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A PROTOTYPE MODEL FOR SIMULATING BARRIER FIRE PERFORMANCE: *CFAST.GYPST* - FOR EVALUATING THE THERMAL RESPONSE OF GYPSUM-PANEL/STEEL-STUD WALL SYSTEMS

Leonard Y. Cooper and Paul A. Reneke

Building and Fire Research Laboratory
Gaithersburg, MD 20899

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National Institute of Standards and Technology
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ABSTRACT

Zone-model-type simulations of compartment fire environments, which include the thermal response of barrier/partition structural elements, are discussed in the context of the adequacy of using a one- *vs* multi-dimensional heat transfer analyses for the barriers/partitions. Introductory discussion focuses on the identification of barrier/partition designs and fire scenarios where such a one-dimensional analysis is valid even when a two- or three-dimensional analysis would be required to study the thermal-structural response. The ideas presented are implemented in a prototype model, ***CFAST.GYPST***, an advanced version of ***CFAST***, which uses the algorithm and associated FORTRAN subroutine ***GYPST***, developed previously to simulate the thermal response of fire-environment-exposed wall systems constructed of arbitrary-thickness gypsum panels mounted on either side of vertical steel studs. ***GYPST*** was designed as a modular algorithm/subroutine for integration into zone-type compartment fire models and for use in "stand-alone" analyses.

CFAST.GYPST is validated by using previously acquired experimental data from ASTM E119 furnace tests of two different, full-scale wall-system designs. This is accomplished by first establishing a particular room fire scenario where the simulated room fire environment closely follows the ASTM E119 furnace environment. It is then verified that, when the upper layer gases are opaque (analogous to a typical wall furnace exposure) and closely track the ASTM E119 temperature-time curve, the ***CFAST.GYPST***-simulated thermal wall-system response compares favorably to the corresponding experimental thermal-response data acquired during the furnace-exposed wall-system tests.

In example "real-fire-type" simulations that are relatively-severe (i.e., the upper layer temperature rises above that of the ASTM E119 standard fire for several minutes and then drops below it), ***CFAST.GYPST*** is used to calculate the fire environment and associated wall response for each of the above-referenced wall systems for a room geometry and fire energy-release history that is related to that of a newly developing ASTM room fire test standard. For these simulations, the thermal responses of the two wall systems are predicted and then evaluated relative to respective expected fire resistance.

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

INTRODUCTION - MODELING THE ROOM FIRE ENVIRONMENT AND THE THERMAL RESPONSE OF ROOM PARTITIONS/BARRIERS

Compartment Fire Modeling (Including Thermal Response of Patitions/Barriers) and the Room Fire Environment; Thermal/Structural Response and Fire Resistance

Compartment fire models typically include (in the general set of governing equations) an analysis for the thermal response of compartment barriers and partitions. These models yield simulation solutions for the fire environment that can be used to provide input to an uncoupled thermal-structural model for simulation and evaluation of the combined thermal-structural performance of the barriers/partitions. The objective of the 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 turns out, there are several quality tools of analysis that are available for use in solving the latter problem (see, e.g., References [1], [2], and [3]). 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 foreseeable future.

Using One-Dimensional Analyses of Barrier/Partition Thermal Response in a Fire Model

Reference [4] presented 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. Then, as above, the simulation results could be used, in turn, to provide necessary input to complete the thermal-structural part of the problem, using two- or three-dimensional analyses, as required. 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 important, in the sense of affecting significantly barrier/partition fire performance, these regions may be relatively sparse, and involve relatively negligible heat transfer. This is the characteristic design feature of the category of barrier/partition assembly considered here.

In the above, 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 within regions of multi-dimensional response are insignificant compared to the overall effects of energy conservation. Thus, we are considering assemblies where: 1) most of the through-barrier/partition heat transfer phenomena are well modeled by locally one-dimensional analysis, and 2) sparse regions of two- or three-dimensional barrier/partition behavior can be ignored in the room fire model analysis since, even if modeled accurately, they would have little effect on modifying room fire environments.

Locally One-Dimensional Analyses; Accounting for Temperature Dependent Properties

As is the case in most existing compartment fire models, the simulation of barrier/partition thermal response is by way of locally one-dimensional analyses. The idea is to "break up" the barrier/partitions of a modeled facility into a number of discrete segments or slabs, and to simulate the thermal response of each.

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: 1) the characteristic thicknesses of partitions/barriers are usually much smaller than their characteristic spans and, as a result of this, 2) 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.

When compartment fire model simulations are used to 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. Therefore, accurate simulation of the through-barrier/partition heat transfer requires an accurate accounting of property variations.

The Objective

Reference [4] presented and discussed examples of barrier/partition assembly designs where the above ideas on one-dimensional analyses were valid and designs where they were not valid. One design example was a class of gypsum-panel/steel-stud wall system. The objective of the present work is to describe a prototype fire model, that includes accurate accounting of the effects of the thermal response of such wall systems, where the results of model simulations can be used to 1) establish barrier/partition fire resistance relative to the potential for thermal failure, and 2) define surface heat transfer boundary conditions for the multi-dimensional analysis of thermal-structural response that are necessary, in the case of load-bearing systems, to establish barrier/partition fire resistance relative to the potential for structural failure.

THE GYPSUM-PANEL/STEEL-STUD WALL SYSTEM AND THE PROTOTYPE FIRE MODEL

General Description of the Wall System

Figure 1, adopted from References [5] and [6], is a sketch of the gypsum-panel/steel-stud wall system design considered here. 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 [5] 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.

Validity of Using a One-Dimensional Analysis in Modeling the Room Fire Environment; Need for Multi-Dimensional Analysis to Model Thermal/Structural Response

Extensive thermocouple data on the thermal response of a Fig. 1 1x2-type wall system to ASTM E119 [7] standard-fire furnace exposures were acquired and presented in Reference [5]. 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 [6] and [8] 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 loaded wall systems and in terms of the critical evaluation of wall system fire resistance and possible wall system failure, it is the spacially-varying loss of strength of the steel studs due to spatially-varying elevated temperatures that would lead to wall system structural failure, and that would have to be simulated. Nevertheless, for Fig. 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.

The Prototype Room Fire Model *CFAST.GYPST*

This work will describe the protoype fire model ***CFAST.GYPST***, an advanced version of the fire model ***CFAST*** [9], that was designed to implement the above ideas for the above class of gypsum-panel/steel-stud wall system. ***CFAST.GYPST*** uses the modular wall model/algorithm, called ***GYPST***, that was developed in Reference [8]. 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 Fig. 2. The reader is referred to Reference [8] for the details of the wall system heat transfer model and its associated computer subroutine, ***GYPST***.

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

With the above assumptions, simulation results of an adopted compartment fire model would yield 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. The computed surface fluxes would be used as the boundary conditions of initial/boundary value problem(s) that would be used to determine the detailed multi-dimensional thermal response of the facility partitions/barriers. (The one-dimensional estimates of thermal response would already be available from the compartment fire model simulation.).

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, [1], [2], and [3]. With the availability for input of the now-known surface heat fluxes, these computer models would typically first be used to 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.

Through multi-institution collaborative agreements between NIST, the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University [10], the University of Maryland [11], and University of Liege, the thermal/structural model ***SAFIR*** [12], developed and currently being advanced at the University of Liege, is the computational model now being used to explore and implement the latter ideas.

COUPLING THE EQUATIONS OF BARRIER/PARTITION SEGMENT THERMAL RESPONSE TO THE EQUATION SET OF A ZONE-TYPE COMPARTMENT FIRE MODEL

Formulating the Fire Model's Basic Equation Set

Formulations of the mathematical problem associated with zone-type compartment fire models typically involve a basic coupled set of ordinary differential equations (first derivatives in time of some solution variables) and algebraic-type equations. These express mathematically the basic principals of conservation of energy, mass, and products of combustion and the equations of state for the assumed-spatially-uniform upper and lower gas layers of each space of the modeled compartment facility.

Consider the numbered set of exposed surface elements of the barrier/partition segments, defined for a particular facility and fire scenario to be simulated. Let $T_{S,M}$ represent the temperature at a generic surface element number M. If the functional relationships of the above equation set involve some of these temperatures, and if such temperatures *are not* specified explicitly, then additional equations, expressing conservation of energy at the corresponding surfaces, would be added to the equation set, and the $T_{S,M}$'s would be added to the list of solution variables. (An *explicit* specification would result if, e.g., it is reasonable to assume that during the course of a simulation a particular surface temperature, $T_{S,M}$, will not vary significantly from is original ambient value, T_{AMB}. In such case, the specification would be $T_{S,M} = T_{AMB}$.)

If the fire model uses the equation of heat conduction to describe energy transfers away from an exposed surface and into the depth of a barrier/partition segment, the latter additional equations are of the form

$$\dot{q}''_{S,M} = -\, k_{S,M} \partial T_{S,M} / \partial x_N \qquad (1)$$

where: $\dot{q}''_{S,M}$ is the net rate of heat transfer per unit area from the environment to the Mth surface element; x_N is the normal to surface element M, directed into the surface along the x axis; and $k_{S,M}$ is the thermal conductivity of the barrier/partition segment material in the vicinity of surface element M. In Eq. (1), $k_{S,M}$ would typically be a function of $T_{S,M}$. Also, $\dot{q}''_{S,M}$, would generally include heat transfer to the surface by both convection and radiation. Depending on the particular fire model, a given $\dot{q}''_{S,M}$ would typically be described by a function of the $T_{S,M}$'s, and of other solution variables and parameters of the problem.

In Eq. (1), $\partial T_{S,M}/\partial x_N$ would be determined in a subroutine designed to solve the inital-/boundary-value problem (I/BVP) for the thermal response of the barrier/partition segment that includes the Mth exposed surface. Thus, the Eq. (1)-type equations that correspond to the solution-variable-type $T_{S,M}$'s are the means by which the I/BVP's of barrier/partition thermal response are coupled to the basic fire model equation set. There would be one such I/BVP associated with each barrier/partition segment that has a solution-variable-type $T_{S,M}$ associated with one or both of its outer exposed surface elements. [A segment could have two surface elements with solution-variable-type $T_{S,M}$'s if both of its outer surface elements are exposed to significant adjacent-room fire environments. If this is the case, then the right hand sides of the two Eq. (1)'s that correspond to these two $T_{S,M}$'s would be determined from the same I/BVP.]

Different strategies of solving the above type of coupled problem are discussed in Reference [13]. A type of strategy that treats solutions to the above-mentioned I/BVP's as "side calculations," in the sense that the I/BVP calculations do not introduce new solution variables into the basic problem formulation, is referred to as a "gradient matching method." This is the method currently used in the ***CFAST*** compartment fire model [15]. It will also be used in the new prototype model to be introduced below.

Solving the Basic Equation Set, the Method of Advancing From One Time Step to the Next

Fire model computer codes typically solve an initial value problem for any particular fire scenario to be simulated. As mentioned, this involves a basic equation set that includes first order ordinary differential equations (time as the independent variable) and algebraic-type equations. Here, the latter algebraic-type equations would include those of the Eq. (1)-type, one such equation for each solution-variable-type $T_{S,M}$.

Assume that the solver has determined the values of the solution variables up to an arbitrary time, t_1 (i.e., with these values, each of the equations of the basic equation set are satisfied to user-specified accuracy). Assume also, that side calculations with the I/BVP subroutine have, to similar accuracy, yielded descriptions of the thermal state of the barrier/partition segments, i.e., their in-depth temperature distributions, designated as $T_{I,DEPTH}(t_1, x)$ for segment number I of the modeled facility. The determination of the solution over the course of the next time step would then proceed as follows:

1. The fire model solver would use current values of the solution variables, and their values as computed at previous time steps, to estimate new rates-of-change of the variables and an appropriate next time step, Δt, for use in advancing the solution, to the specified accuracy, from t_1 to $t_2 = t_1 + \Delta t$. The solver would use this information to estimate the values of all solution variables at t_2. These would include the solution-variable-type $T_{S,M}$'s.

2. Using the estimates of the solution variables at $t = t_2$, the elements of all non-Eq. (1)-type equations of the basic equation set, as well as the $\dot{q}''_{S,M}(t_2)$'s and $k_{S,M}(t_2)$'s of Eq. (1)-type equations would determined.

3. For t in the range $t_1 < t \leq t_2$, and for each barrier/partition segment I with at least one of its exposed surface elements having a solution-variable-type $T_{S,M}$, the I/BVP subroutine is used to solve the initial-/boundary-value problems, to specified accuracy, for the in-depth thermal response of the segments. The problem for any particular segment has the following initial and boundary conditions:

initial conditions:

$$\text{at } t = t_1: \; T_{I,DEPTH} = T_{I,DEPTH}(t_1, x)$$

boundary condition (at a surface element with solution-variable-type $T_{S,M}$):

$$T_{I,DEPTH}(t, x_{S,M}) = T_{S,M}(t_1) + [T_{S,M}(t_2) - T_{S,M}(t_1)](t - t_1)/\Delta t \tag{2}$$

boundary condition (at a surface element with specified $T_{S,M}$):

$$T_{I,DEPTH}(t, x_{S,M}) = \text{specified value of } T_{S,M}(t)$$

Thus, for solution-variable-type $T_{S,M}$'s, the surface temperatures are specified as varying linearly with time between specified initial and final values, $T_{S,M}(t_1)$ and $T_{S,M}(t_2)$, respectively.

The solution to the I/BVP for each segment I would include the final temperature distribution, $T_{I,DEPTH}(t_2, x)$ and the surface gradient(s), $\partial T_{S,M}/\partial x_N\,(t_2)$.

4. Using the $t = t_2$ estimates of all solution variables, from item 1, the $\dot{q}''_{S,M}(t_2)$'s and $k_{S,M}(t_2)$'s from item 2, and the $\partial T_{S,M}/\partial x_N\,(t_2)$'s from item 3, the solver would determine whether or not each equation of the basic equation set, including the the Eq. (1)-type equations, was satisfied to specified accuracy. If each equation is so satisfied, the set of just-determined new values for the solution variables at $t = t_2$ is adopted, and the procedure is implemented again, now working to advance the solution beyond $t = t_2$, etc. If any of the equations are *not* satisfied to specified accuracy, then the entire new solution is not valid. Under the latter circumstance, the procedure would be implemented again, starting once more from the established $t = t_1$ set of solution variables, but using a reduced value of Δt, etc.

A Prototype Model for Evaluating the Thermal Response of Gypsum-Panel/Steel-Stud Wall System

The above computational procedure is currently used in ***CFAST***, in conjunction with the I/BVP solver subroutine ***CNDUCT*** [15]. ***CNDUCT*** solves the conduction problem associated with a relatively simple barrier/partition design having one-to-three layers of different material, where the thermal properties of each material are spacially uniform and independent of temperature [16].

Justification for the use of a one-dimensional thermal analysis to describe the thermal response of relatively-complex, two-dimensional-like, barrier/partition structures was presented in the first section of this work. One structure discussed there was the gypsum-panel/steel-stud wall system. As mentioned, ***GYPST*** has been developed as a one-dimensional model with associated computer subroutine for the analysis of such wall systems [8]. The model includes an accounting of temperature-dependent properties, and it is very versatile in that it is designed to handle arbitrarily-specified boundary condition at the two outer surfaces of the wall system. Also, the subroutine incorporates a robust solver for the I/BVP. The ***GYPST*** subroutine is designed for general use in zone-type fire models, and for stand-alone simulations.

The difference between the current version of ***CFAST*** and the new prototype version, ***CFAST.GYPST***, being introduced in this work, is in the option to use the subroutine ***GYPST***. Thus, ***CFAST.GYPST*** can simulate fire in a room with barriers/partitions having a mix of ***GYPST*** and ***CNDUCT*** wall/floor/ceiling systems.

GYPST FOR STAND-ALONE CALCULATIONS AND FOR GENERAL USE IN ZONE-TYPE FIRE MODELS AND IN *CFAST.GYPST*

The subroutine ***GYPST*** simulates the thermal response of a fire-exposed gypsum-panel/steel-stud wall system segment bounded by left- and right-hand surfaces, surfaces 1 and 4, respectively, as sketched in Fig. 2. Temperatures are predicted at NPTS equidistant points through the thickness of each of the two gypsum panels, panels 1 and 2. In using ***GYPST***, nine possible options are available (IBCTYP = 1 - 9) for solving the I/BVP for the temperature distribution through the wall system segment, where the appropriate choice depends on the nature of the user-defined type of exposure (i.e., the boundary conditions) of surfaces 1 ($x_1 = 0$) and 4 ($x_4 = L_1 + L_{GAP} + L_2$).
For example, use of option 6 (IBCTYP = 6) allows stand-alone simulation of the response of a particular wall system design when it is exposed on surface 1 to time-dependent heat transfer from an ISO 834, standard-fire, furnace environment [17] and on surface 4 to heat transfer from an ambient-temperature laboratory environment.

With muliple calls to the subroutine ***GYPST***, options 4 and 9 of the above nine options, can be used in zone-type fire models to implement the solution strategy of the previous section.

Option 4 would be used when a wall system segment is exposed to two different fire environments, surface 1 being exposed to the fire environment in one room of a facility and surface 4 being exposed to a fire environment in the adjacent room, on the other side of the wall segment. ***CFAST*** does not yet allow for direct specification of option 4-type double-sided wall exposures. Such allowance will require an advanced means of specifying geometrically the correspondence between the numbered exposed- surface pairs of the numbered wall segments of a multi-room facility and the connectedness of the numbered rooms of the facility. As indicated in Reference [15], this advance of ***CFAST*** is under active study.

Option 9 would be used when surface 1 of a wall segment is exposed to a fire environment, while surface 4 is exposed to the ambient environment. This is the generic wall system fire exposure modeled currently by ***CFAST***. The combined use of ***CFAST*** and option 9 of ***GYPST*** leads to the new prototype fire model ***CFAST.GYPST***.

In a call to the subroutine ***GYPST***, the input data include the values of NPTS and IBCTYP and parameters that describe: the physical geometry of the particular wall system design being considered; the emissivity of the four bounding surfaces of the two gypsum panels; density of the gypsum panels at 20 °C; and a specified accuracy for the I/BVP solution.

Input to ***GYPST*** also includes arrays of property-temperature pairs, used to specify by interpolation/extrapolation the temperature-dependent density, specific heat, and thermal conductivity of the gypsum panels. The calculations presented here always use the temperature-dependent properties plotted in Fig. 3-5. These are based on interpolation between property-temperature pairs adopted and presented in **APPENDIX A** of [8].

A concise summary description of the problem solved by **GYPST**, and the nine solution options available to the user of the **GYPST** subroutine are presented in **APPENDIX A**. This is from the listing of the introductory "comments" portion of the **GYPST** source code. As mentioned, advanced zone-type fire models, including anticipated future versions of ***CFAST***, would typically use **GYPST** with the input condition IBCTYP = 4 or 9.

The solution algorithm asociated with the IBCTYP = 4 and 9 options of **GYPST**, is presented in **APPENDIX B**.

Table 1 lists the input data used in all ***CFAST.GYPST*** calculations to be presented in this work.

SIMULATIONS TO EVAUATE AND VALIDATE *CFAST.GYPST*

Selecting the Room Fire Scenarios

This section identifies the room fire scenarios that were used to test and apply ***CFAST.GYPST***.

Two sets of simulations were carried out, where each set involved two scenarios, one with the 1x1 NRC-furnace-tested gypsum-panel/steel-stud wall system and the other with the 1x2 design [5, 6].

All simulations involve a fire scenario in a single-room enclosure (i.e., the outside surfaces of all six wall/ceiling/floor partitions are exposed to an ambient environment) with a single door vent. All four walls are of a particular gypsum-panel/steel-stud wall design under investigation, either the 1x1 or the 1x2 design. The ceiling and floor are taken to be plywood and solid gypsum board, respectively. In simulating the thermal response of these barrier/partitions, the ***CNDUCT*** subroutine [15] was used to model the floor and ceiling, which is taken to have the thicknesses and constant properties indicated in Table 2. The ***GYPST*** subroutine [8] was used to model the walls, where the design parameters for these are listed/defined in Table 1 and in Fig. 1 and 2. Note that the emissivity of the four surfaces of the gypsum panels are all taken to be 0.9, i.e., $\epsilon_i = 0.9$, $i = 1, 4$. In Reference [8], stand-alone ***GYPST*** simulations using these values were found to predict wall thermal responses that compared favorably with the corresponding measured results reported in [5] and [6].

Simulations with an ASTM E119-temperature upper layer. The first set of simulations involves a "contrived" fire that generates a fire environment in the enclosure corresponding closely to an ASTM E119 furnace-fire environment. The upper layer of the room fire environment mostly fills the space, the upper layer temperature history follows closely that of the ASTM E119 temperature-time curve [7], and the relative contribution of heat transfer to the exposed wall surfaces from flame radiation and any direct flame impingement is not significant. The latter is accomplished by specifying the upper layer gas as being completely opaque, i.e., zero upper layer transmission factor corresponding to a total upper layer emissivity of one. This specification is to be compared to use of the ***CFAST.GYPST*** (i.e., ***CFAST***) default method of calculating the radiative characteristics of the gas layers, where the latter methodology is from [14]. It was anticipated that the room-fire environment with the opaque upper layer will lead to wall thermal responses that follow closely the thermal responses of the 1x1 and 1x2 wall systems as measured during in actual ASTM E119 furnace tests, and as reported in References [5] and [6].

The objective of this first set of simulations is: 1) to show that ***CFAST.GYPST*** can yield compartment fire model predictions that include detailed, experimentally-validated, in-depth wall temperatures; and 2) to verify that the full fire model ***CFAST.GYPST***, which includes the ***GYPST*** subroutine software , leads to simulation results that correspond appropriately to that of the ***GYPST*** software as used in its stand-alone mode.

As will be seen, it was instructive to carry out an additional pair of simulations within his first set. This is identical to the above first pair, except that instead of specifying the upper layer to be opaque, time-dependent radiative characteristics of the gas layers are actually calculated (according to the ***CFAST.GYPST*** default method) and used throughout the ***CFAST.GYPST*** simulation.

Simulations with a severe, but "realistic" fire threat. The second set of simulations involves a fire threat that is relatively severe, but more realistic than that of the ASTM E119 standard fire; one that leads to a rapidly-growing deep upper layer, with temperature that rises above that of the ASTM E119 fire, within a few minutes of ignition, and then drops below it as the fire strength decays with the depletion of available combustibles. Here again, two pair of simulations were carried out, one with a specified opaque upper layer, and one with calculated upper layer radiative characteristics.

Table 3 provides a listing of all the above simulations, the results of which will be reported below.

Guidelines for Choosing Simulation-Enclosure Geometry and Fire Strength

A new ASTM standard is in review: Standard Test Method for Room Fire Test of Wall and Ceiling Materials [18]. This will be referred to below as the *New Standard.* This involves a fire in the corner of a room of dimension 3.66 m (length) x 2.44 m (width) x 2.44 m (height), with a single (doorway) vent, 0.76 m (width) x 2.03 m (height), located in the center of one of the 2.44 m x 2.44 m walls. In the New Standard test, the fire is generated by a square gas burner 0.30 m x 0.30 m, with the horizontal top surface, through which propane gas is supplied, 0.30 m above the floor surface, and where the burner enclosure is in contact with both walls of a corner of the room opposite the door.

The heat output of the gas burner is specified as 40 kW for an initial five minutes followed by 160 kW for the next ten minutes.

The New Standard was used as a guide in choosing the room fire simulation scenarios with which to evaluate ***CFAST.GYPST***. In this regard, it is noteworthy that the purpose of the New Standard is to evaluate the response of the portions of the wall and ceiling assemblies, located near the corner of the room, that are *exposed directly* to the burner fire combustion zone (with flame temperatures always higher than standard fire temperatures) and plume. In contrast to this, the purpose of using ***GYPST*** in ***CFAST.GYPST*** is to simulate the response of the portions of the room's wall assemblies, that are located *away from the immediate vicinity of the room fire's combustion zone*, and that are only *exposed indirectly* to the combustion zone and to the high temperature regions of its plume. (The indirect exposure environment involves quasi-steady gas temperatures that are typically significantly lower than flame temperatures. This is in contrast to intense direct exposure associated with steady flame impingement, where gas temperatures would always exceed that of the standard fire.) This corresponds to the implicit purpose of ASTM E119 and ISO 834 standard fire furnace testing; namely, to evaluate the response of a structural assembly when exposed to a room fire environment with average temperatures equal to the appropriate standard-fire temperature-time curve. The reader is referred to Reference [19] for a discussion of the two types of threat associated with the direct and indirect effects of exposure to a compartment fire combustion zone and plume.

Equivalence Between a *CFAST.GYPST*-Modeled Scenario and A New-Standard-Type Test Scenario

In view of the above, the following ***CFAST.GYPST***-modeled scenario (room geometry and fire location and strength) is proposed as being equivalent to a New-Standard-type test scenario (a single room with a single vent near one corner and with fire placed near the opposite corner), in the sense that the simulated wall exposure is expected to approximate well the test wall exposure for walls in the test room that are well removed from the fire-corner:

> **Simulation-room geometry**: The simulation room is two times the length and two times the width of the New Standard test room, and is of identical height, e.g., 7.32 m (length) x 4.88 m (width) x 2.44 m (height). It has the equivalent of four door vents, each one of which is identical to that of the test room, i.e., in the case of the New Standard test room, four vents with dimensions 0.76 m (width) x 2.03 m (height), and symmetrically placed around the perimeter of the room. (In ***CFAST.GYPST***, effects of vent placement around the periphery of the room are not taken into account and the four door vents would be modeled as a single vent with height and bottom elevation identical to that of the test room, but where vent width is four times the width of the single test-room vent.) In short, the test room can be though of as a quadrant of the simulation room.
>
> **Simulation-room fire**: The simulation room fire is represented by a fire in the center of the simulation room, with four times the strength of the test fire. This corresponds to a "four-fold reflection" into the two, corner, test-wall surfaces of the test room. For, example, if

simulation of the effects of exposure to the specified fire of the New Standard is desired, then the simulation fire would be: a propane fire from a square 0.6 m x 0.6 m gas burner, in the center of the simulation room, with burner surface 0.3 m above the floor and with heat output of 160 kW (= 4 x 40 kW) for an initial five minutes followed by 640 kW (= 4 x 160 kW) for the next ten minutes.

Room Geometry and Fire for a Modified, More-Severe, New-Standard Fire Scenario

The New-Standard test scenario is not expected to lead to a fire environment that is particularly threatening to the integrity of "corner-removed" portions of the wall assemblies. The main reason for this is that the strength of the above-described specified fire will not lead to particularly high upper layer temperatures. Also, the doorway vent is wide enough to preclude any significant growth of the upper layer, i.e., the upper-layer/lower-layer interface will never drop much below the top of the doorway vent. The purpose of the work recommended here is to evaluate ***CFAST.GYPST*** for fire scenarios that *do* lead to potentially-threatening wall system thermal responses. To achieve this, calculations to be carried out here will simulate the response of the gypsum-panel/steel-stud-type wall systems to modified *larger* simulation fires with a *restricted-width* vent (i.e., a nearly-closed New-Standard room vent). In terms of the width of the vent, ***CFAST.GYPST*** calculations here will involve a simulated 1/8-open New-Standard room vent, i.e., a vent with a width of 0.76/8 m = 0.095 m. Then, every such simulated fire, whatever its strength, is expected to lead to a wall reponse that is equivalent to the response of fire-removed walls of test scenarios involving the New-Standard room geometry, with a 1/8-width vent, and with a test fire of approximately one-quarter of this strength. (Note that in the New-Standard test fire scenario with the fire *in the corner*, there will be heat transfer losses to the two wall surfaces that intersect at the "burner corner" of the room, with significant losses to the parts of these surfaces exposed directly to the combustion zone and plume. However, for the simulation fire scenario, which involves a fire *in the center* of the simulation room, there will be no such corresponding losses. For this reason the four-to-one ratio of simulated- to test-fire strength is expected to only approximately reproduce simulated *vs* measured wall system response. Indeed, when the four-to-one ratio in fire strength is followed, the above-mentioned losses in the test fire case is expected to lead to a tested-wall response that is somewhat *less severe* than the corresponding simulated-wall response.)

The Simulation Enclosure and Fire Source Geometry and the Fire Strength

Simulation enclosure and fire source geometry: The above ideas and guidelines, leads to the following choice for simulation enclosure and fire source geometry:

> *7.32 m (length) x 4.88 m (width) x 2.44 m (height)., with a single (doorway) vent 0.38 m (width) x 2.03 m (height). The fire is burning propane gas injected from a square horizontal gas burner surface, 0.60 m x 0.60 m, in the center of the room.*

This enclosure and fire source geometry is adopted for use in all ***CFAST.GYPST*** simulations to be reported below.

Simulation fire strength: As discussed above, simulations to be carried out here, including thermal response of gypsum/stud wall systems, will involve two different specified fires. The first fire is one that is designed to generate a fire environment corresponding closely to an ASTM E119 furnace-fire environment, i.e. the upper layer of the room fire environment mostly fills the space and the upper layer temperature history follows closely that of the ASTM E119 temperature-time curve. The second fire is one that involves burning of a realistic fuel load that is severe in the sense that it leads to a rapidly-developing deep upper layer with upper-layer temperatures that initially exceed those of the ASTM E119 fire, but later diminish in a manner characteristic of real room fire environments.

The data point pairs of Table 4 correspond to the temperature-increase history, $\Delta T(t)$, over the initial ambient temperature, of the ASTM E119 temperature-time curve [7]. The criterion chosen for a satisfactory match between the temperature increase of the ASTM E119 fire and that of the upper layer temperature of the simulated room fire environment is that, after a relatively short-duration initial build-up of the upper layer thickness and temperature, the two match to within 20 K.

A simulated ASTM E119-like fire: It was determined with the use of ***CFAST.GYPST*** calculations that fires in the above simulation-enclosure geometry having energy-release rate histories, $\dot{Q}(t)$, defined by linear interpolation between the data-point pairs of Table 5, will lead to a room fire environment with the desired rapidly developing and relatively-thick upper layer and with a temperature-time history that matches, to within 20 K, the ASTM E119 data points of Table 4. Table 5 includes two columns of $\dot{Q}(t)$ data. For both the 1x1 and 1x2 wall systems, the left column of $\dot{Q}(t)$ data was found to generate the ASTM E119-temperature upper layer for the case of a specified-opaque upper layer. Similarly, the right-column data was found to generate ASTM E119 upper layer temperatures when the default ***CFAST.GYPST*** calculation of upper layer absorbtivity was used. The two energy release rates are plotted in Fig. 6. Note that a significantly larger energy release rate was required to achieve ASTM E119 temperatures in the case of the opaque layer than in the case of the layer with calculated radiative properties (e.g., in Table 5, at $t/s = 1000$, $\dot{Q}(t)/kW = 985$ and 691 in the left and right columns, respectively). This is because the calculated absorptivity values are consistent with a relatively transparent upper layer. As will be seen below, the opaque-upper-layer case requires a higher energy release rate fire since, compared to the transparent layer case, there is much higher gas-to-wall-surface heat transfer rates, and, in turn, higher surface and in-depth wall temperatures.

A simulated severe fire from a realistic fuel load: Energy-release-rate data from an experiment of a single freely-burning "traditional loveseat" (wood frame, olefin-covered upholstery), always refered to below as a "sofa," is reported in Fig. 36 of Reference [20]. These were used to construct the data-point pairs of Table 6, which, with linear interpolation, can be expected to describe approximately the energy-release-rate during sequential burning of an array of three such sofas in the above simulation-enclosure geometry. This is the $\dot{Q}(t)$ that is used below for the "real fire" applications of ***CFAST.GYPST***. The energy release rate of the three-sofa fire, as defined by Table 6 is plotted in Fig. 6.

PARTIAL EXPERIMENTAL VALIDATION OF *CFAST.GYPST*

This section will present a partial experimental validation of ***CFAST.GYPST***. Here, experimental validation will be indicated in the sense that simulated ASTM E119-like room fire environments will be shown to lead to simulated wall thermal responses that compare favorably to corresponding responses measured during ASTM E119 furnace fire exposures. The validation will be only "partial" in the sense that will *not* be based on comparisons with measurements actually acquired during real room fires. Data are presented without the usually required uncertainties because they were not available from the original sources.

Measured Thermal Response of the Wall Systems During ASTM E119 Furnace Test Exposures

ASTM E119 furnace tests on the 1x1 and 1x2 wall systems. Extensive tabulated thermocouple data on the thermal response of a full-scale, 3.0 m (width) x 3.7 m (height), Fig. 1-type wall system to standard-fire furnace exposures were acquired and presented in Reference [5] (refer to the test of Assembly F-07). The wall system tested was a 1x2-type assembly, where the single-layer panel was the one exposed to the furnace environment. In the particular case of the F-07 wall design, all panels were 0.0127 m thick, i.e., a 0.0127 m thick gypsum panel on the fire-exposed side of the studs and a 0.0254 m-thick two-panel-sandwich arrangement on the other. Assembly F-07 test data are also presented in Fig. 6 of [6]. This assembly and test will be referred to below as the "1x2 wall system/test."

In the 1x2 test, the furnace was operated to reproduce the CAN/ULC-S101-M89 [21], standard-fire temperature-time curve, which is similar to ASTM E119 [6].

In Fig. 8 of Reference [6] there are also presented plotted test data of the thermal response of another 3.0 m x 3.7 m Fig. 1-type wall system, which was also subjected to an ASTM E119-type exposure. This assembly was a 1x1-type design, where the panels used were each 0.0159 m thick. This will be referred to below as the "1x1 wall system/test."

Location of temperature measurements. During the above-referenced tests, temperatures of the assemblies were measured by thermocouples that were attached to gypsum panel and steel stud surfaces at different elevations and at different lateral positions of the assembly. Of interest here are the temperatures on the gypsum panel surfaces. Generic locations of relevant thermocouples, indicated in Fig. 1, were:

Fire-exposed panel:

surface exposed to the cavity; (as in [5] and [6] refer to these as) **BL/Cav.[exp.]**

Unexposed panel:

surface exposed to the cavity; **BL/Cav.[unexp.]**

contact surface between the two gypsum boards, in the middle of the panel (only for 1x2 assembly); **BL/FL[unexp.]**

surface exposed to the ambient/laboratory, where the thermocouples were unprotected; **UnExp.[bare]**

surface exposed to the ambient/laboratory space, where the thermocouples were protected by insulating pads; **UnExp.[under pads]**. (Since these thermocouples are protected from radiative heat transfer exchanges, they presumedly yield measurements of the temperatures of the surfaces to which they are attached that are more accurate than those of the **UnExp.[bare]** thermocouples.)

The reader is referred to References [5] and [6] for details of thermocouple locations.

Unless stated otherwise, in the case of the 1x2 test, experimental data plotted below for temperatures at the above generic locations will always refer to average temperatures as reported in Table 4 of [5] and as plotted in Fig. 6 of [6]. Note that the data for **BL/FL[unexp.]**, which is from Table 4 of [5], does not appear in Fig. 6 of [6].

In the case of the 1x1 test, experimental data to be presented below will always refer to average temperatures as plotted in Fig. 8 of [6].

From the above referenced data, and consistent with T_{AMB} in Table 3, the measured T_{AMB} for the 1x2 and 1x1 tests were 26 °C and 23 °C, respectively.

Expected Limits for the *CFAST.GYPST* Simulations; A Suggested Failure Criterion for Thermal Performance of a Fig. 1-Type Wall System

For both the 1x2 and 1x1 wall systems/tests of [5] and [6], it was found that the measured temperatures of the two cavity-exposed surfaces, surfaces 2 and 3, became nearly equal, in an abrupt manner, as they reached approximately 600 °C. This was interpreted in [6] as indication of a failure in the fire exposed panel, panel 1, and led to the conclusion that, for the two tests reported the "gypsum board is no longer in place when [throughout its thickness] its temperature exceeds 600 °C." Since the ***GYPST*** wall model can not be expected to provide valid simulations when one of the panels is "no longer in place," e.g., when a portion of the fire-exposed panel cracks and falls away, the validity of the present ***CFAST.GYPST*** simulations cannot be expected to go beyond the time when the temperature of surface 2, **BL/Cav.[exp.]**, reaches 600 °C.

From the latter experimental results, it is reasonable to propose, tentatively, the following criterion for failure in the thermal performance of a Fig. 1-type wall system:

> *Potential thermal failure, due to cracking or some other sort of panel "break-up" of a fire-exposed gypsum panel can be expected to occur subsequent to the time that the entire thickness of such a panel exceeds 600 °C.*

Room Fire Environment and Wall Response When Upper Layer Temperature Matches that of the ASTM E119 Temperature-Time Curve; Specified Opaque Upper Layer

1x1 wall system. ***CFAST.GYPST*** was used to simulate the room fire environment scenario of a Table 5-type fire in the simulation enclosure with a 1x1 wall system. As mentioned, in order that the wall heating from the simulated room fire exposure closely matches the wall heating from an ASTM E119 test furnace fire exposure, the upper-layer in the particular simulation reported here was specified to be opaque.

The predicted upper- and lower-layer temperature-time histories, T_{ULAY} and T_{LLAY}, respectively, are plotted in Fig. 7. Included in the plot are data points of Table 2 for the ASTM E119 curve. As can be seen, according to design, the Table 5 simulation fire leads to an upper layer temperature history in the simulation enclosure that closely tracks the ASTM E119 temperature-time curve.

The predicted layer interface elevation history is plotted in Fig. 8. As can be seen, according to design the interface drops quickly (within approximately 30 s of the initiation of the fire) from the ceiling, at elevation H = 2.44 m, to a relatively low quasi-steady-state elevation above the floor, at approximately h = 0.3 m. At this elevation the upper layer fills aproximately ninety percent of the upper volume of the enclosure.

The predicted thermal responses of various surfaces of the 1x1 wall system and corresponding temperatures measured during the ASTM E119 furnace test of [6] are plotted in Fig. 9. Included in the plots are the calculated temperatures for: the room-fire-environment-exposed surface of panel 1, designated as **Exp.**; the upper layer, T_{ULAY}, as plotted in Fig. 7; and the surfaces at positions in Fig. 1 corresponding to **BL/Cav.[exp.]**, **BL/Cav.[unexp.]**, and **UnExp.[under pads]** (or **UnExp.[bare]**).

As can be seen in Fig. 9, the comparisons between simulated and measured temperature are favorable up to the time when the calculation is invalidated because of panel 1 failure, when the measured temperature at **BL/Cav.[exp.]** reaches approximately 600 °C.

1x2 wall system. ***CFAST.GYPST***, with specified opaque upper layer, was also used to simulate the room fire environment scenario of a Table 5-type fire in the simulation enclosure with a 1x2 wall system.

In a Fig. 7-type plot, the predicted upper- and lower-layer temperature-time histories, T_{ULAY} and T_{LLAY}, respectively, for the 1x2 wall system simulation were found to be virtually indistinguishable from the above-reported corresponding temperatures obtained for the 1x1 wall system. This result is indicated in the labeling of Fig. 7, i.e., in the figure, each plotted result is identified as representing the simulations for both the 1x1 and the 1x2 wall systems.

Similarly, in a Fig. 8-type plot, the predicted layer interface elevation history for the 1x2 wall system was found to be virtually indistinguishable from the corresponding layer interface elevation history obtained for the 1x1 wall system. This result is indicated in the labeling of Fig. 8.

The predicted thermal responses of various surfaces of the 1x2 wall system and corresponding temperatures measured during the ASTM E119 furnace test of [5] and [6] are plotted in Fig. 10. Included in the plots are the calculated temperatures for: the room-fire-environment-exposed surface of panel 1, designated as **Exp.**; the upper layer, T_{ULAY}, as plotted in Fig. 7; and the surfaces at positions in Fig. 1 corresponding to **BL/Cav.[exp.]**, **BL/Cav.[unexp.]**, **BL/FL[unexp.]**, and **UnExp.[under pads]** (or **UnExp.[bare]**).

As was the case for 1x1 wall system, and as can be seen in Fig. 10, the comparisons between simulated and measured temperatures for the 1x2 wall system are favorable up to the time of panel 1 failure, when the measured temperature at **BL/Cav.[exp.]** reaches approximately 600 °C.

Using *CFAST.GYPST* as a Basis for Evaluating the Thermal Performance of Fig. 1-Type Wall Systems; A Tentative Conclusion and a Revised Tentative Criterion for Thermal Performance

With the above partial validation of ***CFAST.GYPST***, and with the validation of ***GYPST*** in its stand-alone mode [8], it is reasonable to conclude tentatively that:

> ***CFAST.GYPST*** *or stand-alone* ***GYPST*** *simulations of the thermal response of the gypsum panels of a Fig. 1-type wall system are reliable up to a time where either of the two gypsum panels is predicted to uniformly exceed 600 °C.*

This result together with the previously-stated criterion for failure leads to the following second conclusion and revised statement of the failure criterion:

> *For Fig. 1-type wall systems, potential thermal failure, due to cracking or some other sort of "break-up" of a fire-exposed gypsum panel, can be expected to occur subsequent to, but not before the time that* ***CFAST.GYPST*** *or stand-alone* ***GYPST*** *simulations indicate that the entire thickness of such a panel exceeds 600 °C.*

The above tentative conclusion and failure criterion provides an analytic means, to be applied below, for evaluating the fire resistance of the Fig. 1-type wall designs. The two results are tentative in the sense that they require experimental validation under real compartment fire conditions.

Room Fire Environment and Wall Response When Upper Layer Temperature Matches that of the ASTM E119 Temperature-Time Curve; Calculated Radiative Properties Leading to a Relatively Transparent Upper Layer

All the above ASTM E119-type room calculations with specified opaque upper layer were carried out a second time, where time-dependent radiative layer properties were calculated with use of the ***CFAST.GYPST*** default algorithm. In contrast to results with the previous opaque-layer specification, the new calculations were found to predict a relatively-transparent upper layer

1x1 wall system. The predicted upper- and lower-layer temperature-time histories, T_{ULAY} and T_{LLAY}, respectively, are plotted in Fig. 11. As can be seen, according to design, the Table 5 simulation fire (right-hand column) again leads to an upper layer temperature history that closely tracks the ASTM E119 temperature-time curve. Comparing Fig. 11 to Fig. 7, it is seen that the lower layer temperature is less than that predicted in the earlier opaque-upper-layer calculations. This is the result of the significantly reduced level of radiative heat transfer from the now-relatively-transparent high-temperature upper layer to the lower layer of the enclosure.

As indicated in the labeling of Fig. 8, the predicted layer interface elevation history was found to be virtually identical to that in the opaque upper layer scenario.

The predicted thermal responses of various surfaces of the 1x1 wall system and corresponding temperatures measured during the ASTM E119 furnace test of [6] are plotted in Fig. 12. Included is a plot of T_{ULAY} from Fig. 11.

As can be seen, in contrast to the previous opaque-upper-layer results, the simulated wall temperatures are now significantly different from the ASTM E119-measured temperatures. Also, comparing Fig. 12 to Fig. 9, it is seen that the temperature of surface 1, the surface exposed directly to the room fire environment, is predicted to be significantly lower than it was in the case of an opaque upper layer environment. The reason is again due to the fact that, because of its relative transparency, the radiative heat transfer from the upper layer to exposed enclosure surfaces is now relatively ineffective. Indeed, the major radiative exchanges are basically confined to exchanges between the initially-ambient-temperature, high-emissivity, exposed, inside bounding surfaces of the room, and through the relatively transparent gas volume. As a result of this, convective heat transfer, which in the earlier calculation was significantly less than the radiative transfer (e.g.,from upper layer to wall surface), now becomes a relatively important, albeit relatively-low-level mechanism for surface heating.

Application of the tentative thermal failure criterion to the Fig. 12 results leads to the conclusion that in the simulated room fire environment, a 1x1 wall system would sustain exposure to an ASTM E119-temperature calculated-absorptivity upper layer, well beyond 4200 s.

1x2 wall system. As indicated in Fig. 8 and 11, for the 1x2 wall system, the upper- and lower-layer temperatures and the history of layer growth is virtually identical to the corresponding temperatures and layer growth predicted for the 1x1 wall system.

The predicted thermal responses of various surfaces of the 1x2 wall system and corresponding temperatures measured during the ASTM E119 furnace test of [5] and [6] are plotted in Fig. 13. Included is a plot of T_{ULAY} from Fig. 11.

Above comments comparing the 1x1 wall system response in the case of the opaque upper layer and in the case of the relatively-transparent calculated-absoptivity upper layer are entirely relevant here. Thus, as can be see in Fig. 13, and in contrast to the opaque-upper-layer results of Fig. 10, the simulated wall temperatures are now significantly reduced from the ASTM E119-measured temperatures. Also, comparing Fig. 13 to Fig. 10, it is seen that the temperature of surface 1, the surface exposed directly to the room fire environment, is predicted to be significantly lower than it was in the case of an opaque upper layer environment. The reasons for this are as stated earlier for the 1x1 wall system.

Applying of the tentative thermal failure criterion to the Fig. 13 results leads to the conclusion that in the simulated room fire environment, a 1x2 wall system would sustain exposure to an ASTM E119-temperature calculated-absoptivity upper layer, well beyond 4200 s.

CFAST.GYPST SIMULATIONS OF THE THERMAL RESPONSE OF THE WALL SYSTEMS WHEN EXPOSED TO A SEVERE "REAL-FIRE" SCENARIO

Room Fire Environment and Wall Response During Sequential Burning of An Array of Three Reference-[20]-Type Sofas; Specified Opaque Upper Layer

1x1 wall system. *CFAST.GYPST* was used to simulate the room fire environment scenario generated by a Table 6/Fig. 6-type fire (sequential burning of three sofas) in a simulation enclosure with a 1x1 wall system. In the calculation, the upper layer was specified as opaque.

The predicted upper- and lower-layer temperature-time histories, T_{ULAY} and T_{LLAY}, respectively, are plotted in Fig. 14. Included for comparison is a plot of the ASTM E119 temperature-time curve. Also, the predicted layer interface elevation history is plotted in Fig. 15. As can be seen in the latter two figures, the simulated fire-generated environment achieves the objectives of 1) a rapidly dropping upper layer that fills most of the room of fire origin and 2) an upper layer temperature that provides for a severe and realistic fire exposure, in the sense that its temperature initially exceeds the temperature of the ASTM E119 curve, but finally, after approximately 700 s, drops below the E119 curve, and then continues to decay in a manner characteristic of real fires.

The predicted thermal responses of various surfaces of the 1x1wall are plotted in Fig. 16. Included is a plot of the ASTM E119 temperature-time curve and a plot of T_{ULAY} from Fig. 14.

From Fig. 16 it is seen that for the opaque-layer scenario, ***CFAST.GYPST*** predicts that during approximately 600 s, when the fire environment is particularly intense, the exposed surface of constant, Eq. (4). the exposed panel of the 1x1 wall system will be sustained at a temperature between 600 °C to 700 °C. However, throughout the entire duration of the fire, the unexposed surface of that panel always remains below 200 °C. Recalling and invoking the revised failure criterion of the last section, it is therefore concluded tentatively that:

> *Throughout an entire Table 6/Fig. 6-type fire threat (with opaque upper layer), thermal failure of a 1x1 wall system, due to cracking or some other sort of "break-up" of the fire-exposed gypsum panel is never expected to occur.*

1x2 wall system. ***CFAST.GYPST***, with specified opaque upper layer, was also used to simulate the room fire scenario of a Table 6/Fig. 6-type fire in the simulation enclosure with a 1x2 wall system.

As indicated in Fig. 14 and 15, the upper- and lower-layer temperatures and the history of layer growth are virtually identical to the corresponding temperatures and layer growth predicted for the 1x1 wall system.

The predicted thermal responses of various surfaces of the 1x2 wall are plotted in Fig. 17. Included is a plot of the ASTM E119 temperature-time curve and a plot of T_{ULAY} from Fig. 14.

As was the case for the 1x1 wall system exposure, from Fig. 17 it is seen that for the opaque-layer scenario, ***CFAST.GYPST*** again predicts a sustained and relatively high exposed surface temperature of between 600 °C to 700 °C. However, as before, the unexposed surface of the "front" panel never attains 200 °C. It is therefore concluded tentatively that:

> *Throughout an entire Table 6/Fig. 6-type fire exposure (with opaque upper layer), thermal failure of a 1x2 wall system, due to cracking or some other sort of "break-up" of the fire-exposed gypsum panel is never expected to occur.*

Room Fire Environment and Wall Response During Sequential Burning of An Array of Three Reference [20]-Type Sofas; Calculated Radiative Properties Leading to a Relatively Transparent Upper Layer

1x1 wall system. ***CFAST.GYPST*** was used to simulate the room fire environment scenario generated by a Table 6/Fig. 6-type fire in a simulation enclosure with a 1x1 wall system and with a relatively-transparent, calculated-absorptivity upper layer.

The predicted upper- and lower-layer temperature-time histories, T_{ULAY} and T_{LLAY}, respectively, are plotted in Fig. 18. Included for comparison is a plot of the ASTM E119 temperature-time curve. Also, the predicted layer interface elevation history is plotted in Fig. 19. As can be seen in the latter two figures, the simulated fire-generated environment again achieves the objectives of a rapidly dropping upper layer that fills most of the room of fire origin and an upper layer temperature that provides for a severe and realistic fire exposure, in the sense mentioned above in the case of the opaque upper layer simulations.

The predicted thermal responses of various surfaces of the 1x1 wall are plotted in Fig. 20. Included is a plot of the ASTM E119 temperature-time curve and a plot of T_{ULAY} from Fig. 14.

From Fig. 20 it is seen that for the three-sofa fire, and during approximately 600 s, the ***CFAST.GYPST*** simulation predicts a relatively-transparent upper layer with a very high temperature (compared to the opaque-upper-layer simulation results of Fig. 14), in excess of 900 °C. Also, during this time of intense fire environment, the temperature of the lower layer is predicted to be significantly less than it was in the case of the opaque upper layer (approximately 400 °C compared to 500 °C to 600 °C).

The initially high-temperature upper layer consists of gases originally heated in the fire combustion zone and mixed with plume-entrained air. Because they are relatively transparent, these gases can not effectively transfer heat by radiation to the bounding surfaces of the room, e.g., to the 1x1 walls, or to the lower layer gases. Thus, compared to the opaque-upper-layer simulation, where radiative heat transfer is very effective in equilibrating upper-layer, exposed-wall-surface, and lower-layer temperatures (e.g., compare the upper-layer temperatures and the exposed-wall-surface temperatures plotted in Fig. 16), the current scenario results in a persistence of partitioning of energy between the high temperature upper layer and "everything else" in the simulaion enclosure that is exposed to the fire environment.

The latter partitioning effect is well-illustrated in Fig. 20. There it is seen that the current ***CFAST.GYPST*** simulation predicts that during the entire interval of high intensity fire environment a temperature difference varying from approximately 400 °C to 500 °C is maintained between the upper layer and the exposed wall surfaces. Fig. 20 reveals further that the maximum temperature of the exposed wall surface is somewhat less than 600 °C, and that the remaining three unexposed gypsum panel surfaces of the wall assembly are predicted to never rise above approximately 150 °C.

From the above simulation results it is therefore concluded tentatively that:

> *Throughout an entire Table 6/Fig. 6-type fire threat (with a relatively-transparent calculated-absorptivity upper layer), thermal failure of a 1x1 wall system, due to cracking or some other sort of "break-up" of the fire-exposed gypsum panel is never expected to occur.*

1x2 wall system. ***CFAST.GYPST***, with a relatively-transparent calculated-absorptivity upper layer was also used to simulate the room fire scenario of a Table 6/Fig. 6-type fire in the simulation enclosure with a 1x2 wall system.

As indicated in Fig. 18 and 19, the upper- and lower-layer temperatures and the history of layer growth are virtually identical to the corresponding temperatures and layer growth predicted for the

1x1 wall system.

The predicted thermal responses of various surfaces of the 1x2 all are plotted in Fig. 21. Included is a plot of the ASTM E119 temperature-time curve and a plot of T_{ULAY} from Fig. 18.

From Fig. 18-20 it is seen that the essential features of the above discussion of results for the 1x1 wall system exposure are reproduced here. As was the case for the 1x1 wall system exposure, Fig. 21 indicates that for the relatively-transparent upper-layer scenario, ***CFAST.GYPST*** again predicts a sustained exposed-surface temperature with maximum value less than 600 °C. Because the thickness of the exposed "front" panel of the 1x2 wall system (0.0127 m) is somewhat than that of the 1x1 wall design (0.0159 m), the temperature of its unexposed surface increases somewhat more than in the 1x1 design, but it still never attains 200 °C. And, of course, the temperatures of the surfaces of the "rear panel" are always even lower. It is therefore concluded tentatively that:

> *Throughout an entire Table 6/Fig. 6-type fire threat (with a relatively-transparent calculated-absorptivity upper layer), thermal failure of a 1x2 wall system, due to cracking or some other sort of "break-up" of the fire-exposed gypsum panel is never expected to occur.*

SUMMARY OF RESULTS AND CONCLUSIONS

Zone-model-type simulations of compartment fire environments, which include the thermal response of barrier/partition structural elements, were discussed in the context of the adequacy of using a one- *vs* multi-dimensional heat transfer analyses for the barriers/partitions. Introductory discussion focused on the identification of barrier/partition designs and fire scenarios where such a one-dimensional analysis is valid even when a two- or three-dimensional analysis would be required to study the thermal-structural response.

The above ideas were implemented in a prototype model, ***CFAST.GYPST***, an advanced version of ***CFAST*** [15], [16], which uses the algorithm and associated FORTRAN subroutine ***GYPST*** [8]. ***GYPST*** was developed previously to simulate the thermal response of fire-environment-exposed Fig. 1-type wall systems constructed of arbitrary-thickness gypsum panels mounted on either side of vertical steel studs.

CFAST.GYPST was validated by comparing simulation results to previously-acquired experimental data from ASTM E119 furnace tests of two, different, full-scale Fig. 1-type wall-system designs [5], [6]. This was done by carrying out fire simulations in a 7.32 m (length) x 4.88 m (width) x 2.44 m (height) room with a single nearly-closed doorway. To simulate a furnace fire exposure, the upper layer in the simulations was assumed to be opaque, and specified time-dependent fire energy releases were contrived to lead to a ***CFAST.GYPST***-predicted upper layer temperature history that closely followed that of the temperature-time curve of the ASTM E119 standard fire. Validation was achieved in the sense that the ***CFAST.GYPST***-simulated thermal wall responses were found to compare favorably with the furnace-tested thermal wall responses.

From the favorable comparisons between simulated and measured thermal wall response, and from other aspects of the referenced test program, it was concluded tentatively that for Fig. 1-type wall systems, potential thermal failure, due to cracking or some other sort of "break-up" of a fire-exposed gypsum panel, can be expected to occur subsequent to, but not before the time that ***CFAST.GYPST*** or stand-alone **GYPST** simulations indicate that the entire thickness of such a panel exceeds 600 °C. The result is considered tentative because of the need for experimental data from actual room fire tests.

The latter ***CFAST.GYPST*** simulations included an investigation of the effect on thermal wall response of the radiative characteristics of the upper layer of the room fire environment. Two separate simulations were carried out for each fire scenario, one with the assumed opaque upper layer and one with a relatively-transparent upper layer (i.e., with a ***CFAST.GYPST***-default-determined upper layer absorptivity). It was found that the opaque, ASTM E119- temperature, upper layer simulations led to significantly higher wall temperatures than the corresponding simulations with a relatively-transparent upper layer. (Compare Fig. 9 to Fig. 12 and Fig. 10 to Fig. 13.) Relative to possible thermal failure of the wall systems, application of the above criterion indicated that in a scenario with an opaque, ASTM E119-temperature, upper layer, both wall systems would fail after a 3000 s to 3500 s exposure. In contrast to this, simulation results indicated that in scenarios with the relatively-transparent calculated-absorptivity upper-layer, both of the wall system designs would be able to sustain the ASTM E119 temperature exposure well beyond the 4200 s of the simulation runs.

In severe, example, "real-fire" simulations involving sequential burning of three sofas in the above simulation room/door geometry, ***CFAST.GYPST*** was used to calculate the fire environment and associated wall response for both of the above-referenced wall systems. For these simulations, the thermal responses of the two wall systems were predicted and then evaluated relative to respective expected fire resistance. Both opaque and calculated-absorptivity upper layer scenarios were investigated. In all cases, it was determined that thermal failure of the fire-exposed gypsum panel is never expected to occur.

CFAST.GYPST was developed as a prototype fire model in the sense that it deals with a class of barrier/partition design where a one-dimensional simulation of barrier/partition thermal response can yield an accurate simulation of room fire environment, but where simulation of thermal-structural response demands a multi-dimensional analysis. Thus, a ***CFAST.GYPST*** simulation was shown to yield estimates of the fire resistance of gypsum-panel/steel-stud wall systems, but only relative to the potential for thermal failure (possible cracking and "break-up" of a fire-environment-exposed gypsum panels).

CFAST.GYPST is also a prototype model in the sense that its fire environment simulations, which are based on (only) a one-dimensional analysis of barrier/partition thermal response, yield predictions of fire environment that can be used to describe the surface heating boundary conditions necessary for the multi-dimensional analyses of thermal-structural response. For load-bearing wall sytems, the latter-type of analysis would itself yield estimates of fire resistance of gypsum-panel/steel-stud wall systems relative to the potential for structural failure.

SUGGESTED FURTHER WORK

Preliminary efforts on use of the ***SAFIR*** thermal/structural model [12] to evaluate the thermal/structural response of load-bearing, Fig. 1-type, gypsum-panel/steel-stud wall systems were reported in [11]. It is appropriate to continue this work, and to include the use of ***CFAST.GYPST*** simulations to define fire exposure boundary conditions. The objective would be to advance and bring to completion the current prototype model concept by developing a means of carrying out the entire sequential analysis of: 1) fire-environment/(1d)wall-thermal-response (with ***CFAST.GYPST***) leading to 2) (2d)-wall-thermal-response/(2-3d)-wall-structural-response (with ***SAFIR***). The product of such an effort is envisaged as a practical, special-purpose, ***CFAST.GYPST/SAFIR*** fire/thermal/structural computer model capable of determining both thermal and structural aspects of the fire resistance of gypsum-panel/steel-stud wall systems.

NOMENCLATURE

$k_{S,M}$	thermal conductivity of the barrier/partition at surface element M
L_1, L_2, L_{GAP}	see Fig. 2
$\dot{Q}(t)$	fire energy release rate
$\dot{q}''_{S,M}$	net rate of heat transfer per unit area into surface element M
T_{AMB}	ambient temperature
$T_{I,DEPTH}$	T through the depth of Ith segment
$T_{S,M}$	T at Mth surface element
T_{ULAY}, T_{LLAY}	T of upper, lower layer
t	time
t_1, t_2	t at beginning, end of time step
x	distance from the surface, see Fig. 2
x_i	x of surface i
x_N	direction of normal into a segment at a surface element M
$x_{S,M}$	x at Mth surface element
Δt	$t_2 - t_1$
ε_i	emissivity of surface i

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APPENDIX A

SUMMARY OF THE PROBLEM SOLVED BY *GYPST* AND THE NINE AVAILABLE SOLUTION OPTIONS (FROM THE *GYPST* SUBROUTINE SOURCE CODE)

```
      SUBROUTINE GYPST(TEMP1,TEMP2,IXM,XM1,XM2,NPTS,IBCTYP,EPS1,EPS2,
     1     EPS3,EPS4,EPSFUR,EPSCAL,TINT,TLAST,TMP1IN,TMP4IN,TMP1FN
     2     ,TMP4FN,TAMB,Q1IN,Q1FN,Q4IN,Q4FN,AL1,AL2,ALGAP,DENAMB
     3     ,MRHOD,RHODDAT,MCP,CPDAT,MCOND,CONDDAT)
C***********************************************************************
C       THIS PROGRAM INTEGRATES THE INITIAL/BOUNDARY VALUE PROBLEM, BETWEEN TIME=TINT AND
C       TIME=TLAST, FOR THE TEMPERATURE OF A PAIR OF GYPSUM PANELS SEPARATED BY AN AIR GAP
C       AND HEATED ON EITHER EXPOSED SURFACE. INPUT INCLUDES THE TEMPERATURE DISTRIBUTION
C       AT TIME=TINT AND AT NPTS EQUIDISTANT POINTS IN EACH OF THE TWO PANEL, INCLUDING A POINT
C       AT EACH PANEL SURFACE.  OUTPUT INCLUDES THE NEW TEMPERATURE DISTRIBUTION  AT  THE
C       SAME POINTS AND, IN THE CASE OF  BOUNDARY  CONDITIONS  WHERE  OUTER  SURFACE  HEAT
C       TRANSFER RATES ARE NOT EXPLICITLY SPECIFIED, THE NEW VALUES FOR THESE HEAT TRANSFER
C       RATES.
C
C       DEFINITIONS:
C
C       AL1
C               THICKNESS OF LEFT PANEL [M]
C       AL2
C               THICKNESS OF RIGHT PANEL [M]
C       ALGAP
C               THICKNESS OF AIR GAP [M]
C       CONDDATA(1,N)=CONDDAT(1,N), N=1,NCOND=MCOND
C               COND [W/(M*K)] OF NTH (COND,TEMP) DATA PAIR USED TO  CALCULATE  COND(TEMP)  IN
C               SUBROUTINE CONDGYP
C       CONDDATA(2,N)=CONDDAT(2,N), N=1,NCOND=MCOND
C               TEMP [C]  OF   NTH   (COND,TEMP)   DATA   PAIR  USED  TO  CALCULATE  COND(TEMP)  IN
C               SUBROUTINE CONDGYP
C       CPDATA(1,N)=CPDAT(1,N), N=1, NCP=MCP
C               CP [J/(KG*K)] OF NTH (CP,TEMP) DATA PAIR USED TO CALCULATE CP(TEMP) IN SUBROUTINE
C               DSPGYP
C       CPDATA(2,N)=CPDAT(2,N), N=1, NCP=MCP
C               TEMP [C] OF NTH (CP,TEMP) DATA PAIR USED TO CALCULATE CP(TEMP) IN SUBROUTINE
C               DSPGYP
C       DENAM
C               RHO OR DENSITY OF GYPSUM AT 20 C [KG/M**3]
C       EPS1,EPS2,EPS3,AND EPS4
C               THE EMISSIVITIES OF GYPSUM SURFACES 1, 2, 3, AND 4, RESPECTIVELY.
C       EPSFUR
C               EFFECTIVE EMISSIVITY OF THE FURNACE, FOR A STANDARD FIRE EXPOSURE OF SURFACE
C               1 OR  OF  SURFACES  1  AND  4,  OR  THE  EFFECTIVE  EMISSIVITY  OF  THE  FIRE/FACING-
C               ROOM-SURFACES FOR ROOM FIRE EXPOSURES OF SURFACE 1 OR SURFACES 1 AND 4.
C       EPSCAL
C               THE SUBROUTINE USED TO CARRY OUT THE INTEGRATION IS MOL1D AND ITS ASSOCIATED
C               SUBROUTINES.  IN THIS, EPSCAL IS THE TIME INTEGRATOR LOCAL ERROR TOLERANCE.
C               PARAMETER ESTIMATES OF THE TIME STEP ERROR AT THE SPATIAL GRID POINTS FOR ALL
C               GRID POINTS FOR ALL THE PDES IS KEPT LESS THAN EPSCAL IN THE ROOT-MEAN-SQUARE
C               (RMS) NORM.  EPSCAL IS ALSO USED TO CHOOSE THE INITIAL STEP.
C       FIRE1DAT(1,N), N=1, NFIRE1
```

```
C              TEMPERATURE [K] OF NTH DATA PAIR (TEMPERATURE,TIME) USED IN SUBROUTINE FRTMP1
C              TO CALCULATE TMPFR1(TIME), THE TEMPERATURE VS TIME OF A FIRE ENVIRONMENT TO
C              WHICH SURFACE 1 IS EXPOSED WHEN IBCTYP = 7 OR 8; NFIRE1 =< 1000.
C        FIRE1DAT(2,N), N=1, NFIRE1
C              TIME [S] OF NTH DATA PAIR (TEMPERATURE,TIME) USED IN SUBROUTINE FRTMP1 TO
C              CALCULATE TMPFR1(TIME), THE TEMPERATURE VS TIME OF A FIRE ENVIRONMENT TO
C              WHICH SURFACE 1 IS EXPOSED WHEN IBCTYP = 7 OR 8; NFIRE1 =< 1000.
C        FIRE4DAT(1,N), N=1, NFIRE4
C              TEMPERATURE [K] OF NTH DATA PAIR (TEMPERATURE,TIME) USED IN SUBROUTINE FRTMP4
C              TO CALCULATE TMPFR4(TIME), THE TEMPERATURE VS TIME OF A FIRE ENVIRONMENT TO
C              WHICH SURFACE 4 IS EXPOSED WHEN IBCTYP = 8; NFIRE4 =< 1000.
C        FIRE4DAT(2,N), N=1, NFIRE4
C              TIME [S] OF NTH  ATA PAIR (TEMPERATURE,TIME) USED IN SUBROUTINE FRTMP4 TO
C              CALCULATE TMPFR4(TIME), THE TEMPERATURE VS TIME OF A FIRE ENVIRONMENT TO
C              WHICH SURFACE 4 IS EXPOSED WHEN IBCTYP = 8; NFIRE4 =< 1000.
C        IBCTYP
C              TYPE OF BOUNDARY CONDITIONS:
C              IBCTYP = 1:    [Q1IN, Q1FN] AND [Q4IN, Q4FN] SPECIFIED; Q1 SPECIFIED AS A LINEAR
C                             INTERPOLATION IN TIME BETWEEN Q1IN, AT TIME TINT, AND Q1FN, AT TIME
C                             TLAST; Q4 SPECIFIED SIMILARLY BY Q4IN AND Q4FN.
C              IBCTYP = 2:    [Q1IN, Q1FN] AND [TMP4IN, TMP4FN] SPECIFIED; Q1 SPECIFIED AS LINEAR
C                             INTERPOLATION IN TIME BETWEEN Q1IN, AT TIME TINT, AND Q1FN, AT TIME
C                             TLAST; TEMPERATURE OF SURFACE 4 SPECIFIED SIMILARLY BETWEEN
C                             TMP4IN AND TMP4FN.
C              IBCTYP = 3:    [TMP1IN, TMP1FN] AND [Q4IN, Q4FN] SPECIFIED; TEMPERATURE OF
C                             SURFACE 4 SPECIFIED AS A LINEAR INTERPOLATION IN TIME BETWEEN
C                             TMP1IN, AT TIME TINT, AND TMP1FN, AT TIME TLAST; Q4 SPECIFIED
C                              SIMILARLY BY Q4IN AND Q4FN.
C              IBCTYP = 4:    [TMP1IN, TMP1FN] AND [TMP4IN, TMP4FN] SPECIFIED; TEMPERATURE OF
C                             SURFACE 1 SPECIFIED AS A LINEAR INTERPOLATION IN TIME BETWEEN
C                             TMP1IN, AT TIME TINT, AND TMP1FN, AT TIME TLAST; TEMPERATURE OF
C                             SURFACE 4 SPECIFIED SIMILARLY BETWEEN TMP4IN AND TMP4FN.
C              IBCTYP = 5:    Q1 SPECIFIED AS HEAT TRANSFER FROM AN ASTM E119 STANDARD-FIRE
C                             FURNACE ENVIRONMENT (TEMPERATURE-TIME ENVIRONMENT IS
C                             TMPSTD(TIME)) AND Q4 SPECIFIED AS HEAT TRANSFER FROM AN AMBIENT
C                             TEMPERATURE (TAMB) LABORATORY ENVIRONMENT.
C              IBCTYP = 6:    Q1 SPECIFIED AS HEAT TRANSFER FROM AN ISO 834 STANDARD-FIRE
C                             FURNACE ENVIRONMENT (TEMPERATURE-TIME ENVIRONMENT IS
C                             TMPSTI(TIME)) AND Q4 SPECIFIED AS HEAT TRANSFER FROM AN AMBIENT
C                             TEMPERATURE (TAMB) LABORATORY ENVIRONMENT.
C              IBCTYP = 7:    Q1 IS THE HEAT TRANSFER FROM A SPECIFIED ROOM-FIRE ENVIRONMENT
C                             (TEMPERATURE-TIME OF THE FIRE ENVIRONMENT IS TMPFR1(TIME), CAL-
C                             CULATED IN THE SUBROUTINE FRTMP1 BY INTERPOLATION/EXTRAPO-
C                             LATION OF DATA IN INPUT COMMON BLOCK FIRE1BLK) AND Q4 IS
C                             SPECIFIED AS HEAT TRANSFER FROM AN AMBIENT-TEMPERATURE (TAMB)
C                             LABORATORY ENVIRONMENT.
C              IBCTYP = 8:    Q1 IS THE HEAT TRANSFER FROM ONE SPECIFIED ROOM-FIRE
C                             ENVIRONMENT (TEMPERATURE-TIME OF THE FIRE ENVIRONMENT IS
C                             TMPFR1(TIME), CALCULATED IN THE SUBROUTINE FRTMP1 BY INTERPO-
C                             LATION/EXTRAPOLATION OF DATA IN INPUT COMMON BLOCK FIRE1BLK)
C                             AND Q4 THE HEAT TRANSFER FROM ANOTHER SPECIFIED ROOM-FIRE
C                             ENVIRONMENT (TEMPERATURE-TIME OF THE FIRE ENVIRONMENT IS
C                             TMPFR4(T), CALCULATED IN THE SUBROUTINE TRTMP4 BY INTERPOLATION/
C                             EXTRAPOLATION OF DATA IN INPUT COMMON BLOCK FIRE4BLK).
C              IBCTYP = 9:    [TMP1IN, TMP1FN] SPECIFIED; THE TEMPERATURE OF SURFACE 1 IS
C                             SPECIFIED AS AS A LINEAR INTERPOLATION IN TIME BETWEEN TMP1IN, AT
C                             TIME TINT, AND TMP1FN, AT TIME TLAST; Q4 SIMULATED TO BE THE HEAT
```

```
C                       TRANSFER TO SURFACE 4 FROM AN AMBIENT TEMPERATURE (TAMB)
C                       ENVIRONMENT.
C     IXM
C           DETERMINES WHETHER XM1(NPTS), XM2(NPTS) IS INPUT OR OUTPUT:
C                 IXM = 1 IF XM1, XM2 ARE TO BE CALCULATED AND THEN PROVIDED AS OUTPUT;
C                 IXM = 2 IF XM1 AND XM2 WERE CALCULATED PREVIOUSLY AND ARE BEING
C                       PROVIDED AS INPUT.
C     NPTS
C           NUMBER OF POINTS IN PANELS WHERE TEMPERATURE IS COMPUTED.
C     NCOND = MCOND
C           NUMBER OF (COND,TEMP) PAIRS USED TO CALCULATE COND VS
C           TEMPERATURE FOR THE GYPSUM PANELS, =< 100.
C     NCP=MCP
C           NUMBER OF (CP,TEMP) PAIRS USED TO CALCULATE CP VS TEMPERATURE FOR THE
C           GYPSUM PANELS, =< 100.
C     NFIRE1
C           NUMBER OF (TEMP, TIME) PAIRS USED TO CALCULATE THE TEMPERATURE-TIME CURVE
C           OF THE FIRE TMPFR1(T) CALCULATED IN THE SUBROUTINE FRTMP1, =< 1000.
C     NFIRE4
C           NUMBER OF (TEMP, TIME) PAIRS USED TO CALCULATE THE TEMPERATURE-TIME CURVE
C           OF THE FIRE TMPFR4(T) CALCULATED IN THE SUBROUTINE FRTMP4, =< 1000.
C     NRHOD = MRHOD
C           NUMBER OF (RHO,TEMP) PAIRS USED TO CALCULATE RHO VS TEMPERATURE FOR THE
C           GYPSUM PANELS, =< 100.
C     Q1
C           RATE OF HEAT TRANSFER TO SURFACE 1 [W/M**2].
C     Q4
C           RATE OF HEAT TRANSFER TO SURFACE 4 [W/M**2].
C     Q1IN, Q1FN
C           INITIAL, FINAL SPECIFIED Q1 [W/M**2].
C     Q4IN, Q4FN
C           INITIAL, FINAL SPECIFIED Q4 [W/M**2].
C     RHODDATA(1,N)=RHODDAT(1,N), N=1, NRHO = MRHO
C           DENSITY [KG/M**3] OF NTH (DENSITY,TEMP) DATA PAIR USED TOCALCULATE RHO(TEMP)
C           IN SUBROUTINE DSPGYP.
C     RHODDATA(2,N) = RHODDAT(2,N), N=1, NRHO=MRHO
C           TEMP [C] OF NTH (DENSITY,TEMP) DATA PAIR USED TO CALCULATE RHO(TEMP) IN
C           SUBROUTINE DSPGYP.
C     SURFACE 1
C           OUTER/LEFT SURFACE OF LEFT PANEL.
C     SURFACE 2
C           INNER/RIGHT SURFACE OF LEFT PANEL.
C     SURFACE 3
C           INNER/LEFT SURFACE OF RIGHT PANEL.
C     SURFACE 4
C           OUTER/RIGHT SURFACE OF RIGHT PANEL.
C     TEMP1
C           TEMPERATURE DISTRIBUTION IN THE LEFT PANEL (I.E., AT THE NPTS POINTS) AT TIME TINT
C           [K].
C     TEMP2
C           TEMPERATURE DISTRIBUTION IN THE RIGHT PANEL (I.E., AT THE NPTS POINTS) AT TIME TINT
C           [K].
C     TINT, TLAST
C           INITAL, FINAL TIMES [S].
C     TMP1IN, TMP1FN
C           INITIAL, FINAL TEMPERATURES OF SURFACE 1 [K].
C     TMP4IN, TMP4FN
```

```
C               INITIAL, FINAL TEMPERATURES OF SURFACE 4 [K].
C       TAMB
C               AMBIENT TEMPERATURE OF LABORATORY/OUTSIDE ENVIRONMENT [K]; REQUIRED IF
C               IBCTYP = 5, 6, 7, OR 9.
C       X
C               DISTANCE FROM LEFT TO RIGHT AS MEASURED FROM SURFACE 1.
C       XM1(N)
C               VALUE OF X IN LEFT PANEL, PANEL 1, AT ITS NTH TEMPERATURE CALCULATED POSITION
C               FROM THE LEFT [I.E., WHERE TEMPERATURE = TEMP1(N) AT TIME TINT], N = 1, NPTS, WHERE
C               THE NPTS ARE EQUALLY SPACED THROUGH  HE  PANEL  THICKNESS  [XM1(1) = 0.  IS  AT
C               SURFACE 1 AND XM1(NPTS) = AL1 IS AT SURFACE 2].
C       XM2(N)
C               VALUE OF X IN RIGHT PANEL, PANEL 2, AT ITS NTH TEMPERATURE-CALCULATED POSITION
C               FROM THE LEFT [I.E., WHERE TEMPERATURE = TEMP2(N) AT TIME TINT], N = 1, NPTS, WHERE
C               THE NPTS ARE EQUALLY SPACED THROUGH THE PANEL THICKNESS [XM2(1) = AL1 + ALGAP
C               IS AT SURFACE 3 AND XM2(NPTS) = AL1 + ALGAP + AL2 IS AT SURFACE 4].
C
C       INPUT (IN ORDER OF CALL TO THIS SUBROUTINE):
C       1)      AT TIME=TINT: TEMP1(N), TEMP2(N), N = 1, NPTS;
C       2)      IXM;
C       3)      XM1(N), XM2(N), N = 1, NPTS; ONLY REQUIRED IF IXM > 1;
C       4)      NPTS;
C       5)      IBCTYP;
C       6)      EPS1,EPS2,EPS3,AND EPS4;
C       7)      EPSFUR; ONLY REQUIRED IF IBCTYPE=5, 6, 7, OR 8;
C       8)      EPSCAL;
C       9)      TINT, TLAST;
C       10)     TMP1IN; ONLY REQUIRED IF IBCTYP = 3, 4, OR 9;
C       11)     TMP4IN; ONLY REQUIRED IF IBCTYP = 2 OR 4;
C       12)     TMP1FN; ONLY REQUIRED IF IBCTYP = 3, 4, OR 9;
C       13)     TMP4FN; ONLY REQUIRED IF IBCTYP = 2 OR 4;
C       14)     TAMB; ONLY REQUIRED IF IBCTYP = 5, 6, 7, OR 9;
C       15)     Q1IN, Q1FN; ONLY REQUIRED IF IBCTYP = 1 OR 2;
C       16)     Q4IN, Q4FN; ONLY REQUIRED IF IBCTYP = 1 OR 3;
C       17)     AL1, AL2, ALGAP;
C       18)     DENAMB;
C       19)     MRHOD,RHODDAT(2,MRHOD),MCP,CPDAT(2,MCP),MCOND,
C               CONDDAT(2,MCOND); MRHOD =< 100, MCP =< 100, MCOND =< 100;
C       20)     COMMON/FIRE1/NFIRE1,FIRE1DAT(2,1000), ONLY REQUIRED IF
C               IBCTYP = 7 OR 8; NFIRE1 =< 1000;
C       21)     COMMON/FIRE4/NFIRE4,FIRE4DAT(2,1000), ONLY REQUIRED IF
C               IBCTYP = 8; NFIRE4 =< 1000.
C
C       OUTPUT:
C       1)      XM1(N), XM2(N), N = 1, NPTS;
C       2)      AT TIME=TLAST:
C               A)      TEMP1(N), TEMP2(N), N = 1, NPTS;
C               B)      Q1FN = Q1, THIS IS ONLY COMPUTED IF IBCTYP = 3,
C                       4, 5, 6, 7, OR 8;
C               C)      Q4FN = Q4, THIS IS ONLY COMPUTED IF IBCTYP = 2,
C                       4, 5, 6, 7, 8, OR 9.
C
C***********************************************************************
C***********************************************************************
```

APPENDIX B

THE *GYPST* SUBROUTINE ALGORITHM AND THE SOLUTION STRATEGY OF THE SECTION "COUPLING THE EQUATIONS, ETC."

This **APPENDIX B** will describe the usage of ***GYPST*** subroutine [8] in a zone-type fire model, when implemented with the options IBCTYP = 4 and 9. This will be done in the context of the solution strategy of the earlier section "COUPLING THE EQUATIONS, ETC."

Refer to Fig. 2 and to the introductory "comments" portion of the ***GYPST*** subroutine, presented in **APPENDIX A.**. The latter describes the problem solved by the subroutine, and defines subroutine variables and parameters used in the presentation to follow.

Option IBCTYP = 4

Option IBCTYP = 4 of ***GYPST*** would be used in a zone-type fire model when a wall system segment is exposed to two different fire environments, surface 1 being exposed to the fire environment in one room of a facility and surface 4 being exposed to a fire environment in the adjacent room, on the other side of the wall segment.

At any particular time, t = TINT, in a fire model simulation, the temperature distribution through the wall system [TEMP1(N), TEMP2(N) N=1, NPTS] will have been determined to specified accuracy. Of these wall temperatures, the temperatures of the surface-1 and surface-4 nodes, TEMP1(1) and TEMP2(NPTS), respectively, which correspond to the $T_{S,M}$'s of the earlier section, would be included in the set of fire model solution variables.

The solution over the course of the next time step would then proceed as follows:

1. The fire model solver would take the known, $t \leq$ TINT values of TEMP1(1) and TEMP2(NPTS), along with the $t \leq$ TINT values of all other solution variables of the problem, and estimate the rates of change of the variables and an appropriate next time step, Δt, for use in advancing the solution, to specified accuracy, from TINT to TLAST = TINT + Δt. In dong this, the solver would provide estimates TMP1FN and TMP4FN for surface-1 and surface-4 temperatures at t = TLAST. Similarly, it would provide t = TLAST estimates for all other solution variables.

2. From the estimates of all solution variables at t = TLAST, the associated estimated rates of heat transfer to surfaces 1 and 4, $\dot{q}''_{1,EST}$ and $\dot{q}''_{4,EST}$, respectively, [corresponding to the $\dot{q}''_{S,M}(t_2)$'s of the earlier section] would be calculated with functional relationships or subroutines associated with the particular fire model.

3. Between t > TINT and t = TLAST, the ***GYPST*** software would be used to solve the initial-value/ boundary-value problem for the in-depth thermal response of the wall system, subject

to the initial conditions:

at t = TINT: TEMP1(N), TEMP2(N) N = 1, NPTS are specified at previously determined values (B1)

and boundary conditions:

for TINT < t ≤ TLAST:

TEMP1(1) = TMP1IN + (t - TINT)(TMP1FN - TMP1IN)/(TLAST - TINT) (B2)

TEMP2(NPTS) = TMP4IN + (t - TINT)(TMP4FN - TMP4IN)/(TLAST - TINT) (B3)

where

TMP1IN = known value of TEMP1(1) at t = TINT

TMP4IN = known value of TEMP2(NPTS) at t = TINT (B4)

Included in the output of **GYPST** would be solutions for

at t = TLAST:

TEMP1(N), TEMP2(N) N = 1, NPTS

Q1FN = - k(T)∂T/∂x at surface 1 (B5)

Q4FN = k(T)∂T/∂x at surface 4

where Q1FN and Q4FN are the rates of heat transfer into the solid at surfaces 1 and 4, respectively, as determined from the actual rates of conduction heat transfer, i.e., from the solution temperature distribution, TEMP1 and TEMP2. (Note from Fig. 2 that surface 1, the left-hand surface of the wall system, is at x = 0, and that x is measured positive from left to the right.) Therefore, Q1FN is to be compared to $\dot{q}''_{1,EST}$ and Q4FN to $\dot{q}''_{4,EST}$.

4. Now the differences $\delta 1$ and $\delta 4$ are determined:

$$\delta 1 = |Q1FN - \dot{q}''_{1,EST}|; \quad \delta 4 = |Q4FN - \dot{q}''_{4,EST}| \tag{B6}$$

Note that these differences correspond to the error in satisfying Eq. (1)-type equations of the fire model equation set of the earlier section. If $\delta 1$ and $\delta 4$ are small enough to satisfy specified solution-accuracy criteria, then a successful solution to the overall problem at t = TLAST will have been achieved. If not, then: the solver would return to the procedure of step 1, above; the original estimates for the solution variables and/or the size of Δt would be revised; and steps 2 and 3 would be carried out again, etc.

Option IBCTYP = 9

Option IBCTYP = 9 of ***GYPST*** would be used in a zone-type fire model when surface 1 is exposed to the fire environment in one room of a facility and surface 4 is exposed to a ambient environment. Then, option IBCTYP = 9 would be applied in the same way as option IBCTYP = 4, except for the fact that now only TEMP1(1) (the temperature of surface 1 which is exposed to the fire environment) and not TEMP2(NPTS) (the temperature of surface 4, which is constantly exposed to the ambient-temperature environment) would be considered to be a solution variable of the basic equation set. Thus, in carrying out the calculation, TEMP1(1) is treated exactly as above, while TEMP2(NPTS) is treated in the same way as all the other node points, i.e., the same as TEMP1(N), N = 2, NPTS and TEMP2(N), N = 1, NPTS - 1.

Table 1. Parameters used for input to the *GYPST* subroutine. See Fig.1 and 2.

	1x1 assembly/test	1x2 assembly/test
$\rho(20\ ^\circ C)$	$698\ kg/m^3$	
$\rho(T)/\rho(T = 20\ ^\circ C)$, $C_p(T)$, and $k(T)$	from APPENDIX A of [8]	
L_1	0.0159 m	0.0127 m
L_2	0.0159 m	0.0254 m
L_{GAP}	0.0900 m	
IBCTYP	5	
EPSCAL	10^{-5}	
ε_i, i = 1 - 4	0.9	
NPTS	30	

Table 2. **The thickness and properties used to model the thermal response of the gypsum ceiling and plywood floor in all *CFAST.GYPST* simulations.**

	Gypsum	Plywood
Thermal Conductivity	**0.16 W/(mK)**	**0.12 W/(mK)**
Specific Heat	**900. J/(kgK)**	**1215. J/(kgK**
Density	**790. kg/m^3**	**545. kg/m^3**
Thickness	**0.016 m**	**0.013 m**
Emissivity	**0.9**	**0.9**

Table 3. Table of fire scenarios used to validate and test *CFAST.GYPST*, including specified ambient temperature and corresponding figures where results are presented.

fire /layer characteristics	1x1 gypsum-panel/steel-stud wall	1x2 gypsum-panel/steel-stud wall
fire designed to generate ASTM E119-like upper layer temperatures; opaque upper layer.	Figures 7-9 T_{AMB} = 23 °C	Figures 7, 8, 10 T_{AMB} = 26 °C
fire designed to generate ASTM E119-like upper layer temperatures; default simulation of radiative characteristics of the upper layer, i.e., relatively-transparent upper layer.	Figures 8, 11, 12 T_{AMB} = 23 °C	Figures 8, 11, 13 T_{AMB} = 26 °C
sequential burning of an array of three Reference-[20]-type sofas; opaque upper layer.	Figures 14-16 T_{AMB} = 20 °C	Figures 14, 15, 17 T_{AMB} = 20 °C
sequential burning of an array of three Reference-[20]-type sofas; default simulation of radiative characteristics of the upper layer, i.e., relatively-transparent upper layer.	Figures 18, 19, 20 T_{AMB} = 20 °C	Figures 18, 19, 21 T_{AMB} = 20 °C

Table 4. **Data point pairs that correspond to the temperature-increase history, $\Delta T(t)$, over an initial ambient temperature, of the ASTM E119 temperature time curve [7].**

t/s	$\Delta T(t)$/K
0	0
100	380
200	483
300	548
400	595
600	660
1000	738
1800	819
3000	882
4200	921

Table 5. For a fire in the adopted simulation enclosure and burner configuration, the energy-release-rates , $\dot{Q}(t)$, defined by linear interpolation between the following data-point pairs and plotted in Fig. 6, were used to generate a relatively thick upper layer and a temperature-time history that passes within 20 K of the ASTM E119 temperature-time data points of Table 4.

t/s	$\dot{Q}(t)$/kW	
	opaque upper layer and 1x1 Wall or 1x2 Wall	relatively-transparent calculated-absorbtivity upper layer and 1x1 Wall or 1x2 Wall
0	0	0
100	478	273
200	550	305
300	630	376
400	813	504
600	959	629
1000	985	691
1800	1114	805
3000	1203	895
4200	1261	955

Table 6. **Data-point pairs, which, with linear interpolation, can be expected to describe approximately the energy-release-rate, plotted in Fig. 6, during sequential burning in the adopted simulation enclosure of an array of three sofas of the type tested in [20].**

t/s	$\dot{Q}(t)/\mathrm{K}$
0	0
100	200
200	3000
700	3000
750	500
1800	0

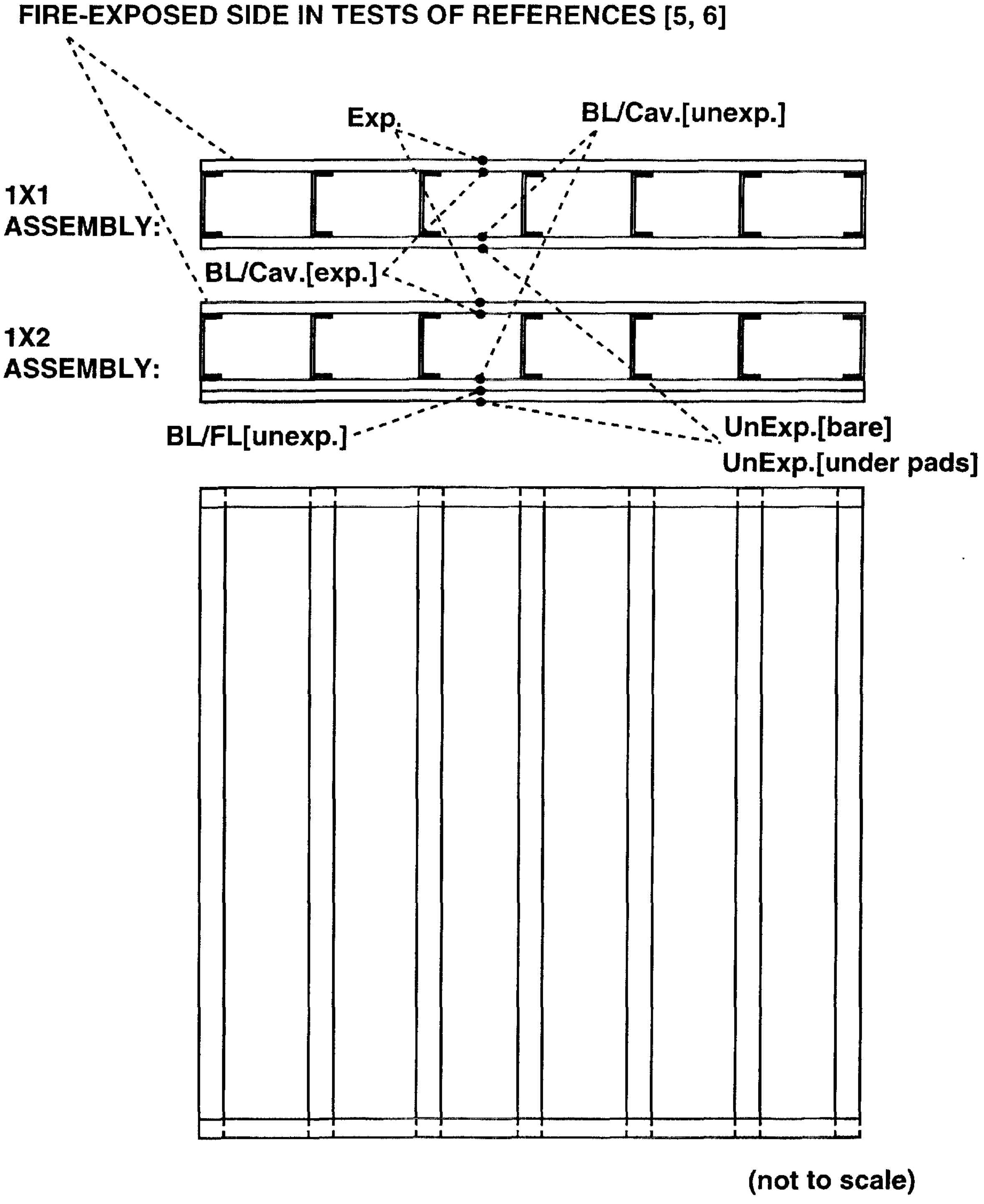

Figure 1. Sketch of example wall system designs (adopted from References [5] and [6]); locations of calculated/measured temperatures in tests of [5] and [6].

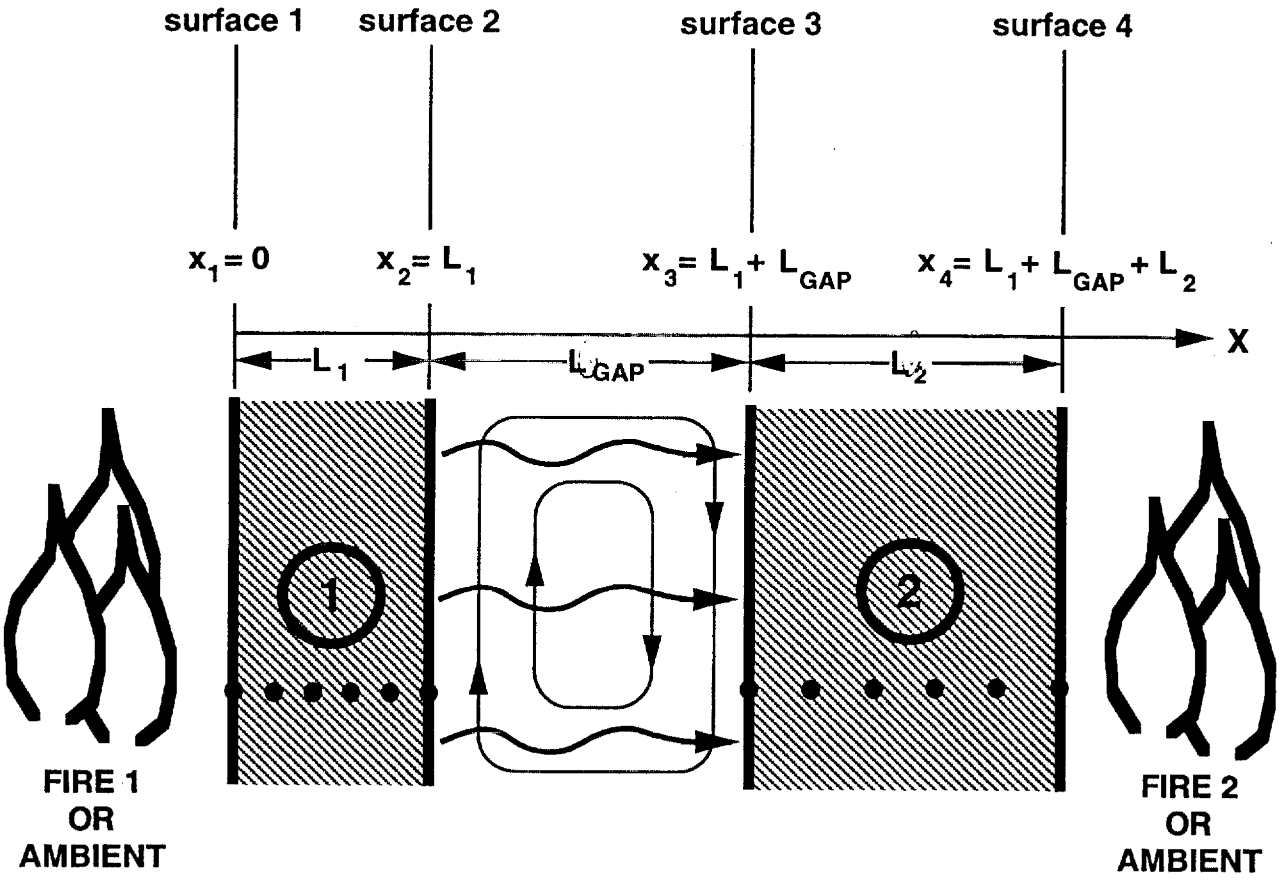

Figure 2. Sketch of the idealized geometry of the gypsum-panel/steel-stud wall system.

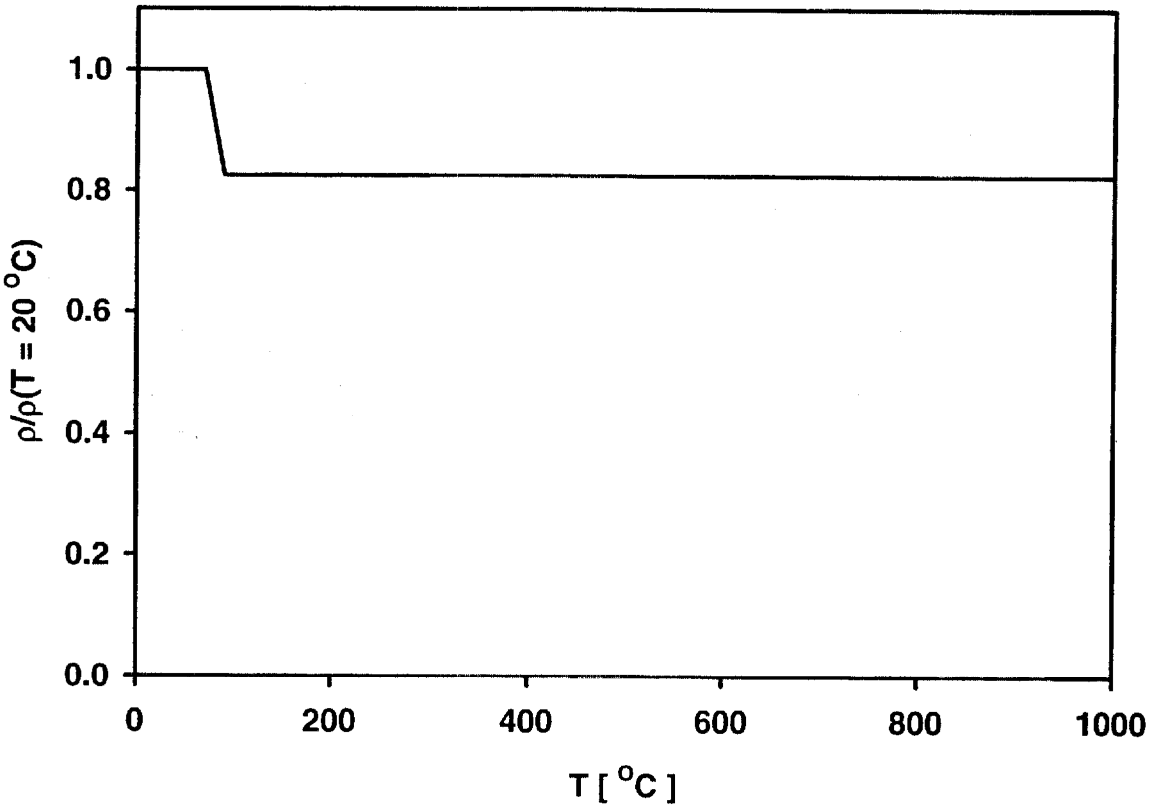

Figure 3. ρ(T)/ρ(T = 20 °C) used in all applications of *GYPST*, as adopted in APPENDIX A of [8].

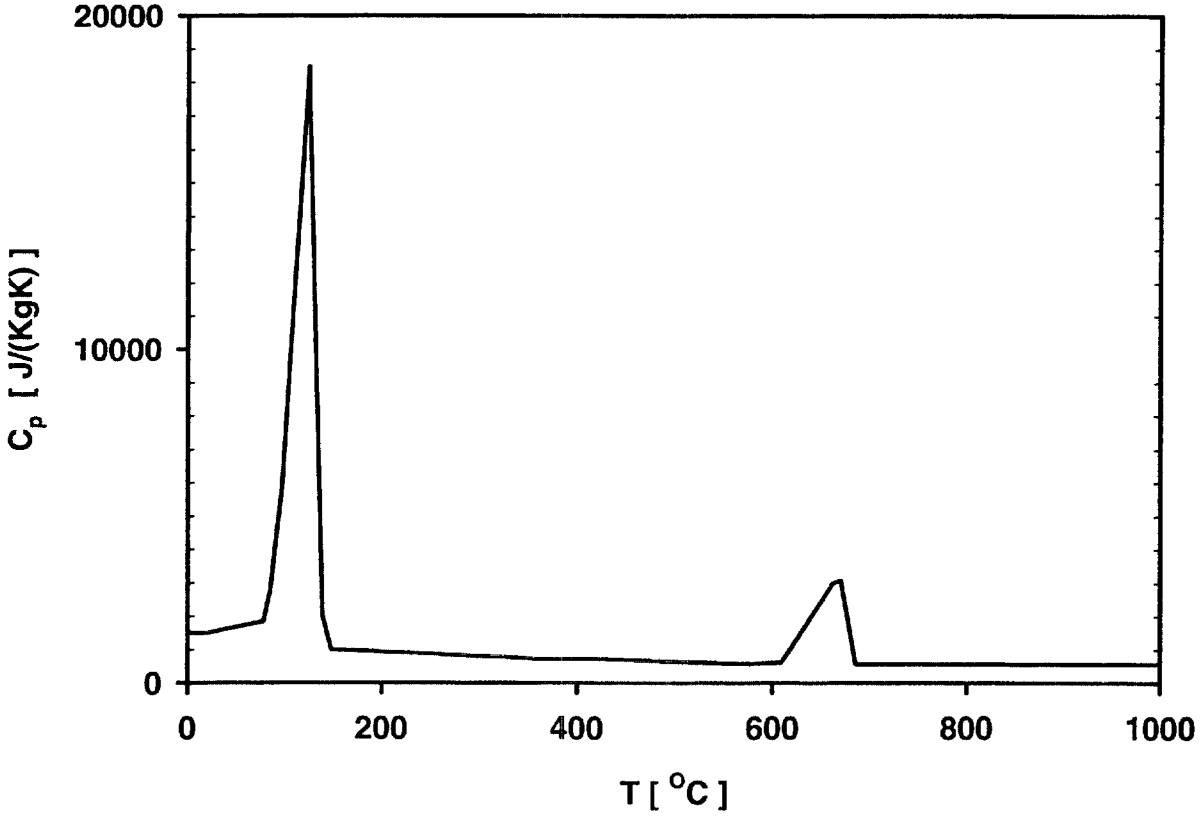

Figure 4. Cp(T) used in all applications of *GYPST*, as adopted in APPENDIX A of [8].

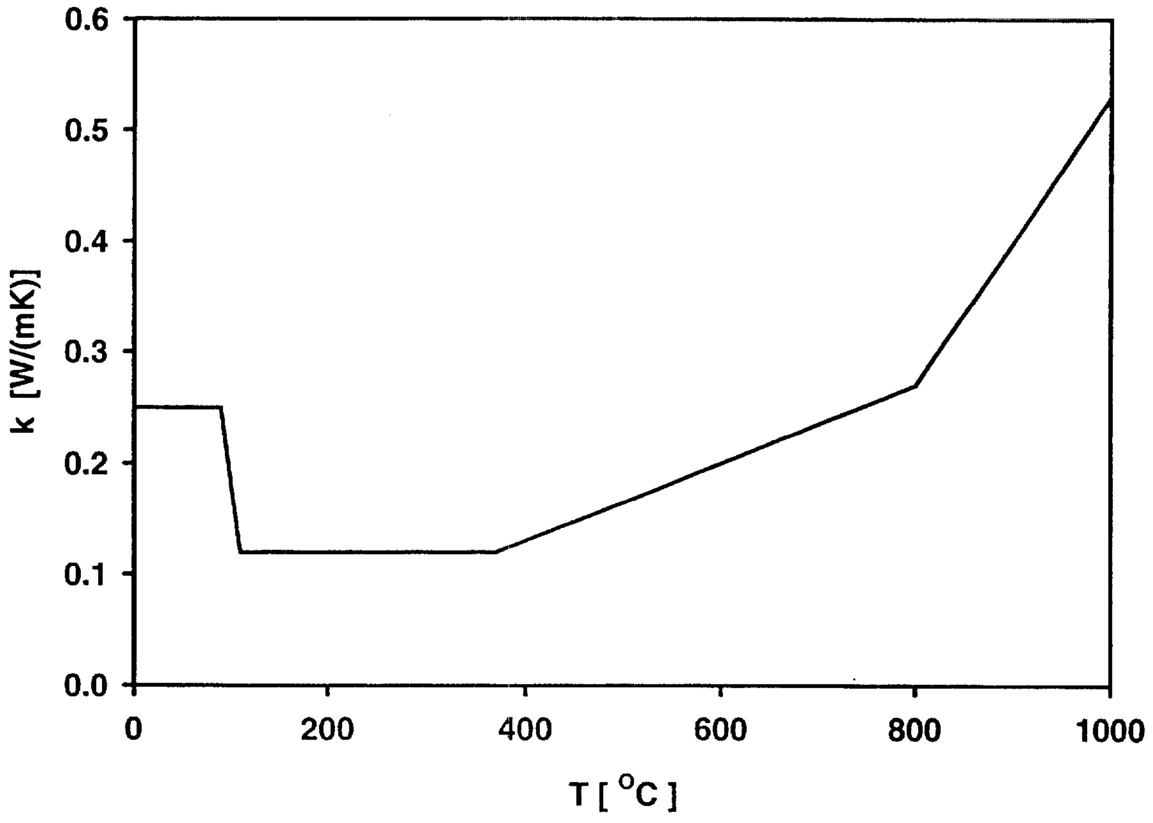

Figure 5. k(T) used in all applications of *GYPST*, as adopted in APPENDIX A of [8].

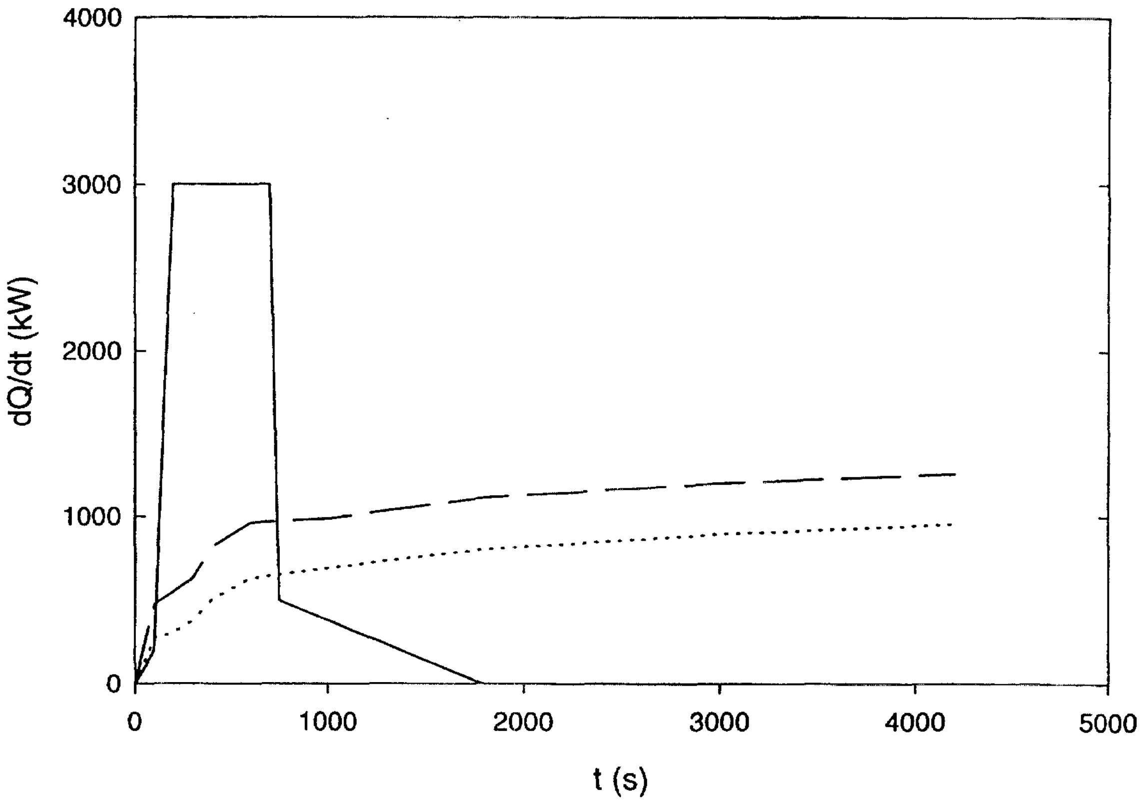

Figure 6. Energy release rates from: 1) Table 5, used to generate approximately an ASTM E119-temperature upper layer in the adopted simulation enclosure and with a 1x1 or 1x2 wall; opaque upper layer ___ ___; relatively-transparent calculated-absorptivity upper-layer . . . . . . ; and 2) Table 6, used to generate a three-sofa fire layer ________.

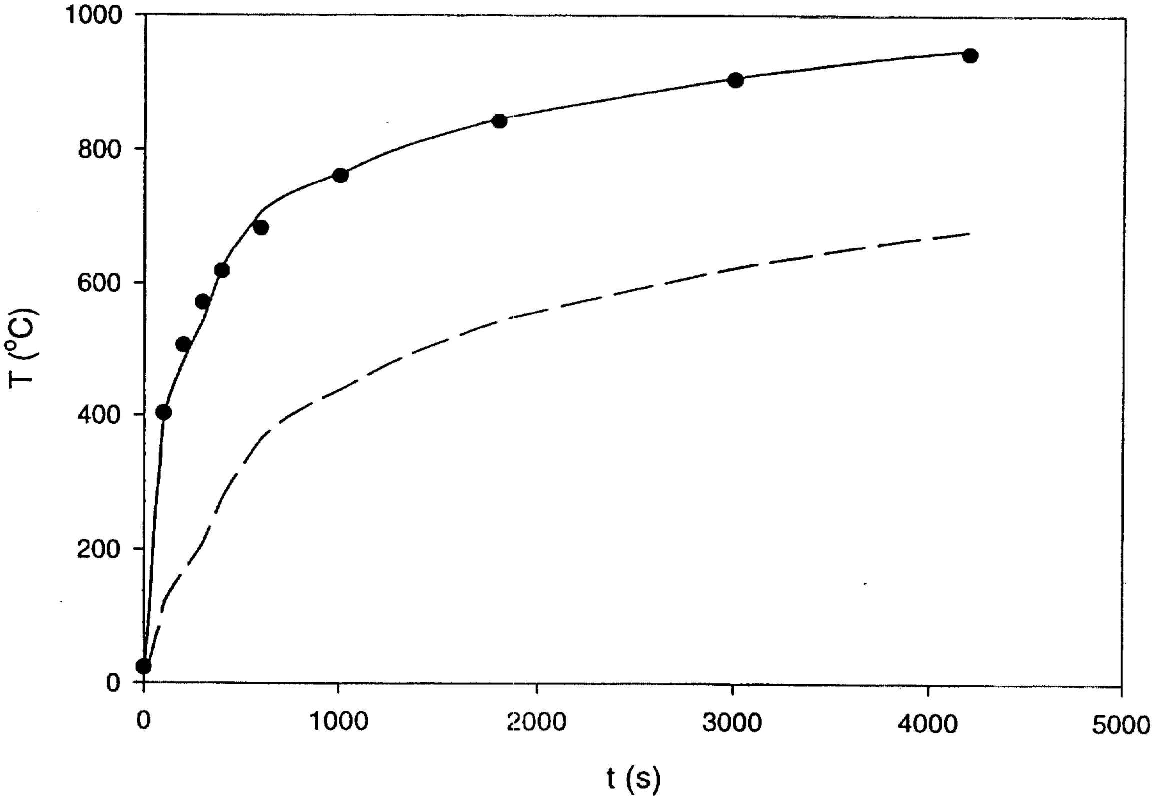

Figure 7. T_{ULAY} (_______) and T_{LLAY} (__ __) for the ASTM E119-type room fire scenario (using either the 1x1 and 1x2 wall systems) with an opaque upper layer. ASTM E119 temperature-time curve (●●●).

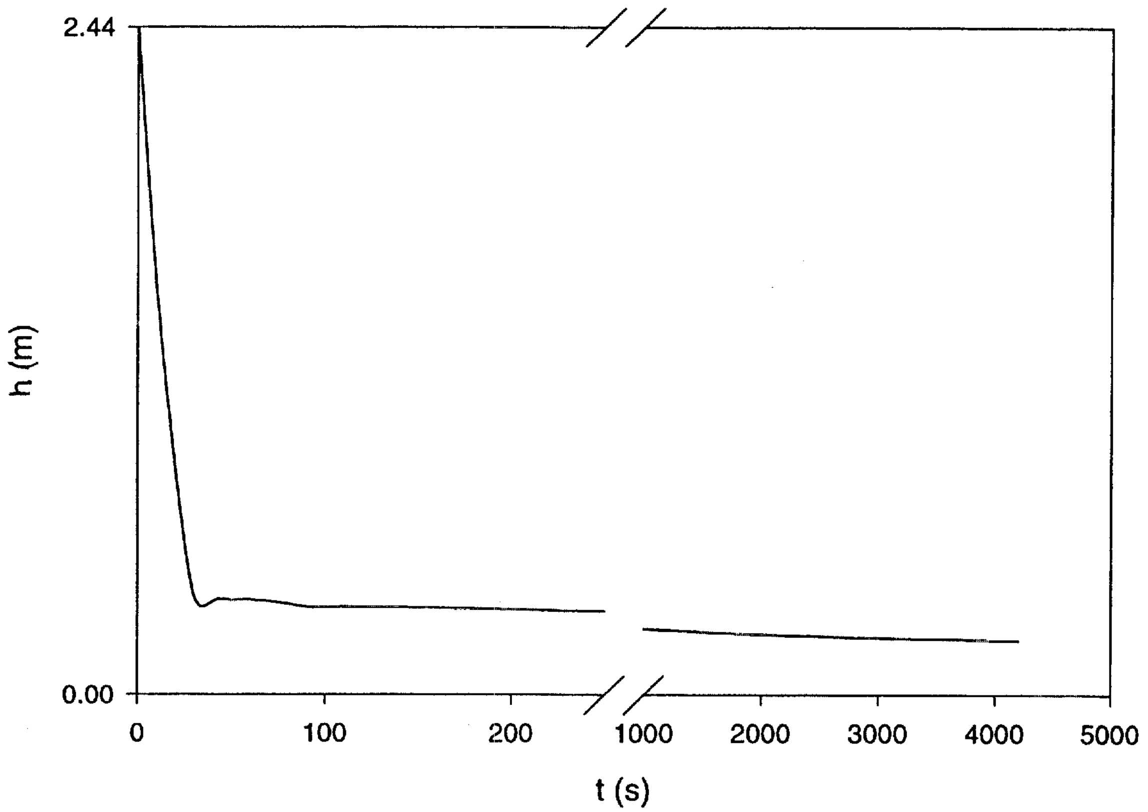

Figure 8. **Elevation *vs* time of the layer interface for a room fire scenario (for both 1x1 and 1x2 wall systems, with an opaque upper layer or a relatively-transparent calculated-absorptivity upper layer) with an ASTM E119-temperature upper layer.**

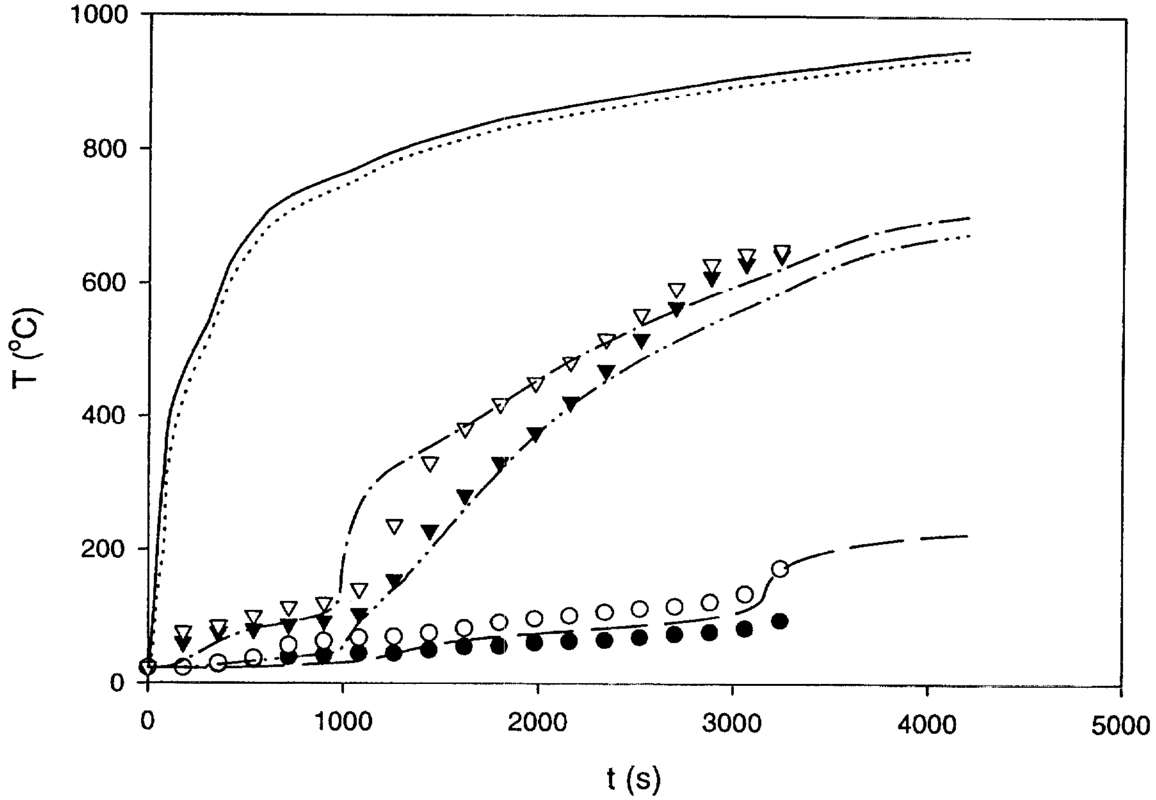

Figure 9. Temperature through a 1x1 wall system *vs* time for a room fire scenario with an opaque ASTM E119-temperature upper layer; calculated and averaged measured (ASTM E119 furnace test) temperatures [6]. See Figure 1.

T_{ULAY} ________; Exp. . . . . . . (calc); BL/Cav.[exp.] ___.___ (calc), ▽▽▽ (meas.); BL/Cav.[unexp.] ___. .___ (calc), ▼▼▼ (meas); UnExp.___ ___ (calc); UnExp.[under pads] ○○○ (meas); UnExp.[bare] ●●● (meas).

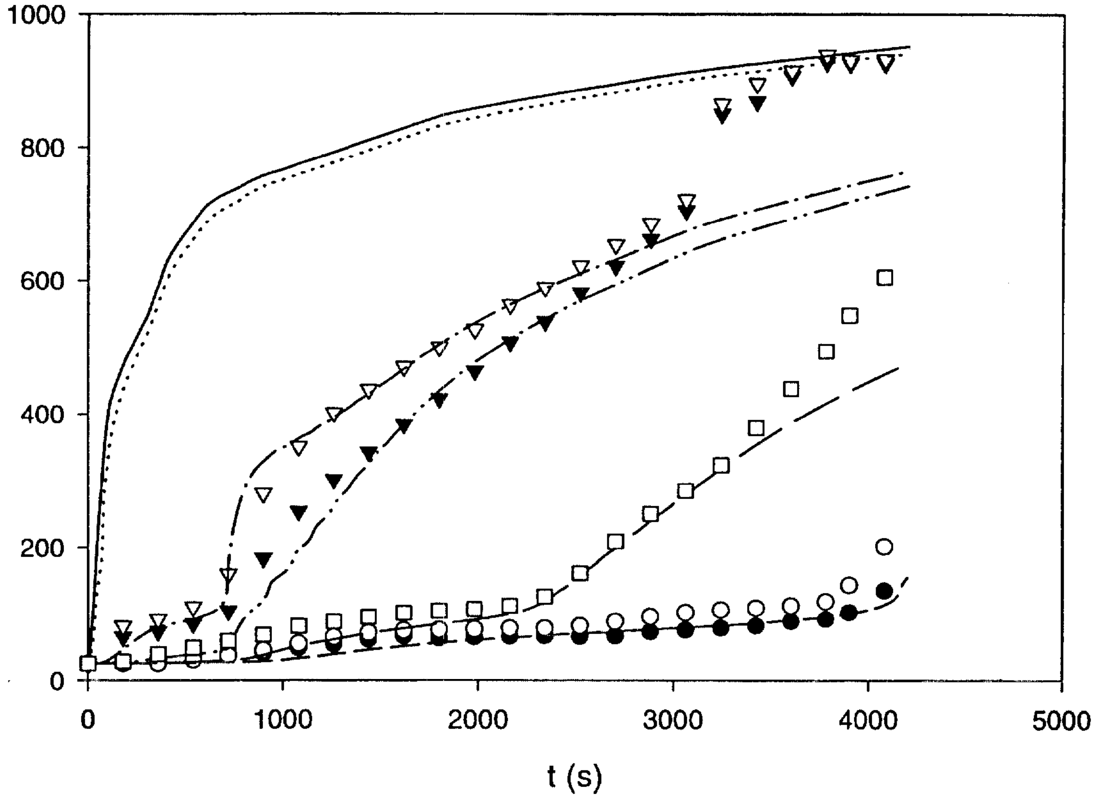

Figure 10. Temperature through a 1x2 wall system *vs* time for a room fire scenario with an opaque ASTM E119-temperature upper layer; calculated and averaged measured (ASTM E119 furnace test) temperatures [5], [6]. See Figure 1.

T_{ULAY} ________; Exp. . . . . . . (calc); BL/Cav.[exp.] ___ . ___ (calc), ▽▽▽ (meas.); BL/Cav.[unexp.] ___ . . ___ (calc), ▼▼▼ (meas); UnExp. ___ ___ (calc); BL/FL[unexp.] ____ ____ (calc), □□□ (meas); UnExp.[under pads] ○○○ (meas); UnExp.[bare] ●●● (meas).

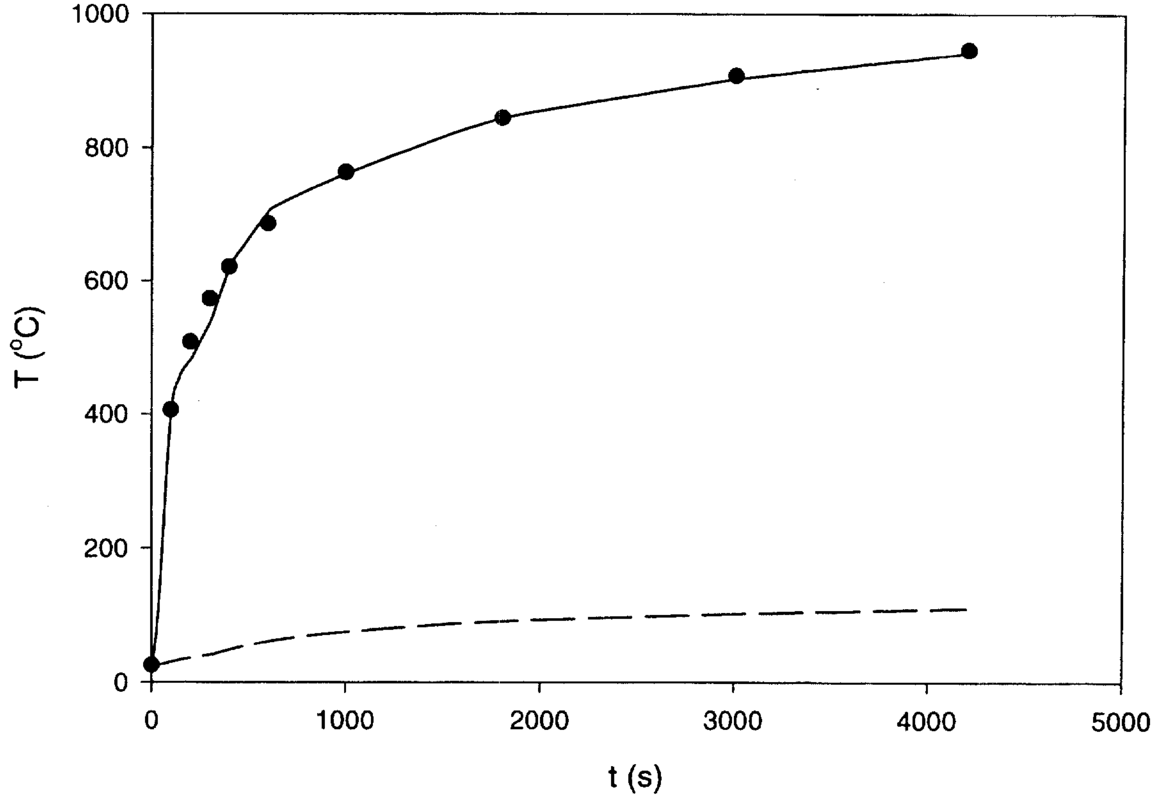

Figure 11. T_{ULAY} (______) and T_{LLAY} (__ __) for the ASTM E119-type room fire scenario (using either the 1x1 and 1x2 wall systems) with a relatively-transparent calculated-absorptivity upper layer. ASTM E119 temperature-time curve (●●●).

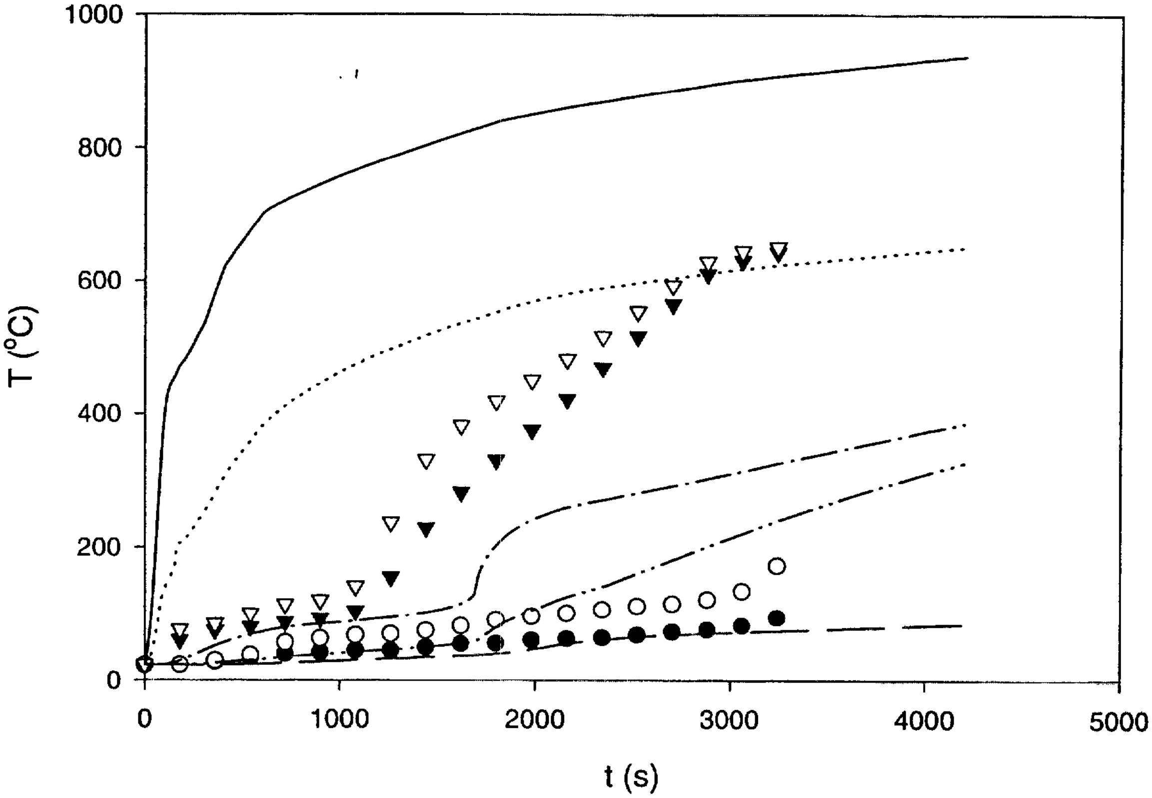

Figure 12. Temperature through a 1x1 wall system *vs* time for a room fire scenario with an ASTM E119-temperature upper layer and a relatively-transparent calculated-absorptivity upper layer; calculated and averaged measured (ASTM E119 furnace test) temperatures [6]. See Figure 1. T_{ULAY} ________;

Exp. ...... (calc); BL/Cav.[exp.] ___.___ (calc), ▽▽▽ (meas.); BL/Cav.[unexp.] ___..___ (calc), ▼▼▼ (meas); UnExp.___ ___ (calc); UnExp.[under pads] ○○○ (meas); UnExp.[bare] ●●●.

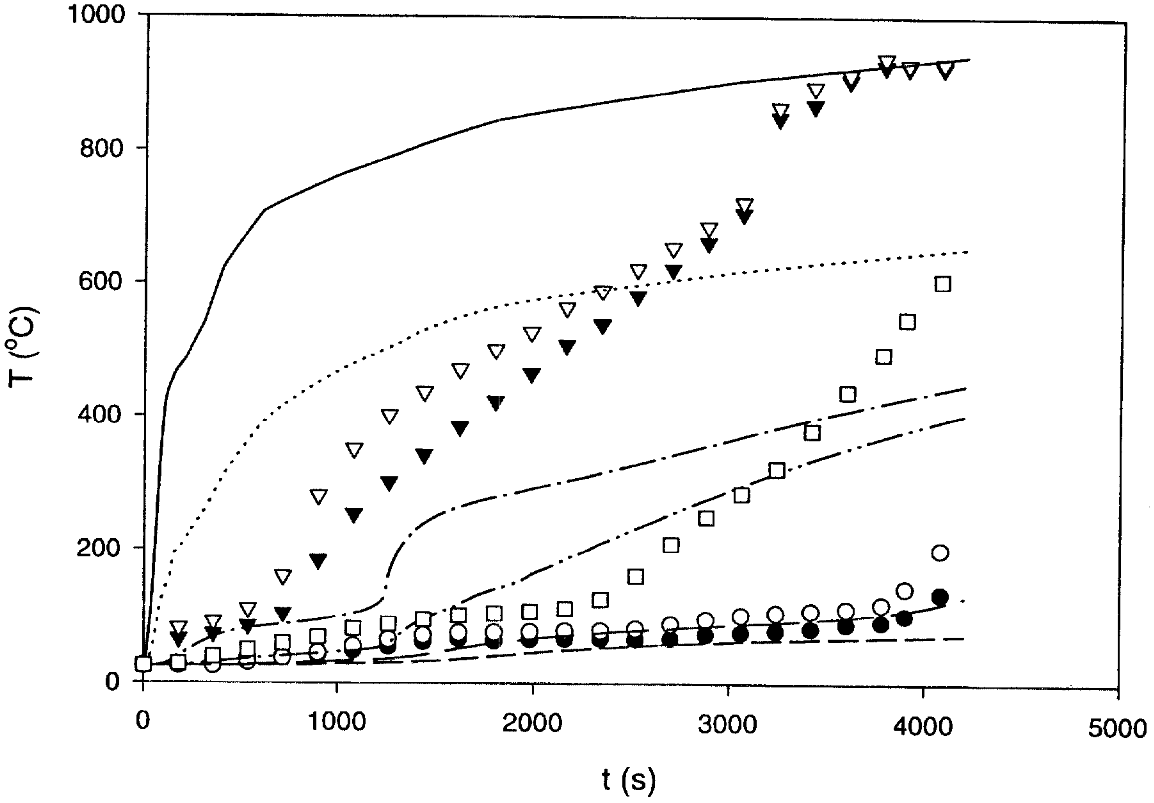

Figure 13. Temperature through a 1x2 wall system *vs* time for a room fire scenario with an ASTM E119-temperature, relatively-transparent, calculated-absorptivity, upper layer; calculated and averaged measured (ASTM E119 furnace test) temperatures [6]. See Figure 1. T_{ULAY} ________; Exp. . . . . . . (calc);

BL/Cav.[exp.] ___.___ (calc), ▽▽▽ (meas.); BL/Cav.[unexp.] ___. .___ (calc), ▼▼▼(meas); UnExp.___ ___ (calc); BL/FL[unexp.] ____ ____ (calc), □□□ (meas); UnExp.[under pads] ○○○ (meas); UnExp.[bare] ●●●.

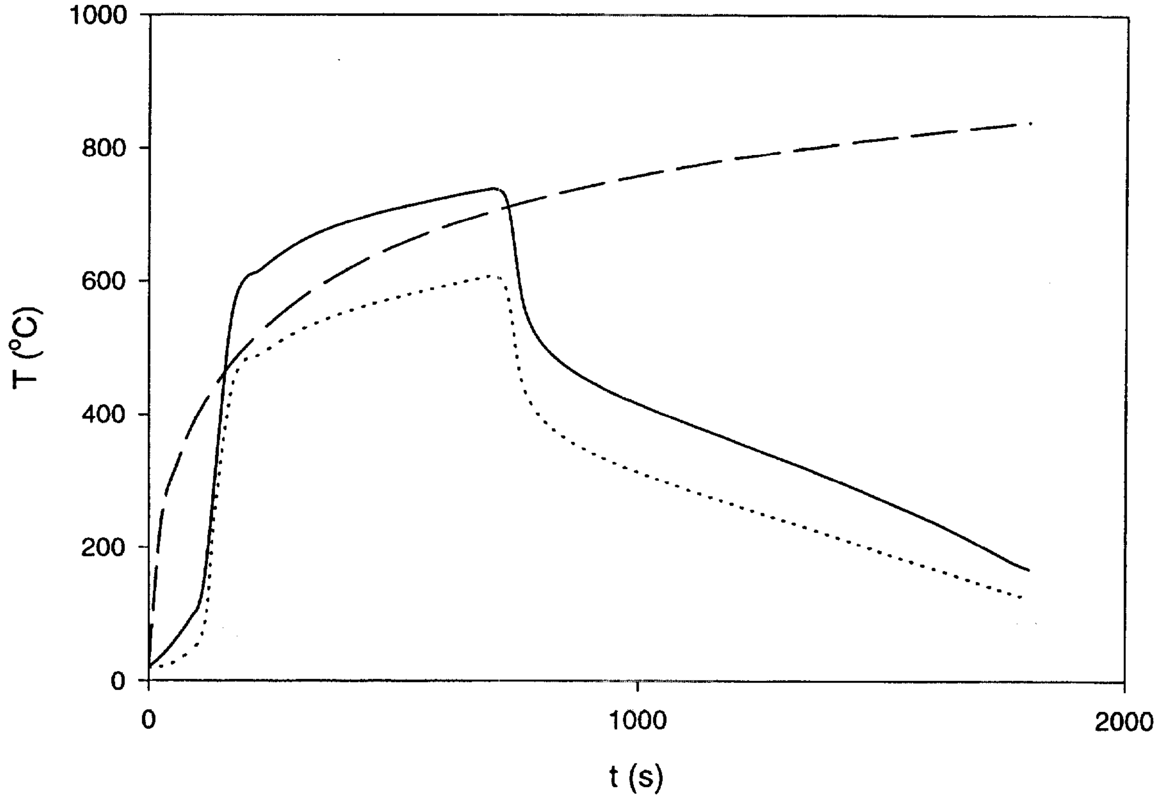

Figure 14. T_{ULAY} (_________) and T_{LLAY} (. . . . . .) for a three-sofa room fire scenario (for both the 1x1 and 1x2 wall systems) with opaque upper layer. ASTM E119 temperature-time curve (___ ___).

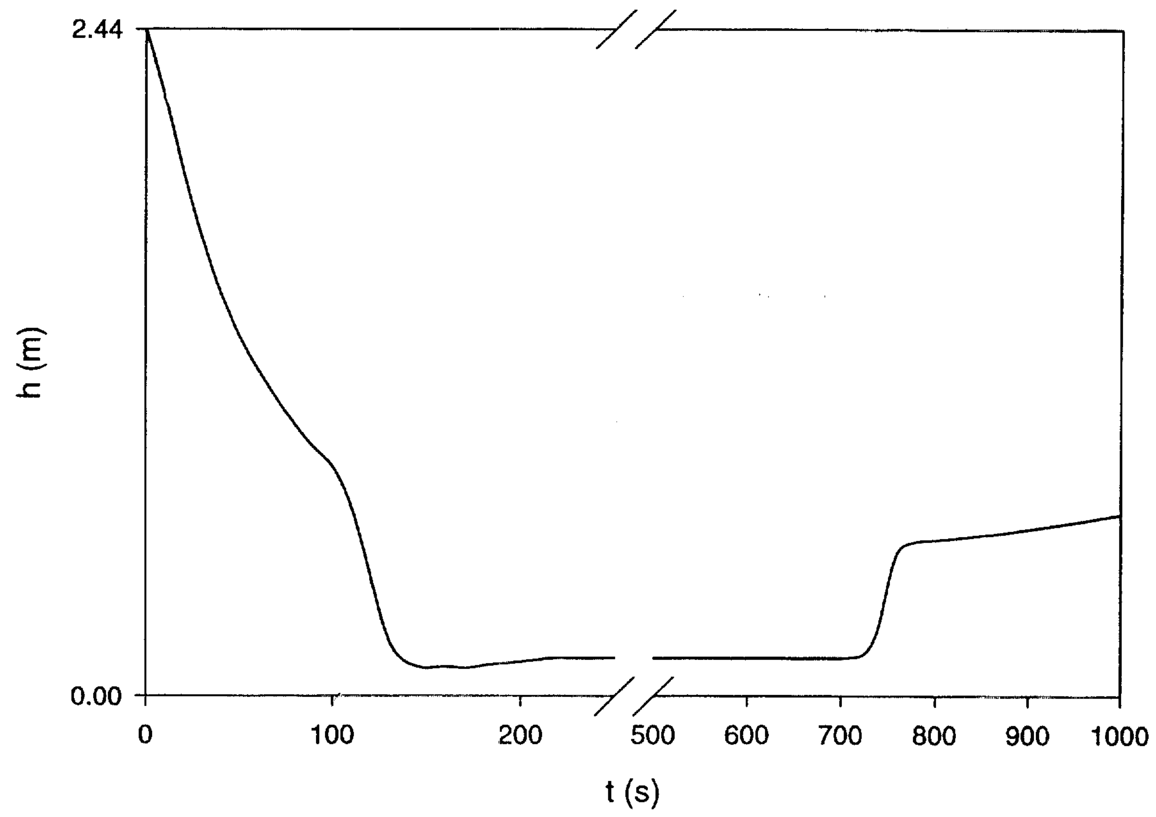

Figure 15. Elevation *vs* time of the upper layer for a three-sofa room fire scenario (for both the 1x1 and 1x2 wall systems) with opaque upper layer.

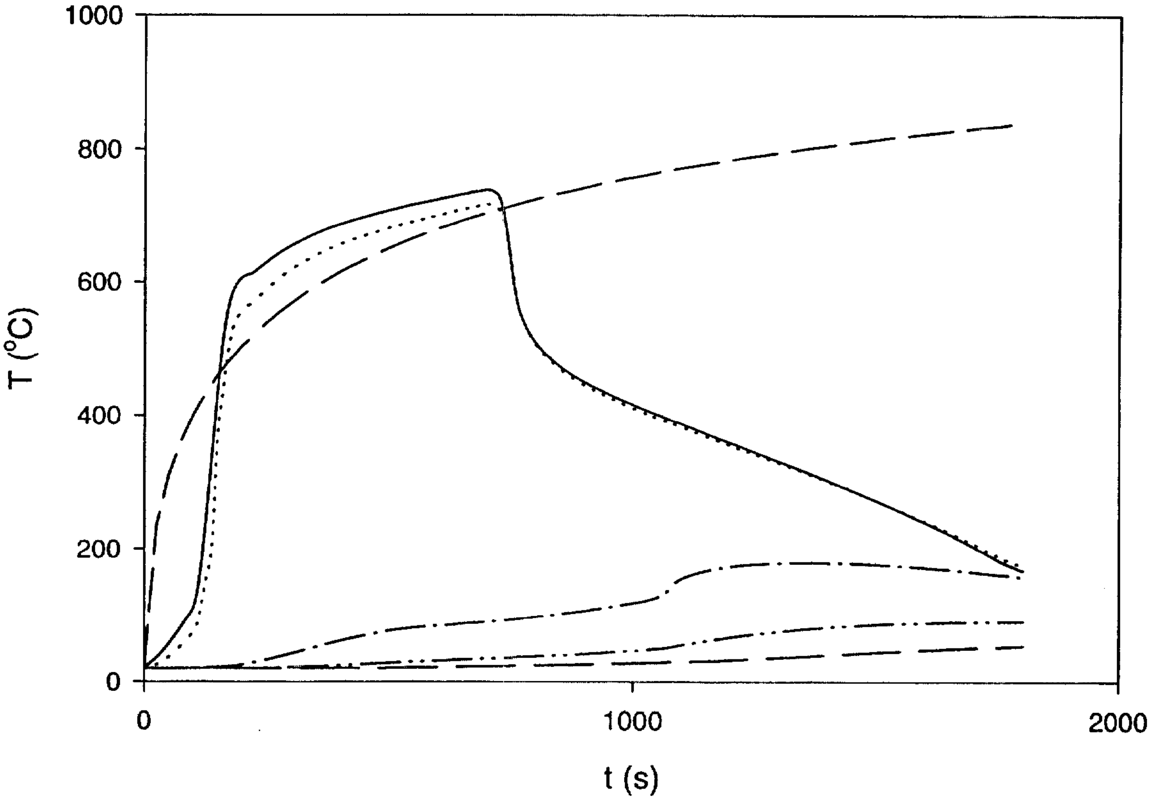

Figure 16. Calculated temperature through a 1x1 wall system *vs* time for a three-sofa room fire scenario with opaque upper layer. See Figure 1. T_{ULAY} ________; Exp. . . . . . . ; BL/Cav.[exp.] ___ . ___; BL/Cav.[unexp.] ___ . . ___; UnExp. ___ ___. ASTM E119 temperature-time curve ___ ___.

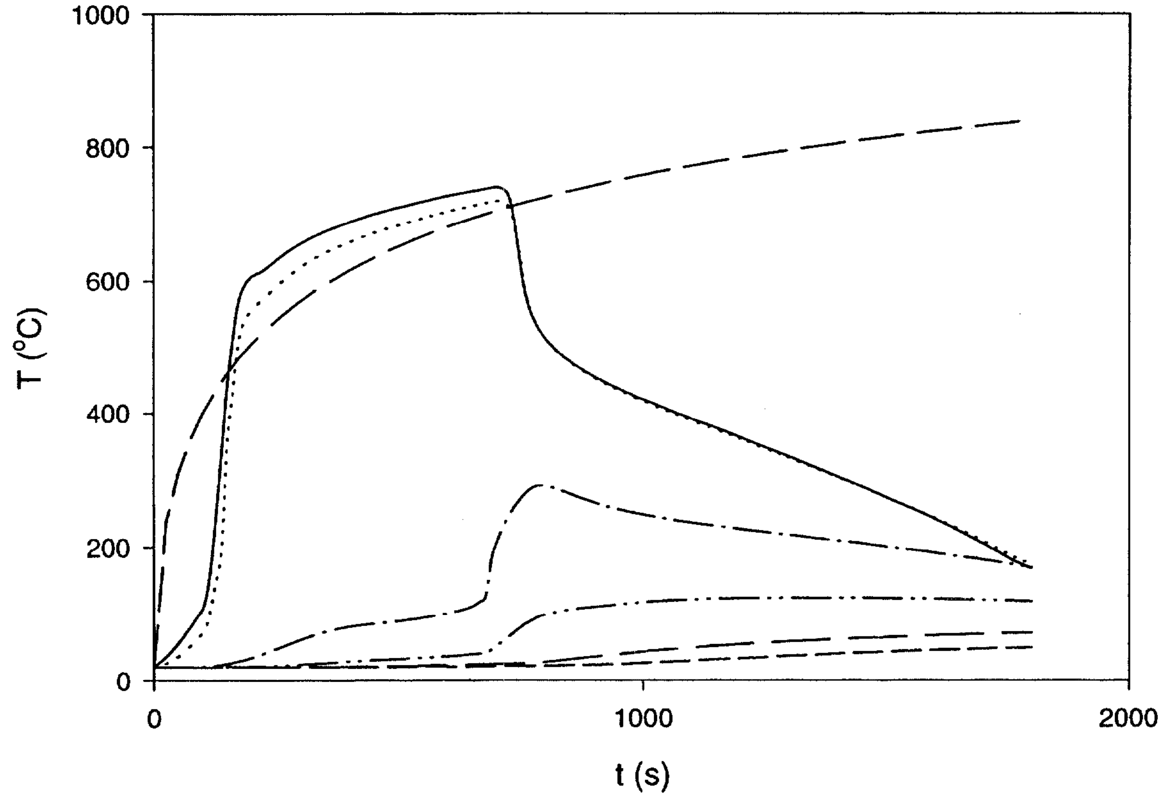

Figure 17. Calculated temperature through a 1x2 wall system *vs* time for a three-sofa room fire scenario with opaque upper layer. See Figure 1. T_{ULAY} ———; Exp. ....; BL/Cav.[exp.] .—.—.; BL/Cav.[unexp.] ..—..—..; UnExp. — — (calc); BL/FL[unexp.] —— ——. ASTM E119 temperature-time curve —— ——.

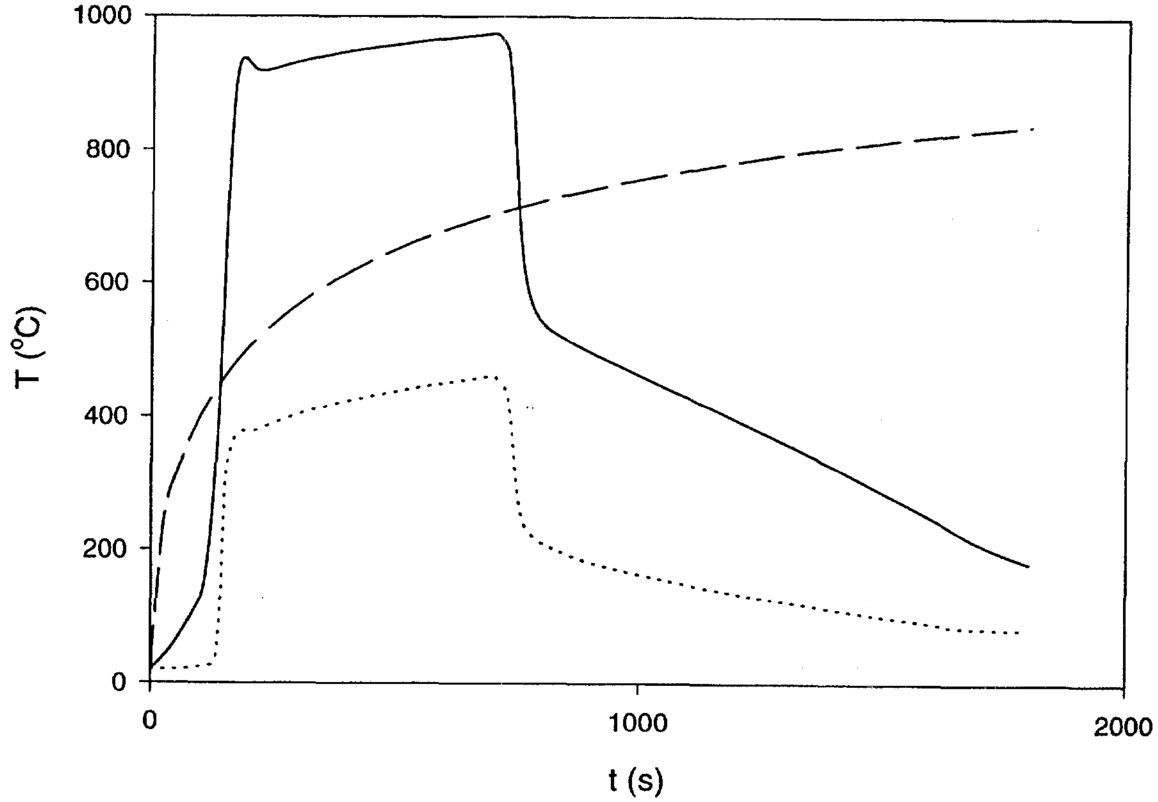

Figure 18. T_{ULAY} (________) and T_{LLAY} (. . . . . .) for a three-sofa room fire scenario (for both the 1x1 and 1x2 wall systems) with relatively-transparent calculated-absorptivity upper layer. ASTM E119 temperature-time curve (__ __).

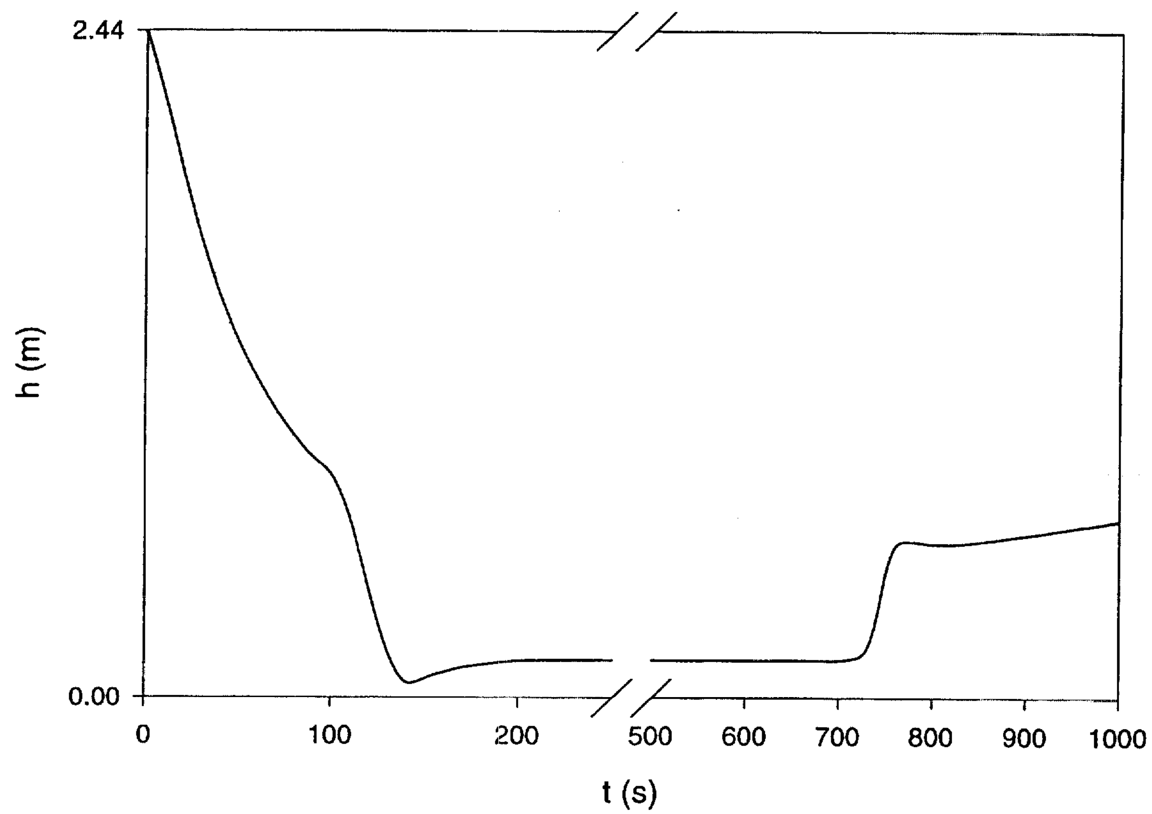

Figure 19. Elevation *vs* time of the upper layer for a three-sofa room fire scenario (for both the 1x1 and 1x2 wall systems) with relatively-transparent calculated-absorptivity upper layer.

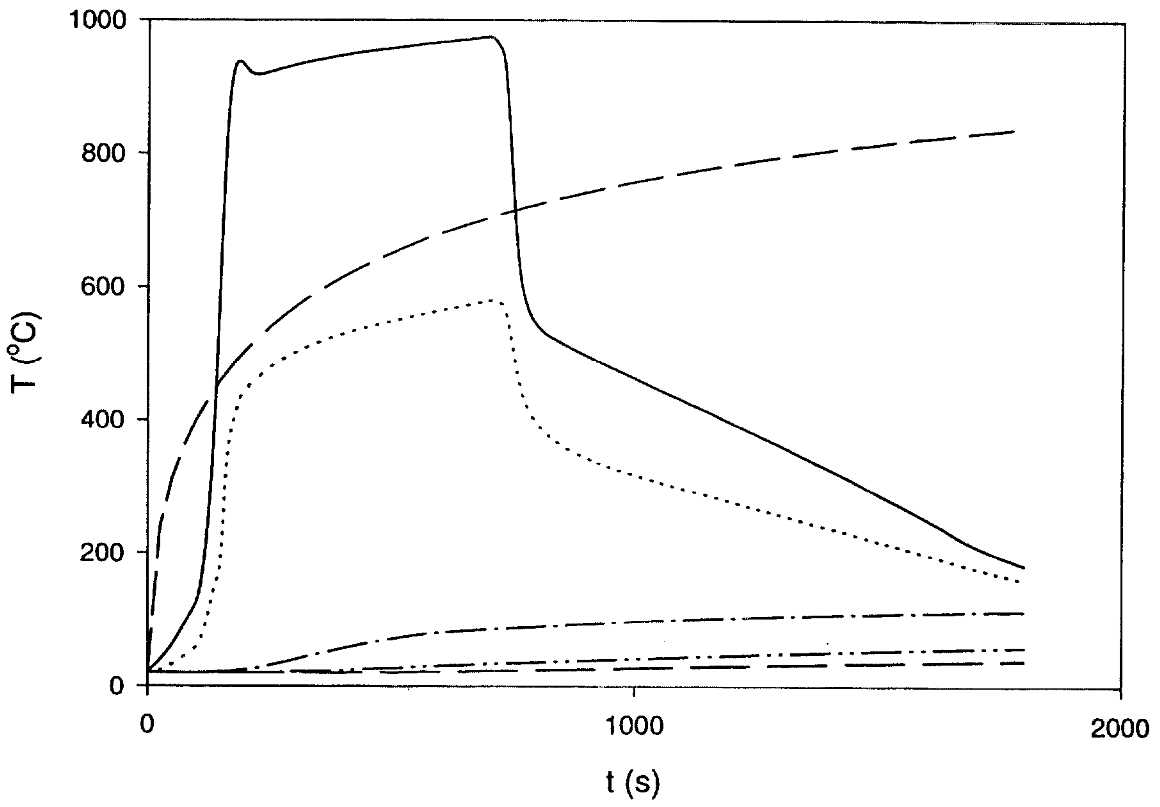

Figure 20. **Calculated temperature through a 1x1 wall system *vs* time for a three-sofa room fire scenario with relatively-transparent calculated-absorptivity upper layer. See Figure 1. T_{ULAY} ————; Exp. ....; BL/Cav.[exp.] .——.——.; BL/Cav.[unexp.] ..——..——..; UnExp. — —. ASTM E119 temperature-time curve —— ——.**

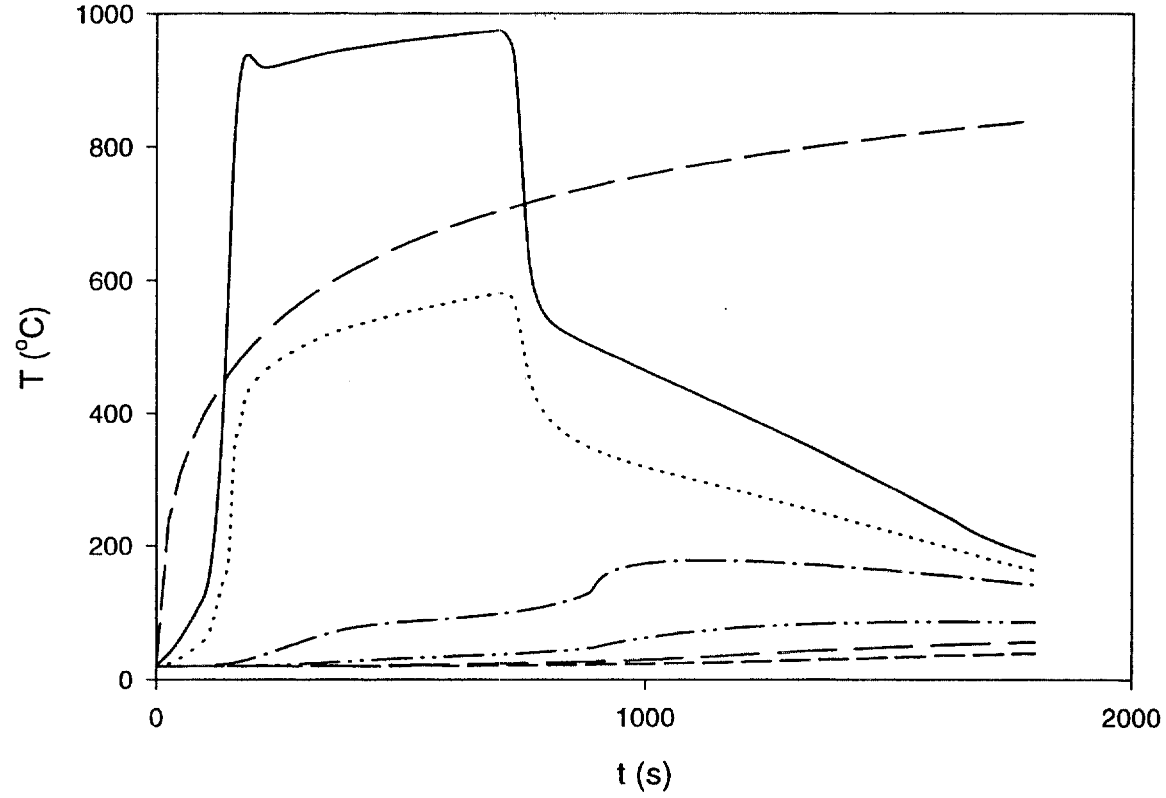

Figure 21. Calculated temperature through a 1x2 wall system *vs* time for a three-sofa room fire scenario with relatively-transparent calculated-absorptivity upper layer. See Figure 1. T_{ULAY} ________; Exp. ....; BL/Cav.[exp.] .___.___.; BL/Cav.[unexp.] ..___..___..; UnExp. ___ ___ (calc); BL/FL[unexp.] ____ ____. ASTM E119 temperature-time curve __ __.