NISTIR 6170

A 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

Leonard Y. Cooper
Jean-Marc Franssen

U.S. Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 6170

A 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

Leonard Y. Cooper
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

and

Jean-Marc Franssen
Institute of Civil Engineering
University of Liège
Liège, Belgium

September 1998

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

TABLE OF CONTENTS

LIST OF FIGURES

Page

A 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

Leonard Y. Cooper
Building and Fire Research Laboratory
National Institution of Standards and Technology
Gaithersburg, MD 20899 USA
and
Jean-Marc Franssen
Institute of Civil Engineering
University of Liège
Liège, Belgium

ABSTRACT

Computer fire models for simulating compartment fire environments typically require a mathematical formulation that couples the thermal response of the gases that fill the compartment and the thermal response of compartment barriers and partitions. The fire environment characteristics calculated by such models can be used to provide input, *via* thermal boundary conditions, to an uncoupled thermal-structural computer model for simulating and evaluating the combined thermal/structural performance of the barriers/partitions. The objective of such a combined analysis would be to determine, through analysis, the structural fire resistance of a barrier/partition design.

Depending on the particular barrier/partition design of interest, the latter thermal/structural part of the problem would generally require a two- and possibly three-dimensional analysis. As it turn out, there are several quality tools of analysis that are available for use in solving the latter problem. However, because of intense computational requirements, the general use of a multi-dimensional (*vs* a one-dimensional) barrier/partition thermal analysis in the fire modeling part of the problem is not now practical, and is not expected to be practical in the forseeable future.

This work presents a basis for identifying the practical range of barrier/partition where the use of one-dimensional thermal analysis in the fire modeling part of the problem would lead to reliable simulations of the fire environment which can, in turn, be used to provide the necessary input to solve the thermal/structural part of the problem, using two- or three-dimensional analyses, as required.

Keywords: **Algorithms, ASTM E119, compartment fires, fire barriers, fire models, gypsum board, steel studs, walls, zone models**

COMPARTMENT FIRE MODELING, THE ROOM FIRE ENVIRONMENT, AND THE THERMAL RESPONSE OF BARRIERS/PARTITIONS

Two-layer zone-type compartment fire models are very useful in simulating analytically the various phenomena that occur during the course of compartment fire scenarios. Any particular model will typically predict some phenomena with relatively greater accuracy (i.e., with a relatively detailed/reliable set of governing equations), and will ignore and/or treat with limited detail/reliability other of the phenomena. As a consequence, the applicability, utility, and accuracy of any particular model will have corresponding strengths, weaknesses, and gaps.

The present work focuses on the aspect of modeling that encompasses the interrelationship between the thermal response of room barrier/partitions and room fire environments, leading to a capability of assessing thermal and structural barrier/partition fire resistance.

In discussing the room fire environment, particular emphasis is placed here on the aspect of accurate simulation of the temperature distributions or spacially-averaged temperature distributions (*vs*, say, the distribution of gaseous products of combustion) throughout the rooms of a simulated facility. Of all the features of the fire environment modeled by any particular compartment fire model, the prediction of the room temperature distributions typically recieve the highest level of priority in modeling detail. This leads to a particular focus on the equations that describe the transport of energy and mass to/from the two layers of each room of the facility, i.e., heat and mass transfer exchanges at openings/vents and (especially heat transfer) at bounding surfaces, and the generation of heat and mass (e.g., from fire sources) within the layers of the rooms. In the usual way, and within the context of the two-layer zone-type description of the fire environment in a room, it is assumed that away from relatively-small-volume regions that encompass and/or contact bounding surfaces, fire plumes, and positive or negatively buoyant sources, the environment in each room of the facility can, at all times, be reasonably described as having uniform-temperature upper and lower layers, where the upper and lower layers have relatively high and low temperatures, respectively, and where, initially, the lower layer fills the room with ambient-temperature air.

Regarding the thermal response of the barriers/partitions, in the present discussion particular emphasis is placed on the accurate simulation of the temperature distributions through the barrier/partitions, where the results of such simulations can be used to assess the integrity of the structures relative to their fire resistance. Here, the fire resistance of a barrier/partition would be an estimated time of possible thermal and/or structural failure, say, in the sense of failure as defined by the traditional evaluation methods of ASTM E119 [1] or ISO 834 [2].

THE DEPENDENCE OF ACCURATE SIMULATIONS OF ROOM FIRE ENVIRONMENTS ON QUALITY ANALYSES OF BARRIER/PARTITION THERMAL RESPONSE

Considerations of conservation of energy lead to the following "basic rule:"

> *When the instantaneous surface-integrated rate of heat transfer to all barrier/partition surfaces of a facility is a significant fraction of instantaneous energy release of all contained fires, then an accurate estimate of the fire environment generally requires an accurate coupled analysis of barrier/partition thermal response (at least at the particular barrier/partition surfaces where the bulk of the heat transfer is taking place).*

The above rule is likely to be applicable when the simulated thermal response of the partitions/barriers will be used to evaluate fire-enhanced barrier/partition failure. It can also be applicable even when partitions/barriers are known to be nowhere near a state of failure, and when the details *per se* of the thermal response of the partitions/barriers are not of particular interest. The situation is exemplified by the set of full-scale, relatively-low-energy, nearly-fully-enclosed multi-room fire experiments of [3] (characteristic fire energy release rates of the order of one hundred to a few hundred kW). There, while wall temperature data were not acquired at all, gas temperature measurements indicated integrated rates of heat transfer to all surfaces as high as ninety percent and greater of the fire's energy release rate.

The above rule together with the experimental results of [3] suggest that, in general, for a compartment fire model to yield accurate simulations of the room fire environments, an accurate analysis of barrier/partition thermal response is required.

When a fire scenario is such that the total integrated surface heat transfer rate is relatively small, then the above rule does not apply and an accurate barrier/partition heat transfer analysis is unnecessary. Indeed, in such cases even the simplest of all analyses, i.e., the analysis defined by the assumption of adiabatic surfaces, is adequate. It is noteworthy that the nearly-fully-enclosed aspect of the Reference [3] tests is significant. Thus, in a well-ventilated single-room fire scenario, a contrasting type of scenario, the fraction of energy transfer to the bounding surfaces of the room is not expected to be nearly as significant. In the latter types of scenario the effects if heat transfer to partitions/barriers would play a much less significant role in affecting the room fire environment. Then, if barrier/partition performance is not a major issue, detailed analysis in a room fire model of the heat transfer through these bounding structures would not be neccessary.

In most existing compartment fire models, the simulation of barrier/partition response is by way of locally one-dimensional (through the thickness) conduction heat transfer calculations. The idea is to "break up" the partitions/barriers of a modeled facility into a number of discete barrier/partition segments or slabs, and simulate the thermal response of each. Typically, the material thermal properties of each segment are assumed to be spacially and temporally constant, e.g., simulation of temperature-dependent properties, or variations in material type through the thickness of a barrier/partition is not taken into account.

For many real barrier/partitions, use of the assumption of local one-dimensionality of the barrier/partition heat transfer problem(s) is likely to be reasonably accurate in the sense that, with small enough segments, a well-simulated accounting of conservation of energy throughout the facility, i.e., in the gas and in the solid barrriers, should usually be achievable. This is because of the fact that in typical facilities the characteristic thicknesses of partitions/barriers are usually much smaller than their characteristic spans and, as a result of this, through-thickness temperature gradients, and, therefore, heat transfer rates are typically much greater than temperature gradients and corresponding heat transfer rates in directions parallel to the barrier/partition surfaces.

There are situations where the use of spacially and temporally constant barrier/partition material property representations can lead to reliable simulations of the fire environment. However, relative to common fire safety concerns, such situations would be restricted to typically uninteresting scenarios/times, where/when the temperature increases of barrier/partition surfaces are relatively small, e.g., possibly in the simulation of some or all of the experiments of Reference [3].

When uses of a compartment fire model include evaluation of potential failure of partitions/barriers, model equations describing barrier/partition thermal response should include the feature of *temperature-dependent properties*. This is because of the fact that in practically realizable and threatening temperature ranges the thermal properties of even the most common building materials vary significantly.

Finally, for a wider range of applicability, a model should ideally also include a capability of accounting for *variations in material type* through the thickness of a barrier/partition.

THE VALIDITY AND UTILITY OF A ONE-DIMENSIONAL BARRIER/PARTITION THERMAL RESPONSE IN CASES WHERE A TWO OR THREE-DIMENSIONAL ANALYSIS WOULD BE REQUIRED TO ASSESS STRUCTURAL PERFORMANCE

Barrier/partition design in many practical facilities is such that, in the overall fire model equation set, use of locally one-dimensional analyses of their thermal response can lead to successful evaluation of their thermal fire performance. The idea is, that even though design features of common barrier/partition assemblies often exhibit regions where two- or possibly even three-dimensional thermal and structural effects are significant, in the sense of affecting significantly structural barrier/partition fire performance, these regions may be relatively sparse, and involve negligible heat transfer. Here the terminology "negligible heat transfer" is used in the sense that for any particular barrier/partition of the facility, the integrated effects of heat transfer in the vicinity of these regions of multi-dimensional response are insignificant compared to the overall effects of energy conservation. Thus, 1) most of the through-barrier/partition heat transfer phenomena are well modeled by a one-dimensional analysis, and 2) the sparse regions of two- or three-dimensional barrier/partition behavior can be ignored in the room fire model analysis since use there of a multi-dimensional analysis would only lead to minor modifications to calculated room fire evironments.

In terms of the the problem of carrying out practical compartment fire model analyses, the above observation is of very great significance. In particular, it essentially eliminates the need for computationally intensive compartment fire models, with model formulations that couple the conservation equations in the gas regions of a facility to two- or three-dimensional barrier/partition heat transfer analyses.

EXAMPLE DESIGNS WHERE THE USE OF A ONE-DIMENSIONAL BARRIER/ PARTITION THERMAL ANALYSIS WOULD AND WOULD NOT BE VALID

To clarify the above ideas, it is instructive to identify barrier/partition systems where the use of one-dimensional barrier/partition thermal analyses would, and would not be valid.

Gypsum-Panel/Steel-Stud Wall Systems

The first example is a class of gypsum-panel/steel-stud wall system design.

Figure 1, adopted from References [4] and [5], is a sketch of the wall system design. In general, two arbitrary-thickness gypsum wall panels are mounted one on either side of an array of vertical steel studs. In practice, each of the two panels shown can involve a single thickness of gypsum board or a sandwich-type multiple-thickness design of two or more well-contacted boards. Figure 1 illustrates two particular assembly designs. One of these is referred to as a 1x1-type assembly, since each of the two panels involves a single layer of gypsum board. The other is a 1x2 assembly, since one panel is a single layer of gypsum board and the other involves a two-layer construction. The studs, separated at regular intervals, form an unfilled air gap between the panels. Also, the studs are typically fabricated from relatively thin-gage steel (the studs used in the experimental study of Reference [4] were 0.46 mm thick) and they are not effective as paths for conductive heat transfer between the panels. As is the case in practical implementations of these kinds of wall systems, the spacing of the studs is several times the thickness of the air gap. Thus, in terms of earlier discussion on one- *vs* two-dimensionality, it is only in relatively "sparse" regions of the wall system that the presence of the studs introduces two-dimensional considerations into the wall system geometry and heat transfer.

Extensive thermocouple data on the thermal response of a Figure 1 1x2-type wall system to ASTM E119 [1] standard-fire furnace exposures were acquired and presented in Reference [4]. These data indicate that the temperature distribution in the gypsum panels, even relatively close to the steel studs, were substantially one-dimensional through the thickness of the panels. This finding and the experimentally-validated one-dimensional thermal response models of [5] and [6] indicate that a compartment fire model whose model equations include a one-dimensional heat transfer analysis for gypsum-panel/steel-stud wall system thermal response can lead to an accurate overall accounting of energy conservation, and can yield accurate wall system thermal response simulations even up to a time of failure.

In spite of the above finding, the fact of the matter is that the heat transfer through gypsum-panel/steel-stud wall systems is not a totally one-dimensional phenomena. In particular, near the "sparse" regions of the stud/gypsum-panel joints, the heat transfer problem is strongly two-dimensional, i.e., an accurate determination of the steel-stud thermal response will require a two-dimensional time-dependent analysis (with two materials, steel and gypsum) of these regions. Furthermore, for load-bearing Figure 1-type wall systems and in terms of the critical evaluation of wall system fire resistance, it is the spacially-varying loss of strength of the steel studs due to spatially-varying elevated temperatures that would lead to possible wall system structural failure, and that would have to be simulated. Nevertheless, for Figure 1-type gypsum-panel/steel-stud wall systems, the use of a one-dimensional analysis in the overall fire model equation set can lead to accurate simulations of room fire environments and, away from the steel studs, an accurate simulation of wall system thermal response.

It is possible to implement the above ideas for the above class of gypsum-panel/steel-stud wall system by incorporating the modular wall model/algorithm, called ***GYPST***, that was developed in Reference [6], into a zone-type fire model such as ***CFAST*** [7]. The ***GYPST*** model assumes that: 1) relative to effects of conduction heat transfer, the steel studs simply act as thermally insulating spacers for the gypsum panels, and 2) radiation exchanges across the air gap, between the facing surfaces of the gypsum panels, can be well-predicted by an analysis involving radiative exchange between two infinite parallel planes, i.e., the steel studs do not have a significant effect on modifying the radiation exchange between the facing panel surfaces. In the analysis, the time-dependent thermal responses of the gypsum panels are simulated by an idealized system involving two initially-uniform-temperature vertical gypsum board panels, infinite in extent and separated by an air gap, where the system is always heated at the two bounding outer surfaces by spatially-uniform heat fluxes. A sketch of the idealized wall system is presented in Figure 2. The reader is referred to Reference [6] for the details of the wall system heat transfer model and its associated computer subroutine, ***GYPST***.

A Reinforced Concrete Beam/Slab System

The second barrier/partition example is that of a reinforced-concrete, beam/slab, floor/ceiling system. For the purpose of discussion, we choose a specific 2.44 m wide, 10 m long, double-tee module design from Problem 5.3 of Reference [8]. A section of this is sketched in Figure 3.

If the above ideas of one-dimensional analysis are applied to this beam/slab design, then implementation of energy conservation in the compartment fire model would involve an accounting of the thermal response of the overall beam/slab system *via* an analysis of heat transfer through a 0.102 m thick concrete slab (i.e., the combined lower 0.051 m-thick continuous cast slab and the 0.051 m-thick "topping"). However, such an analysis would not be consistant with the idea that regions of significant two-dimensional heat transfer are relatively sparse, involving only "negligible heat transfer." Indeed, in the design of Figure 3, the region where two-dimensionality is significant [i.e., through the two beam portions of the section, and through adjacent portions of the slab, say, up to half a beam depth (0.178 m) on either side of the beams] involves about 0.533 m of the width of the beam/slab module for each of the two beams of the module, i.e., 1.07 m or forty-four percent of the total 2.44 m module width. This is not "sparse!" Furthermore, the beams are so deep (0.36 m) that they add a significant amount of exposed surface area to the lower-surface-to-gas heat transfer exchange, compared to the corresponding surface area that would be used in the one-dimensional analysis. In particular, compared to the one-dimensional lower surface area of (2.44 m width) x (10 m length) = 24.4 m^2 per module, the actual lower surface area involves an additional 4 x (0.36 m depth) x (33 m length) = 14.4 m^2, i.e., a fifty-nine percent increase of surface area. Especially at the beginning of a fire scenario, such a large increase in surface area can be expected to lead to significant, rather than "negligible" additional amounts of heat transfer.

In view of the above, it is concluded that when dealing with Figure-3-type beam/slab systems, the appropriate tool of analysis is a compartment fire model with an overall implementation of energy conservation that includes the effects of *two-dimensional heat transfer* (throughout the beam/slab). *It is noteworthy that no such compartment fire models currently exist.*

Other Types of Partitions/Barriers

Additional examples of barrier/partition where use of a one-dimensional thermal analysis *would likely lead to reliable results* are:

- Figure 1-type gypsum-panel wall system with wood instead of steel studs.
- concrete block wall with built-in sparsely-spaced steel columns.
- poured concrete slab supported on steel beams, where, in difference to the Figure 3-type reinforced-concrete beam/slab system, regions of significant two-dimensional beam/slab heat transfer are relatively sparse and involve "negligible" heat transfer

These are sketched in Figure 4.

Other examples where use of a one-dimensional thermal analysis *may not lead to reliable results* are:

- composite concrete slabs with profiled steel sheets (metal deck floors)
- uniform-thickness concrete slabs with regularly-spaced inclusions

These are sketched in Figure 5.

A BASIS FOR USING SIMULATED FIRE ENVIRONMENTS, INVOLVING A ONE-DIMENSIONAL ANALYSIS OF BARRIER/PARTITION THERMAL RESPONSE, TO DETERMINE TWO- OR THREE-DIMENSIONAL STRUCTURAL RESPONSE

In the present work, attention is focused on fire scenarios where regions of multi-dimensional barrier/partition heat transfer are relatively sparse, etc., i.e., fire scenarios where use of a one-dimensional thermal analysis in compartment fire model energy conservation equations is consistant with reliable simulation of the compartment fire environment. For a particular problem of interest, the output from such a simulation would be used to provide the barrier/partition heat flux boundary conditions necessary to solve the now-multi-dimensional thermal/structural part of the problem. The latter problem would be formulated and solved with the use of an appropriate computational/computer tool of analysis, several of which are currently available (see, e.g., [9], [10], and [11]).

Two kinds of fire model output can be used to specify heat flux boundary conditions for multi-dimensional simulations of thermal/structural response. The first kind of output is obtained from models that allow simulated gas layers to be of arbitrary transparency. For such models, the time-dependent rates of incident radiant heat transfer to each of the fire-model-defined barrier/partition surface elements (assumed uniform across the surface of any particular surface element, but generally varying from element-to-element) will have been computed during the fire model simulation. These can be used directly to construct time-dependent net radiant fluxes for the thermal/structural analysis. Also, the calculated adjacent layer gas temperatures and/or, where appropriate, the temperatures and velocities of near-surface boundary flows would be available to construct time-dependent convective heat transfer fluxes.

The second kind of fire model output for specifying heat flux boundary condition to a particular surface element is simply the calculated, adjacent-layer, gas temperature. Existing thermal/structural fire response models typically carry out their multi-dimension thermal analyses with simplified combined radiation and convection surface heat flux boundary conditions calculated from such gas temperature specificatons. The formulation typically follows that prescribed in Reference [12], *viz*,

$$\dot{q}''_{S,M} = \epsilon_{EFF}\sigma(T^4_{G,M} - T^4_{S,M}) + h(T_{G,M} - T_{S,M}) \qquad (1)$$

where $\dot{q}''_{S,M}$ is the net heat flux to surface element M, at temperature $T_{S,M}$, $T_{G,M}$ is the temperature of the gas layer in contact with the element, σ is the Stefan Boltzman constant, ϵ_{EFF} is a resultant emmisivity, and h is an effective convective heat transfer coefficient.

For real room fire scenarios, the first of the above types of specification is more general than the second. However, it would typically be difficult to apply in practice. The second specification is relatively simple to apply, but it can not be relyed on for accuracy except when adjacent gas layers are nearly opaque.

To appreciate the difficulty of applying the general formulation, consider the fact that, even when regions of multi-dimensional heat transfer are "sparse" and "negligible," the rates of heat flux to and the distribution across the relatively-small exposed surfaces of such regions can vary significantly from the previously-predicted spacially-uniform heat flux. For example, in a fire scenario with relatively transparent gas layers, shading of potentially intense radiation from a fire combustion zone to a barrier/partition surface could occur as a result of local surface protrusions, e.g., in the neighborhood of the "sparsely" distributed beams of the beam-supporting floor/ceiling slabs of Figure 4. What is important here, is that such shading could lead to significant variations in rates of heat transfer across these sparse, but now-critical-region surfaces (e.g., the exposed surfaces of the above-referenced "sparsely" distributed beams whose structural integrity is being investigated). Such variations could have a significant effect locally on the multi-dimensional in-depth temperature distribution and, ultimately, on the structural response of the barrier/partition.

In the forseeable future it is not reasonable, and it may never even be practical, to expect an analytic capability that can take general account of the above spacially-variable local flux distributions. This situation leads to a dilemma relative to formulating accurate thermal/heat transfer boundary condition for the thermal/structural part of the problem.

Note that the difficulty in a general analysis of the radiation exchange problem, and the resulting dilemma, comes about as a result of the assumption of a relatively transparent, *vs*, say, a nearly-opaque contacting gas layer. Thus, if the gas layer in contact with the barrier/partion surface is nearly opaque, the effect of through-gas radiant transfer is negligible, and essentially all radiant transfer to surfaces, including the radiation to surfaces local to "sparse" protrusions, is a result of direct gas-layer-to-surface radiation exchange. Whereas the general determination of radiant heat transfer exchanges in the case of relatively-transparent contacting layers is problematic, when the contacting gas layers are nearly-opaque the problem becomes much more manageable. Indeed, it would appear that the nearly-opaque adjacent-gas-layer formulation is a basis for use of the commonly-used Eq. (1)-type heat flux specification.

A practical means of resolving the above dilemma is achieved by adopting the following, reasonable, heuristic assumptions:

1. The more opaque the upper gas layer, the greater the rate of heat transfer to upper-layer-submerged surfaces, i.e., the net radiant heating to such surfaces that would be estimated in the case of an opaque upper layer is assumed to exceed the actual net radiant heating. The latter would include incident radiation from the combustion zone and from often-relatively-low-temperature facing surface elements and through the gas layer(s), and incident radiation from the gas layers themselves.

2. The more intense the heating of particular partition/boundary surface elements, the smaller the fire resistance of the overall barrier/partition structure.

3. The upper-layer gases are near-opaque.

4. The rate of heat transfer to the barrier/partition surfaces in contact with the lower layer gases are adequately estimated by the fire-model-simulated spacially-uniform fluxes to the "one-dimensional" portions of those segments. Note that in the most threatened room of a modeled burning facility, in the room of fire origin, the fraction of lower-layer-exposed wall surfaces would often be relatively small, since the elevated-temperature upper-layer gases would typically fill most of the space, i.e., they would submerge the ceiling surfaces and most of the wall surfaces. Regarding the floor surface, it would typically not include the above-mentioned two-dimensional-type protusions. Therefore, incident heat transfer to floor surfaces elements would be well-simulated by the estimates available from the fire model simulation.

The first three of the above assumptions allows for a relatively-simple, straightforward, and presumedly conservative estimate (relative to calculations of fire resistance based on barrier/partition thermal and structural response) of the rate of heat transfer to all upper-layer-submerged surfaces. This would be based on the simulated time-dependent temperature of the upper layer and the use of Eq. (1).

An even-simpler, but more conservative alternative to assumption 4 is:

4a. The rate of heat transfer to the modeled segments of those remaining portions barrier/partition surfaces, in contact with the lower layer gases, are also conservatively estimated by Eq. (1). In particular, it is assumed that they are heated at the same rate as if they were in contact with and directly exposed to an opaque gas layer with upper-layer gas temperature.

DETERMINING THE TWO- OR THREE-DIMENSIONAL STRUCTURAL RESPONSE OF BARRIERS/PARTITIONS TO COMPARTMENT FIRE ENVIRONMENTS

With the above assumptions 1-3 and 4a, simulation results of an adopted compartment fire model would yield, *via* Eq. (1), rates of heat transfer to *all* surfaces of all rooms of a modeled facility, even to surfaces of sparse regions where in-depth multi-dimensional heat transfer is prevalent. These surface fluxes would be used to specify boundary conditions for the initial/boundary value problem(s) describing the multi-dimensional thermal response of the facility partitions/barriers.

The latter boundary value problems are the of the type that can be solved by a class of computational models designed to determine the thermal and structural response of structural elements exposed to fire or to other elevated-temperature environments (see, e.g., References [9], [10], and [11]). With the availability for input of the now-known surface heat fluxes, these computer models would typically be used to first solve for the temperature field thoughout a structure of interest. In problems of present concern, these would be barrier/partition structural elements. The computed temperature field would then be used, together with appropriate boundary conditions, to solve for desired the structural response.

The thermal/structural fire model, ***SAFIR*** [13], developed and currently being advanced at the University of Liege, has been identified and used as a reliable thermal/structural computational model for exploring and implementing the latter ideas. Preliminary applications of ***SAFIR*** at the Center for Advanced Technology for Large Structural Systems (ATLSS) of Lehigh University [14] and at the University of Maryland [15] indicate that the above approach to coupling a compartment fire model and a thermal/structural fire model will be successful.

REFERENCES

[1] Standard Methods of Fire Tests of Building and Construction Materials, ASTM E119, ASTM Committee E-5, Subcommittee E05.11, American Society for Testing and Materials (ASTM), Philadelphia, August 1988.

[2] Fire Resistance Tests - Elements of Building Construction, ISO-834, International Organization for Standardization, Switzerland, 1992.

[3] Cooper, L.Y., Harkelroad, M., Quintiere, J., and Rinkinen, W., An Experimental Study of Hot Layer Stratification in Full-Scale, Multi-Room, Fire Scenarios, Journal of Heat Transfer, Vol. 104, pp 741-749, 1982.

[4] Sultan, M.A., *et al*, Temperature Measurements in Full-Scale Insulated and Non-Insulated (1x2) Gypsum Board Protected Wall Assemblies with Steel Studs, Internal Rpt. 675, National Research Council Canada (NR) Institute for Research in Construction, 1994.

[5] Sultan, M.A., A Model for Predicting Heat Transfer Through Non-Insulated Unloaded Steel Stud Gypsum Board Wall Assemblies Exposed to Fire, Fire Technology, Vol. 32, No. 3, pp.239-259, 1996.

[6] Cooper, L.Y., The Thermal Response of Gypsum-Panel/Steel-Stud Wall Systems Exposed to Fire Environments - A Simulation for Use in Zone-Type Fire Models, NISTIR 6027, National Institute of Standards and Technology, Gaithersburg MD, June 1997.

[7] Jones, W.W. and Forney, G.P., A Programmer's Reference Manual for ***CFAST***, the Unified Model of Fire Growth and Smoke Transport, Tech. Note 1283, National Institute of Standards and Technology, Gaithersburg MD, 1990.

[8] Gustaferro, A.H. and Martin, L.D., Design of Fire Resistance of Precast Prestressed Concrete, Prestressed Concrete Institute, Chicago, 1977.

[9] Franssen, J-M., A Comparison Between Five Structural Fire Codes Applied to Steel Elements, Fire Safety Science - Proceedings of the 4th International Symposium, Kashiwagi, T., Ed., International Assoc. For Fire Safety Science, pp. 1125-1136, 1994.

[10] Sullivan, P.J.E., Terro, M.J., and Morris, W.A., Critical Review of Fire-dedicated Thermal and Structural Coputer Programs, Jl. Of Applied Fire Science, Vol. 3(2), pp. 113-135, 1993-94.

[11] Palm, J., Temperature Analysis Using ***ABAQUS***, Fire Technology, 3rd Quarter, pp. 291-303, 1994.

[12] EUROCODE 1: Basis of design and actions on structures, Part 2-2: Actions on structures

exposed to fire, ENV 1991-2-2, European Committee for Standardization (CEN), Central Secretariat: rue de Stassart 36, B-1050 Brussels, 1994.

[13] Franssen, J-M., General Presentation of the Numerical Code ***SAFIR***, University de Liege - Institut du Genie Civil, Liege, 1995.

[14] Gilvery, K.G., and Dexter, R.D., Evaluation of Alternative Methods for Fire Rating Structural Elements, NIST-GCR-97-718, prepared by Advanced Technology for Large Structural Systems (ATLSS), Lehigh University, for the National Institute of Standards and Technology, Gaithersburg MD, May 1997.

[15] Dillon, S.E. and Milke, J., The Thermal and Structural Response of Light Steel Frame Wall Assemblies Exposed to Fire Using the SAFIR Finite Element Model, Report prepared by the Dept. Fire Protection Engineering, Univ. of Maryland for the National Institute of Standards and Technology, Gaithersburg MD, May 1997.

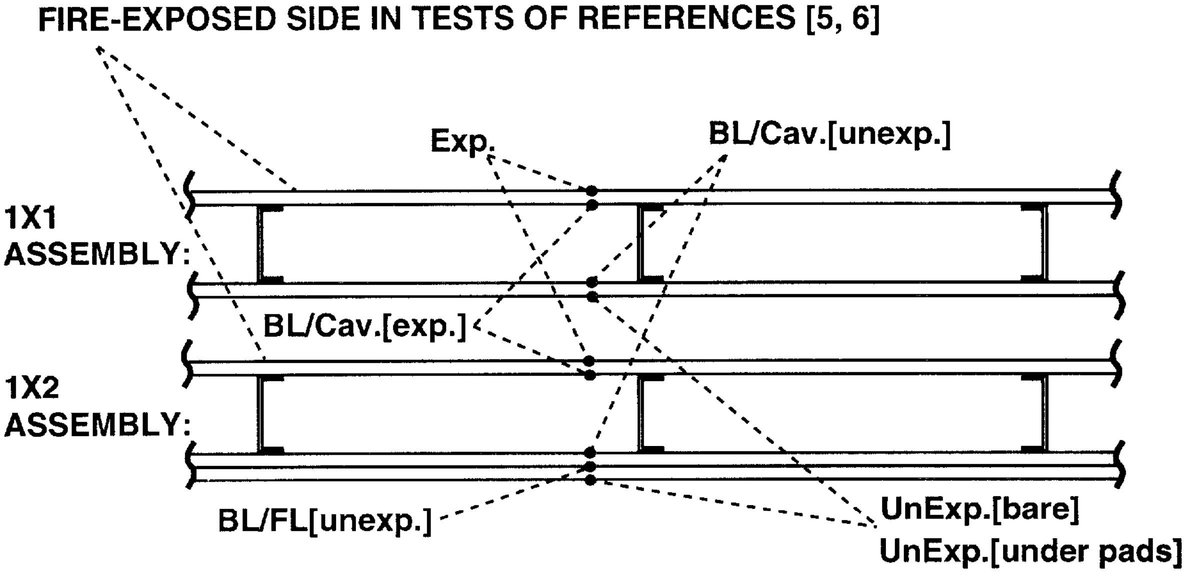

Figure 1. Sketch of example gypsum-panel/steel-stud wall system designs (adopted from References [4] and [5]); locations of calculated/measured temperatures in tests of [4] and [5].

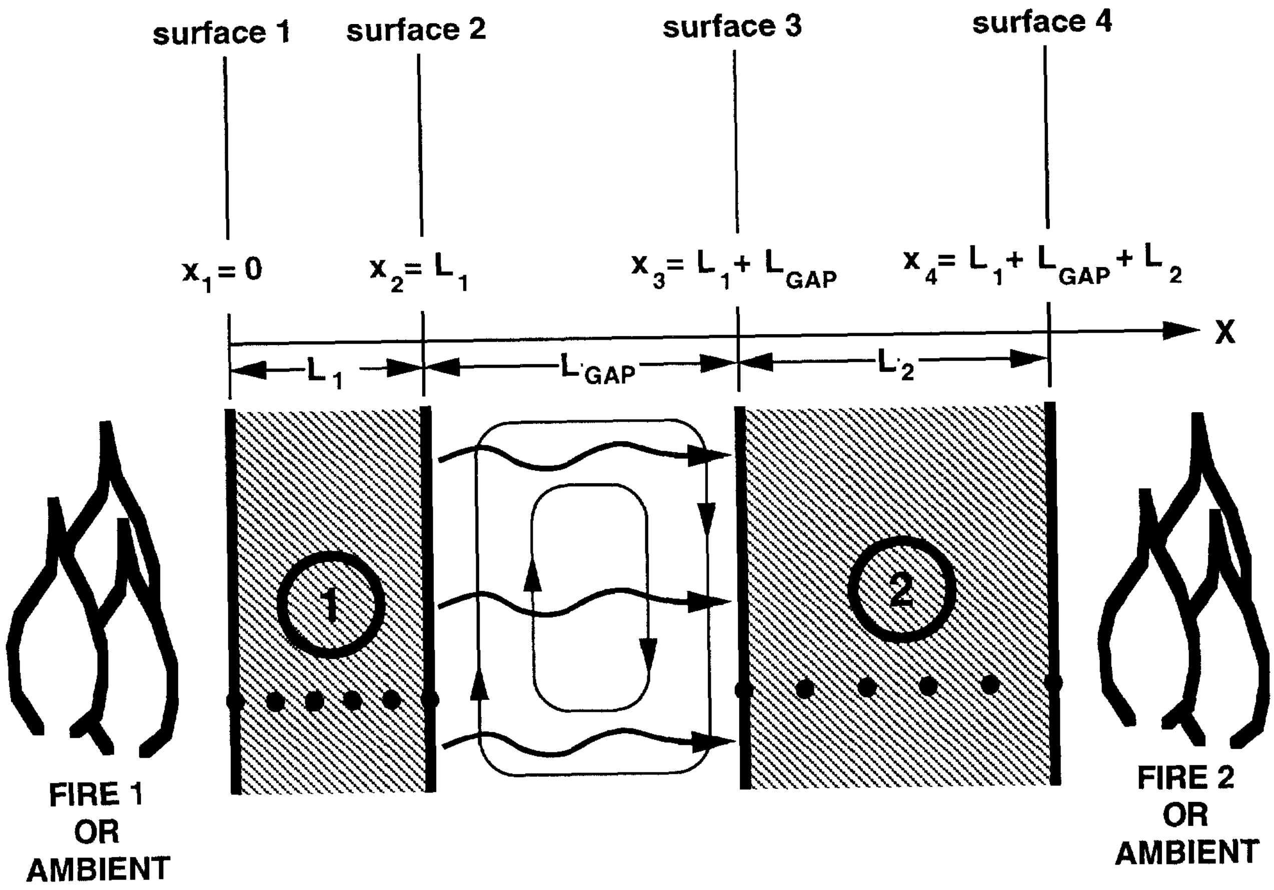

Figure 2. Sketch of the idealized geometry of the gypsum-panel/steel-stud wall system.

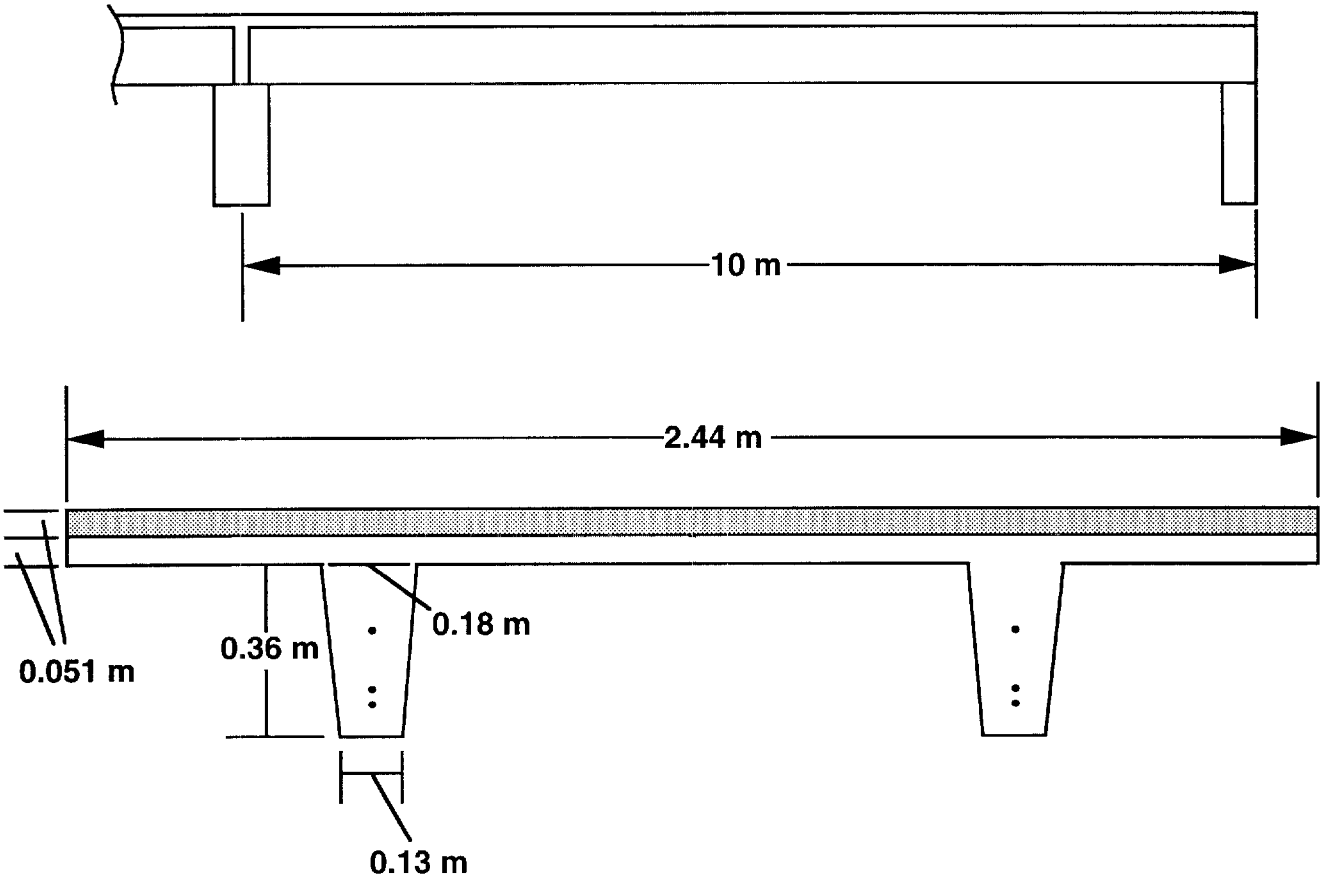

Figure 3. Sketch of a section of a reinforced-concrete, beam/slab, floor/ceiling system (from Problem 5.3 of Reference [9]).

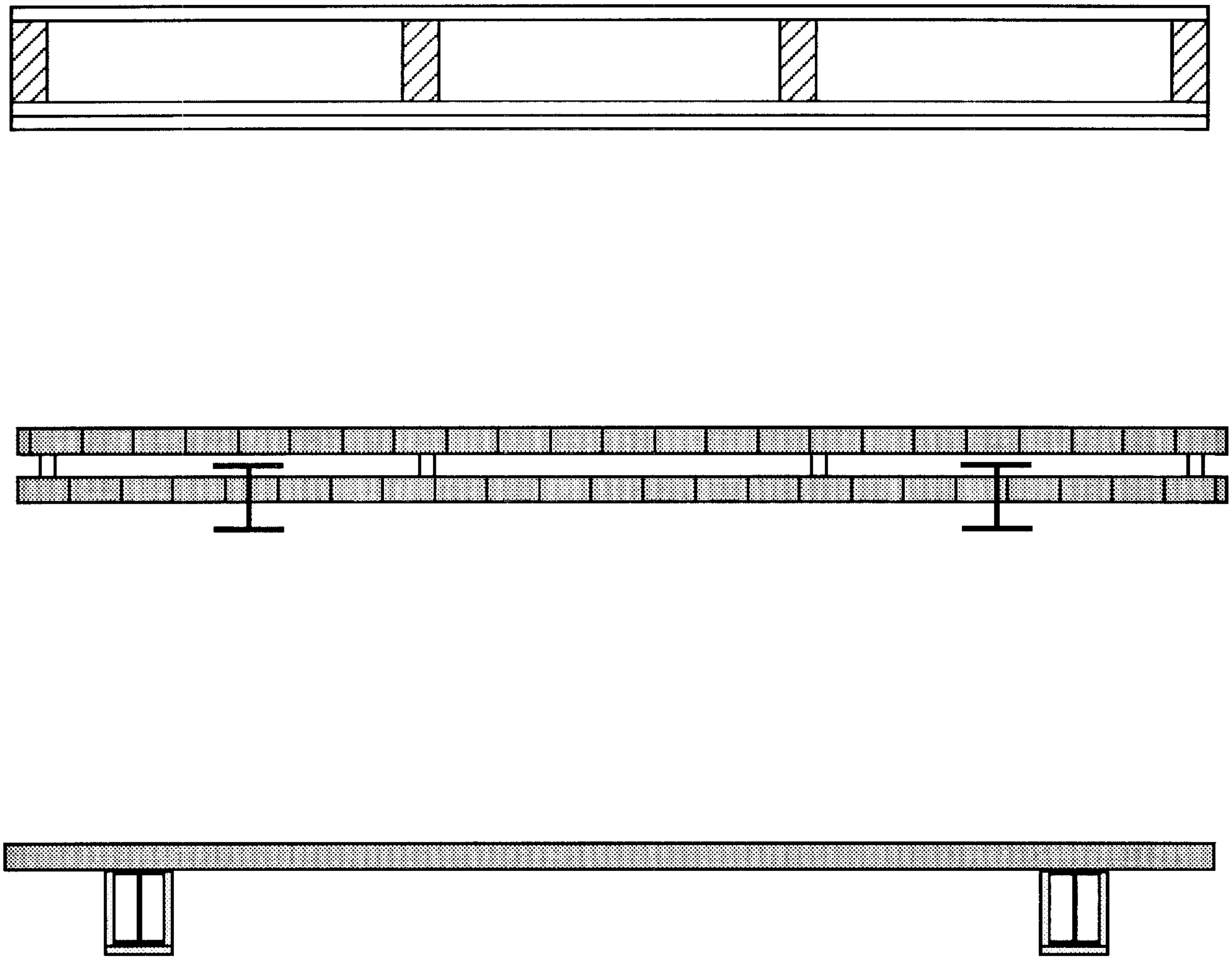

Figure 4. Sketch of examples of barrier/partition design where use of a one-dimensional thermal analysis may lead to reliable results; top: gypsum panel wall system with wood instead of steel studs; middle: concrete block wall with built-in sparsely-spaced steel columns; bottom: poured concrete slab supported on sparsely-spaced steel beams.

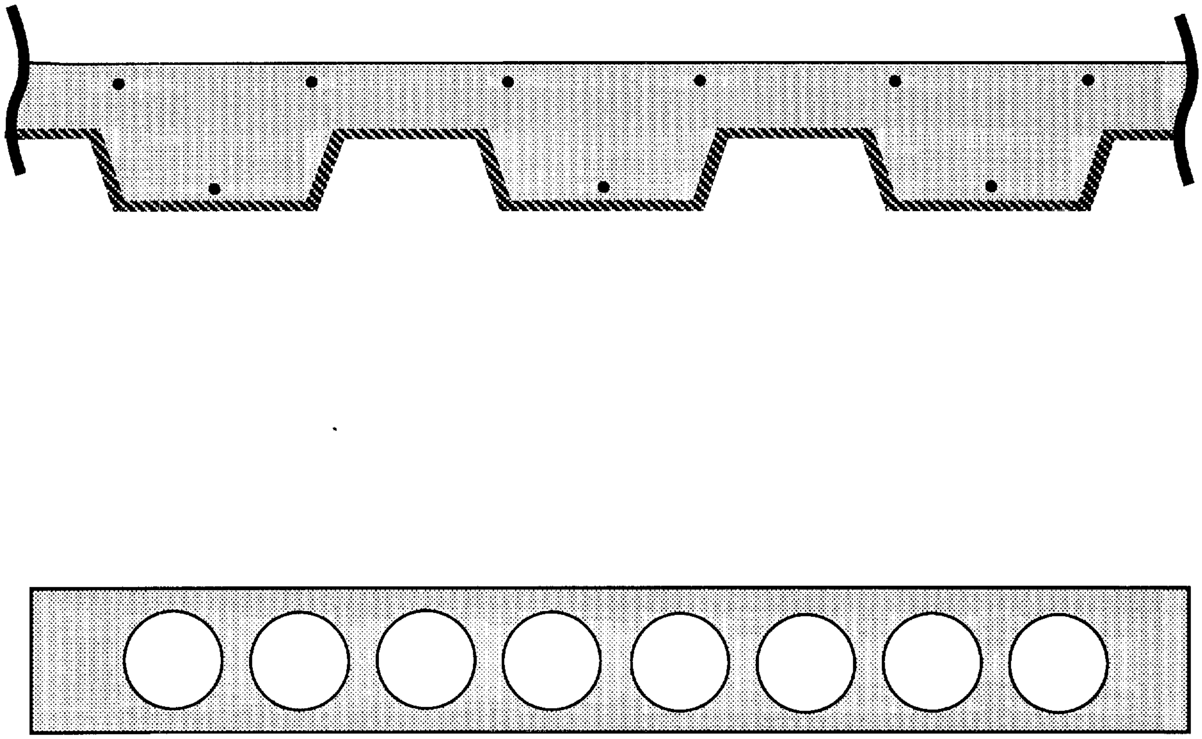

Figure 5. Sketch of examples of barrier/partition design where use of a one-dimensional thermal analysis may not lead to reliable results; top: composite concrete slabs with profiled steel sheets (metal deck floors); bottom: uniform-thickness concrete slabs with regularly-spaced inclusions.

NIST-114
(REV. 6-93)
ADMAN 4.09

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

MANUSCRIPT REVIEW AND APPROVAL

(ERB USE ONLY)	
ERB CONTROL NUMBER	DIVISION
PUBLICATION REPORT NUMBER NISTIR 6170	CATEGORY CODE
PUBLICATION DATE September 1998	NUMBER PRINTED PAGES

INSTRUCTIONS: ATTACH ORIGINAL OF THIS FORM TO ONE (1) COPY OF MANUSCRIPT AND SEND TO THE SECRETARY, APPROPRIATE EDITORIAL REVIEW BOARD

TITLE AND SUBTITLE (CITE IN FULL)

A 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

CONTRACT OR GRANT NUMBER

TYPE OF REPORT AND/OR PERIOD COVERED

AUTHOR(S) (LAST NAME, FIRST INITIAL, SECOND INITIAL)

Cooper, Leonard Y. and Franssen, J.-M.
National Institute of Standards and Technology
Gaithersburg, MD 20899

University of Liège
Liège, Belgium

PERFORMING ORGANIZATION (CHECK (X) ONE BOX)
- ☐ NIST/GAITHERSBURG
- ☐ NIST/BOULDER
- ☐ JILA/BOULDER

LABORATORY AND DIVISION NAMES (FIRST NIST AUTHOR ONLY)

Building and Fire Research Laboratory/Division 864

SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

PROPOSED FOR NIST PUBLICATION
- ☐ JOURNAL OF RESEARCH (NIST JRES)
- ☐ J. PHYS. & CHEM. REF. DATA (JPCRD)
- ☐ HANDBOOK (NIST HB)
- ☐ SPECIAL PUBLICATION (NIST SP)
- ☐ TECHNICAL NOTE (NIST TN)
- ☐ MONOGRAPH (NIST MN)
- ☐ NATL. STD. REF. DATA SERIES (NIST NSRDS)
- ☐ FEDERAL INF. PROCESS. STDS. (NIST FIPS)
- ☐ LIST OF PUBLICATIONS (NIST LP)
- ☒ NIST INTERAGENCY/INTERNAL REPORT (NISTIR)
- ☐ LETTER CIRCULAR
- ☐ BUILDING SCIENCE SERIES
- ☐ PRODUCT STANDARDS
- ☐ OTHER ______

PROPOSED FOR NON-NIST PUBLICATION (CITE FULLY) ☐ U.S. ☒ FOREIGN

PUBLISHING MEDIUM
- ☒ PAPER
- ☐ CD-ROM
- ☐ DISKETTE (SPECIFY) ______
- ☐ OTHER (SPECIFY)

SUPPLEMENTARY NOTES

ABSTRACT (A 2000-CHARACTER OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, CITE IT HERE. SPELL OUT ACRONYMS ON FIRST REFERENCE.) (CONTINUE ON SEPARATE PAGE, IF NECESSARY.)

Computer fire models for simulating compartment fire environments typically require a mathematical formulation that includes a coupled analysis of the thermal response of compartment barriers and partitions. The fire environment characteristics calculated by such models can be used to provide input to an uncoupled thermal-structural computer model for simulating and evaluating the combined thermal/structural performance of the barriers/partitions. The objective of such a combined analysis would be to determine, through analysis, the structural fire resistance of a barrier/partition design.

Depending on the particular barrier/partition design of interest, the latter thermal/structural part of the problem would generally require a two- and possibly three-dimensional analysis. As it turn out, there are several quality tools of analysis that are available for use in solving the latter problem. However, because of intense computational requirements, the general use of a multi-dimensional (*vs* a one-dimensional) barrier/partition thermal analysis in the fire modeling part of the problem is not now practical, and is not expected to be practical in the forseeable future.

This work presents a basis for identifying the wide and practical range of barrier/partition where the use of one-dimensional thermal analysis in the fire modeling part of the problem would lead to reliable simulations of the fire environment. As discussed, such fire model simulation results would provide the necessary input to complete the thermal/structural part of the problem, using two- or three-dimensional analyses, as required.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

Algorithms, ASTM E119, compartment fires, fire barriers, fire models, gypsum board, steel studs,walls, zone models

AVAILABILITY
- ☒ UNLIMITED
- ☐ FOR OFFICIAL DISTRIBUTION - DO NOT RELEASE TO NTIS
- ☐ ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GPO, WASHINGTON, DC 20402
- ☒ ORDER FROM NTIS, SPRINGFIELD, VA 22161

NOTE TO AUTHOR(S): IF YOU DO NOT WISH THIS MANUSCRIPT ANNOUNCED BEFORE PUBLICATION, PLEASE CHECK HERE. ☐

WORDPERFECT