods to Predict the Thermal Performance of Structural and Fire Resistive Assemblies, Bethesda, MD: SFPE, Available at www.SFPE.org, 2013.

A grid resolution study should be performed to ensure that the computed solution of the discretized form of the governing equations becomes increasingly accurate as the spatial or temporal resolution is increased. If possible, convergence to the exact solution should be quantified in terms of its dependence on the size of the time step or grid spacing. For example, most numerical methods exhibit an error that is proportional to the first or second power of the time step or grid cell size.

C 6.3 The verification cases listed in the annex were selected to test the limits of the calculation method(s) used and implementation of the boundary conditions. The actual physical dimensions and material properties may not reflect actual structural assemblies. A verification case should not be dismissed as not being relevant only on the basis that the material properties do not correspond to those of the assembly of interest.

C 6.4 Additional verification cases need to be sought to exercise and test all of the model capabilities. This may require verification cases that go beyond those provided or cited in this document. The following references provide information that may assist in this process.

Carslaw, H.S. & Jaeger, J.C. (1969). *Conduction of Heat in Solids*, 2nd edition. Oxford, England: Oxford University Press.

D. Pintea & J. M. Franssen. (1997). Evaluation of the thermal part of the code SAFIR by comparison with the code TASEF, In M. Ivan (Ed.), MIRTON, Timisoara. *Proc. 8th Int. Conf. on Steel Structures, Vol. 2*, 636-643.

Hamann, J., Müller, R., Rudolphi, R., Schriever, R. & Wickström, U. (1999). Berlin: Anwendung von Temperatur-Berechnungsprogrammen auf kritische Referenzbeispiele des Brandschutzes, Bundesanstalt für Materialforschung und -prüfung.

Sterner, E. & Wickström, U. (1990). *TASEF—Temperature Analysis of Structures Exposed to Fire, SP Report 1990:05*, Borås, Sweden: Swedish National Testing and Research Institute.

Wickström, U. (1999). An Evaluation Scheme of Computer Codes for Calculating Temperature in Fire Exposed Structures. *Interflam '99*. London: Interscience Communications.

C 6.5 Examples of grid resolution studies and the convergence of the solution to the known value are provided in Annex A.

C 7.1 Fundamentally, the validation exercise defines the limitations on use, along with the conditions of the listing of the assembly.

Validation of the method would normally be undertaken by the method developer, but may be undertaken by others as well. Validation may be performed by the following groups:

- Model developers. Almost without exception, model developers perform validation of their model, either publishing results in the literature or maintaining a suite of case studies as part of the model documentation.
- Model users. The benefit to the user is two-fold: first, it confirms that the user can use the software properly, at least for the given application; and second, it assures the user that the model can address the given fire scenario, even providing the user with some estimate of its accuracy.
- Approving officials. To ensure that the model is being used within appropriate limits as defined by the model developers, an approving authority may conduct on its own a validation study of the model.

- Educators and professional organizations. Model validation studies are often performed by students at universities or researchers working for or on behalf of professional societies. These studies often combine public and private resources.

Validation is the process by which results from modeling an experiment are compared with experimental data to demonstrate that the model can adequately predict the physics in the experiment. This process includes selecting the appropriate experimental data for the validation study; understanding how the measurements were made and their uncertainty; performing modeling on the experiments and quantifying the uncertainty of the results; and comparing the model results with experimental data to determine whether the agreement is acceptable. Additional detailed information on the verification and validation of models is provided in the *ASME Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer*.

Experiment selection is the first step in the validation process. Reduced-scale and full-scale experiments can be used to validate models, both of which have pros and cons. It is common to use both reduced-scale and full-scale experiments to fully validate a model.

Reduced-scale experiments could be a representation of the full-scale application or a more simple experiment that isolates specific variables known to be important. Reduced-scale experiments are typically better controlled, with more detailed measurements possible due to the size of the experiment. As a result, the exposure source may be easier to implement into the model with greater opportunity to compare more data with the model results. The smaller scale of the experiments frequently allows more tests to be performed to explore the impact of different variables that may affect the physics of the problem. Repeat experiments are also commonly performed, resulting in a better calculation of the uncertainty in the measurements. The drawback to these tests is that they may not include all of the physics of the large scale experiment, thus limiting the application range of the model.

Validation of the model with full-scale data is recommended to demonstrate the ability of the model to perform predictions over the range of conditions expected in the final applications. As a result, the full-scale data should include fire exposures, dimensions, and other features that are representative of the final application. Due to the size of the experiments, it is common that measurements will not be as spatially resolved and the exposure may be more complex compared with the reduced-scale experiments. Therefore, it may be more difficult to accurately implement the exposure into the model and the model comparison will be done with less spatial resolution. In addition, the uncertainty in the full-scale data is commonly higher due to a more complex exposure and less opportunity for repeat tests. Despite these drawbacks, these tests will ultimately define the application range of the model.

The instrumentation used in the selected experiments and the application of this instrumentation in the tests is an important aspect in the model validation. Measurements may include boundary temperatures as well as measurements for quantifying the boundary condition such as gas phase temperature, gas velocity, and heat flux. The manner in which instrumentation is applied may affect the measurement uncertainty and require special analysis to account for instrument details or installation sensitivity. Some examples of this include the method by which a thermocouple is attached to the surface to measure surface temperature that may affect the uncertainty in the measurement; temperature measurements within the material may be affected by the length of the thermocouple leads in the plane of measurement; location of thermocouples in high temperature gradient regions may have high uncertainty; or the size of the thermocouple bead may affect the response time of the thermocouple. Frequently uncertainty is not reported as part of the experimental effort. In these cases, the modeler needs to estimate the uncertainty of the measurements based on available data and knowledge of the instrumentation. Models may also have to be used to justify the potential for uncertainty in the measurements and differences between the model and the data.

Modeling experiments must consider properties of the structure being analyzed, boundary conditions on the structure, and structure geometry. The uncertainty in the modeling results must consider the impact of these parameters as well as the error in the model numerical solution itself, which was determined as part of the model verification. An example of this is the material thermal properties used in the modeling. If these properties are not provided as part of the experimental data, then the modeler must provide these input data from a separate source. In addition, these properties must be determined using the methods that will be used in the final application. There will still be uncertainty introduced into the modeling results due to the fact that material properties of the actual material were not used. As a result, the modeler needs to investigate the sensitivity of the model to reasonable variations in the properties for the material and use to help quantify the modeling results uncertainty. The implementation of boundary conditions into the model is a critical step in the modeling process. Experiments must be selected where boundary conditions are sufficiently known through measurement or calculation, so that they can be included into the model. The sensitivity of the modeling results to the potential variation in the boundary conditions must be evaluated and included in the modeling uncertainty. The structure geometry is also sometimes simplified to allow for inclusion into a model. The impact of simplifying the geometry must be evaluated to determine the uncertainty introduced by these simplifications.

Comparison of the modeling results and experimental data can be performed once uncertainties have been quantified. This final step should include a comparison of the results and data with uncertainty error bars using the best representations of the boundary conditions and structure geometry. Though it is desirable that the agreement between the model and data be within the uncertainty of the model results and data, the level of agreement between the model and data is up to the authority having jurisdiction. For example, it may be acceptable that the agreement is not within the defined uncertainties if the comparison demonstrates that the model results are sufficiently conservative.

The criteria for selecting experiments are:

- The scale and scope of the experiments should be consistent with the fire scenarios under consideration;
- The experimental results ought to be available and fully documented or otherwise interested modelers cannot replicate what was done in the validation study or attempt to do their own validation study;
- An assessment of the measurement uncertainty should be included in the test report because it is not possible to assess model accuracy without first quantifying the uncertainty of the measurements against which the model predictions are compared.

Several data sets have been put forward as potential candidates:

- Hamins et al. (2005) describes 6 compartment fire experiments performed by the Building and Fire Research Laboratory as part of its investigation of the collapse of the World Trade Center on September 11, 2001. The compartment measured approximately 7 m by 4 m by 4 m high with heat release rates of 2 MW to 3 MW. The measurements include gas and component temperatures for a steel box column, two bar joist trusses (unloaded), and several steel bars. Three tests were performed with thermal insulation, three without. The tests are completely documented and the data publicly available.

- Lennon (2004) details the results and observations from a full-scale fire test carried out on the steel-framed building at Cardington in January 2003.The data is presented in a form suitable for subsequent analysis and interpretation by others.

Uncertainties in the experimental data must be determined. These may be reported by the experimenters or may need to be defined based on information provided by the experimentalist.

There are two major forms of experimental uncertainty to consider in a validation study. The most obvious is the uncertainty of the measurement of the selected quantity used to compare with the model prediction. For example, a thermocouple measurement is subject to uncertainty related to the bead size, time response, and so on. The second form of measurement uncertainty is related to the physical parameters that are input into the model.

For example, the thermal properties of the structural components, the exposing temperature, even in some cases the heat release rate of the fire, are all measurements with some amount of uncertainty. The uncertainty in the input parameters needs to be propagated through the model to ascertain its impact on the final prediction. This can be done most easily by performing the calculation with varying values of the input parameters. Sometimes analytical solutions of simpler configurations can serve as a way of assessing the impact of the uncertainty of input parameters.

When comparing predictions and measurements, both forms of experimental uncertainty need to be considered. A common means of combining the two forms of uncertainty is via a relative uncertainty that combines the two forms of experimental uncertainty— one resulting from the propagation of input uncertainty and the other directly related to the measurement of the predicted quantity. It is preferable that the combined uncertainty be expressed in the same form as the relative difference, so that the comparison of model and measurement can be assessed in light of the uncertainty of all the measurements associated with the experiment.

References

ASME V&V 20. (2009). *Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer*. New York, NY: American Society of Mechanical Engineers.

ASTM E 1355: Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models. West Conshohocken, PA: ASTM International.

Hamins, A. et al. (Sept. 2005). Experiments and Modeling of Structural Steel Elements Exposed to Fire. In *NIST NCSTAR 1-5B, Federal Building and Fire Safety Investigation of the World Trade Center Disaster*. Gaithersburg, MD: National Institute of Standards and Technology.

Lennon, T. (Feb. 2004). Results and observations from full-scale fire tests at BRE Cardington, 16 January, 2003. In *Client Report Number 215-741, Building Research Establishment (BRE)*. Garston, Watford, United Kingdom.

C 7.2 Validation should be conducted using the same temporal and spatial discretization techniques planned for use in the validation studies and final application. In finite element software, this includes using the same element type. Each problem will require consideration of the appropriate time step and spatial resolution to ensure model convergence. The time step and spatial resolution used in the validation will likely be different from those used in verification studies as well as in the final application.

C 7.3 Validations would ideally include the full scale furnace testing used to list the assembly. Since these test reports may not be available, it may be necessary for comparable furnace tests to be conducted to obtain the required data.

C 7.6.5 Mechanical integrity can generally only be assured when the thermal exposure conditions bound the thermal exposure conditions in application of the method. For instance, an E119 test would not assure mechanical integrity for exposures that exceed the E119 time-temperature curve. UL 1709 testing may provide broader ranges of assured mechanical integrity than an E119 test.

C 8.2 Final application modeling should be conducted using the same temporal and spatial discretization techniques planned for use in the validation studies and final application. In finite element software, this includes using the same element type. Each problem will require consideration of the appropriate time step and spatial resolution to ensure model convergence. The time step and spatial resolution used in the final application modeling will likely be different from those used in verification and validation studies.

C 8.3 The following is a general description of the factors that should be taken into consideration with regard to the characterization of the assembly:

- Is the assembly part of the primary structural frame of the building element in question? Examples include columns, beams, girders, trusses, composite beams or slabs, and load bearing walls.
- Will the assembly include protection beyond the inherent fire resistance associated with the thermal mass of the element in question? Protection could consist of integral protective features, such as concrete-encased steel columns or beams, or surface applied protection such as an intumescent coating or spray applied fire-resistant materials. The potential additional protection features that will be taken into consideration in the analysis should be defined as part of the initial characterization of the assembly, where possible.
- Will the assembly be part of a barrier type of system, such as walls, partitions, horizontal assemblies, shafts, and other elements intended to maintain separation and containment within buildings and similar spaces?
- What types of penetrations or openings will be included in or through the assembly, and how will these penetrations be protected? For example, will barriers include doors; windows; joints; mechanical, electrical and plumbing penetrations or openings; or through penetrations? How will this be addressed in the evaluation?

When citing verification or validation studies as justification for applying the calculation method for a given application, the following parameters are recommended as a means of comparison:

Weight (or mass) to heated perimeter ratio. This is a commonly used quantity to characterize the mass of a metallic structural member relative to its heated perimeter. Since metal temperature increase is a strong function of thickness, this ratio is useful in applications where the material thickness is similar over the cross-section. It is typically expressed as W / D in the United States, where W is the weight in units of pounds per linear foot, and D is the heated perimeter in units of inches. In other conventions (e.g. ISO), the ratio of the heated perimeter to cross-sectional area is used. Elsewhere, it is expressed as M / D, where M is the mass in units of kilograms per linear meter, and D is the heated perimeter in units of either meters or millimeters.

Ratio of heat capacities. This dimensionless parameter is essentially the ratio of the effective heat capacity of the insulation to that of the steel or other solid member requiring thermal protection:

$$N = \frac{\rho_{ins}\ c_{ins}\ \delta_{ins}}{c_s\ M / A}$$

where ρ_{ins}, c_{ins}, and δ_{ins} are the density, specific heat, and thickness of the insulation, c_s is the specific heat of the steel, M is the mass of steel per unit length, and A is the area of the interface between insulation and steel per unit length.

Fourier number: This dimensionless parameter is a convenient heat penetration time scale. It is defined as:

$$\mathrm{Fo} = \frac{\alpha_{ins}\ t}{\delta_{ins}^2}$$

where t is the exposure time and δ_{ins} is the insulation thickness. The thermal diffusivity is defined as:

$$\alpha_{ins} = \frac{k_{ins}}{\rho_{ins}\ c_{ins}}$$

where k_{ins} is the thermal conductivity, ρ_{ins} is the density, and c_{ins} is the specific heat of the insulation. Along with the ratio of heat capacities, this parameter is useful in predicting the time to reach a critical temperature.

Reference

Lie, T.T. (1972). Theoretical Prediction of Fire Resistance. In *Fire and Buildings*. London, England: Applied Science Publishers, Ltd..

C 8.3.3 Loss of mechanical integrity during the thermal exposure will invalidate the thermal prediction unless the particular form of loss of mechanical integrity is included within the model.

SFPE Engineering Standard on Calculation Methods to Predict the Thermal Performance of Structural and Fire Resistive Assemblies

This standard provides requirements for the development and use of methods to predict the thermal response of structures using listed fire resistive assemblies to time dependent thermal boundary conditions imposed by fires.

The design of structural fire resistance requires three major steps: (1) determination of the thermal exposure to a structure resulting from a fire; (2) determination of the temperature history within the structure, or portion thereof; and (3) determination of the structural response. This standard is limited to the second step in this process.

The purpose of this standard is to provide requirements for calculation methods that provide time-dependent temperature field information resulting from fire exposures required for engineered structural fire design (including structural systems and fire barriers).

ABOUT SFPE

SFPE is a global organization representing those practicing in the fields of fire protection engineering and fire safety engineering. SFPE's mission is to define, develop, and advance the use of engineering best practices; expand the scientific and technical knowledge base; and educate the global fire safety community, in order to reduce fire risk. SFPE members include fire protection engineers, fire safety engineers, fire engineers, and allied professionals, all of whom are working towards the common goal of engineering a fire safe world.

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