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Procedures for Quantitative Sensitivity and Performance Validation Studies of a Deterministic Fire Safety Model

Nadir Khoudja

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PROCEDURES FOR QUANTITATIVE SENSITIVITY AND PERFORMANCE VALIDATION STUDIES OF A DETERMINISTIC FIRE SAFETY MODEL

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NOTICE

PROCEDURES FOR QUANTITATIVE SENSITIVITY AND PERFORMANCE VALIDATION STUDIES OF A DETERMINISTIC FIRE SAFETY MODEL

A Dissertation

by

NADIR KHOUDJA

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ABSTRACT

Procedures for Quantitative Sensitivity
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Chair of Advisory Committee: Dr. Waynon L. Johnston.

The increasing number of users of fire models demands their validation by a third party team to investigate the reliability of the models with respect to concerns of potential users. Due to insufficient documentation of the subject fire model, verification of it was limited and informal. However, quantitative and detailed procedures for sensitivity study and performance validation were applied. A deterministic model, predicting fire behavior in structure, was selected to illustrate partial model assessment procedures.

The development and application of two generic methodologies for sensitivity analysis and performance validation are described. The subject fire model is FAST from which 16 input parameters were selected for sensitivity analysis study. Comparative graphical results are illustrated over simulation time for the input parameters.

Output variables for both sensitivity analysis and performance validation were chosen to be the upper layer temperature and the smoke layer thickness. These two variables, among an array of variables, are viewed to be most informative and compromising. A set of 100kW fire size was chosen with all possible configurations of the experimental set ups to conduct the performance validation. A nonparametric statistical methodology (Mann-Whitney Test) based on ranking was utilized. Graphical statistical results illustrate the quantitative comparison of the fire model's data to experimental data.

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Certainly, without the encouragements, assistance, and guidance of Dr. Waymon L. Johnston this research project would not have been possible. I am most appreciative to my entire committee members from whom I have received constructive criticism of this document.

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1. GENERAL INTRODUCTION AND BACKGROUND

Prediction of fire safety attributes is dependent on the accumulation of scientific knowledge on the behavior of fire. Indeed, before attempting to construct any models depicting potential reality of fire behavior, a clear understanding of physical and chemical fire phenomena is required.

1.1 Some Fire Characteristics

The fire process can be perceived to start with ignition of a given fuel, develop to a peak status, then decay to its termination. Since hostile fires are undesirable, it is quite important to understand the stages of their birth and growth in particular. The first stage is related to the ignition process which comprises the ignition sources, the type of fuels, and the environmental conditions. The second stage focuses on the fire development and growth. It deals primarily with the fire plume and its contributions, namely the flame height, the flow distribution, the flame, the temperature quotient, the air entrainment, and the concentration of combustion products.

The format used for this dissertation is that of the American Industrial Hygiene Association Journal.

Three types of fires are utilized in fire modeling. These are the gas burner fire, the pool fire, and the growing fire. The gas burner fire is characterized by a constant fuel flow, which is the same as the burning rate, and a constant burning fuel surface area. The pool fire is characterized by a constant burning fuel surface area, but it has a burning rate dependent on the energy balance at its surface. Finally, the growing fire is characterized by a variable burning rate as well as a variable burning fuel surface area. For this type of fire, ignition is less predictable because of a number of parameters such as the necessary heating up period and the pyrolysis period, which are more significant for the growing fire. The fire process characterization, through the knowledge of the fire's attributes is required in fire modeling because it serves as input and/or as building blocks to fire models.

The purpose of this chapter is to familiarize the reader with the primary fire characteristics relevant to fire modeling, specifically to zone fire models which are the main focus in this study. The following are discussions of research results efforts on different fire characteristics.

The occurrence of a fire is conditional upon the simultaneous presence of fuel, ignition source, and oxidant. Usually, the oxidant in common fires is assumed to be air. Even though most zone models assume an established ignition for any type of fires considered, some models that involve more than one fuel package require criteria of fire spread, i.e., the condition of fuel ignition process.

1.1.1 Ignition Process

It is imperative to recognize that the ignition process is composed of two phases, the pre-heat phase and pyrolysis phase.

The heating-up period of a given fuel varies with its physical-chemical nature.[1,2] The more complex the fuel, the more extensive the heating-up period would be. For example, the heating-up time is longer for a cellulosic material than a liquid hydrocarbon; even less time is required for gaseous fuels. There is no demarkation line between the heating-up phase and the pyrolysis phase; even though for most fuels the pyrolysis is initialized at a well determined temperature.

It was found that for most fuels, the heating period is determined by the following law:

$$T_s - T_o = 2\,Q''\sqrt{\frac{t}{\pi(k\rho c)}} \qquad \text{(Ref. 3)}$$

where

T_s = Surface temperature at time t

T_o = Initial surface temperature

Q'' = Net incident heat flux

t = time

π = pi, 3.14

k = Fuel thermal conductivity

ρ = Fuel density

c = Fuel specific heat

Note that ($k\rho c$) is known as the thermal inertia of a fuel.

As the endothermic process continues through the pyrolysis phase, a positive heat balance should be present; in spite of some expected lost flux through conduction, convection, or radiation. The process of pyrolysis causes the evolution of gaseous fuel, which leads to ignition if the air-fuel mixture is within the flammability limits. In addition, it has been reported that ignition is dependent on fuel temperature, amount of radiation applied, and ambient pressure.[4] In fire modeling, the fuel temperature is assumed to be at "normal" ambient pressure and temperature. Therefore, only the amount of radiation to which a fuel is subjected can influence when an ignition will occur. Most room fire models do consider only a single fuel package with an established ignition, therefore, they do not require the physics of the ignition process. However, some zone models handling fire spread scenarios need the flame-initiating process information to model fire involvement of more than one fuel package. This calls attention to the ignition testing methodology. There are a number of testing techniques; the two most used are discussed below. Testing apparatus used is vertically set-up where one of the two parallel panels is holding the sample while the other is emitting known level of radiations. Note that the pilot flame is located on top of the sample panel. This implies that once ignition occurs one would expect to observe the spread of flaming ignition downward along the panel surface. Similarly, the horizontal testing apparatus is set-up where one would observe the oversized radiant panel compared to the sample panel, and the pilot flame is positioned at the center of the sample.

Intuitively, we would expect that the two ignition testing methodologies would produce different results for similar sample material. The reason seems to be related to the fact that in order to obtain ignition, the pyrolysis process depends on the mass gas rate evolution per unit area and the geometry of the testing apparatus.[5]

Indeed, Kashiwagi demonstrated that ignition was obtained sooner for a sample mounted horizontally than one presented vertically, because of the convective forces that minimized the pyrolysis products. He concluded that the required ignition energy is a function of geometric relations between the sample (fuel), the convective flame, and the radiation beam.[6,7,8,9] These conclusions were obtained from radiative ignition of solids and liquids, experiments utilizing a black body radiant source and a high power carbon dioxide laser controlled energy applied to a sample at a single wavelength.

1.1.2 Fire Plume

Following fuel ignition, the fire plume can be observed. The properties of fire plumes are important in dealing with problems related to fire modeling.

A number of properties are associated with fire plumes. These are illustrated in Figure 1. In general, one would observe a turbulent flame crowned by a bryant turbulent gas stream, which could be smoky depending on the nature of the burning fuel. Coupled with the flame and bryant gas flow are temperature and plume velocity profiles. Smoky fires would assist in observing the entrained fresh air flow toward the fire plume boundaries.[10] Fire plume features just depicted above are qualitative and general; they can vary with numerous factors such as environmental conditions, nature of burning fuel, etc. The flow profile above the flame provoked by time average values of temperature rise describes a normal distribution. The temperature as well as the plume velocity higher at the flame level decrease with plume's height as can be seen on Figure 1.[11,12,13]

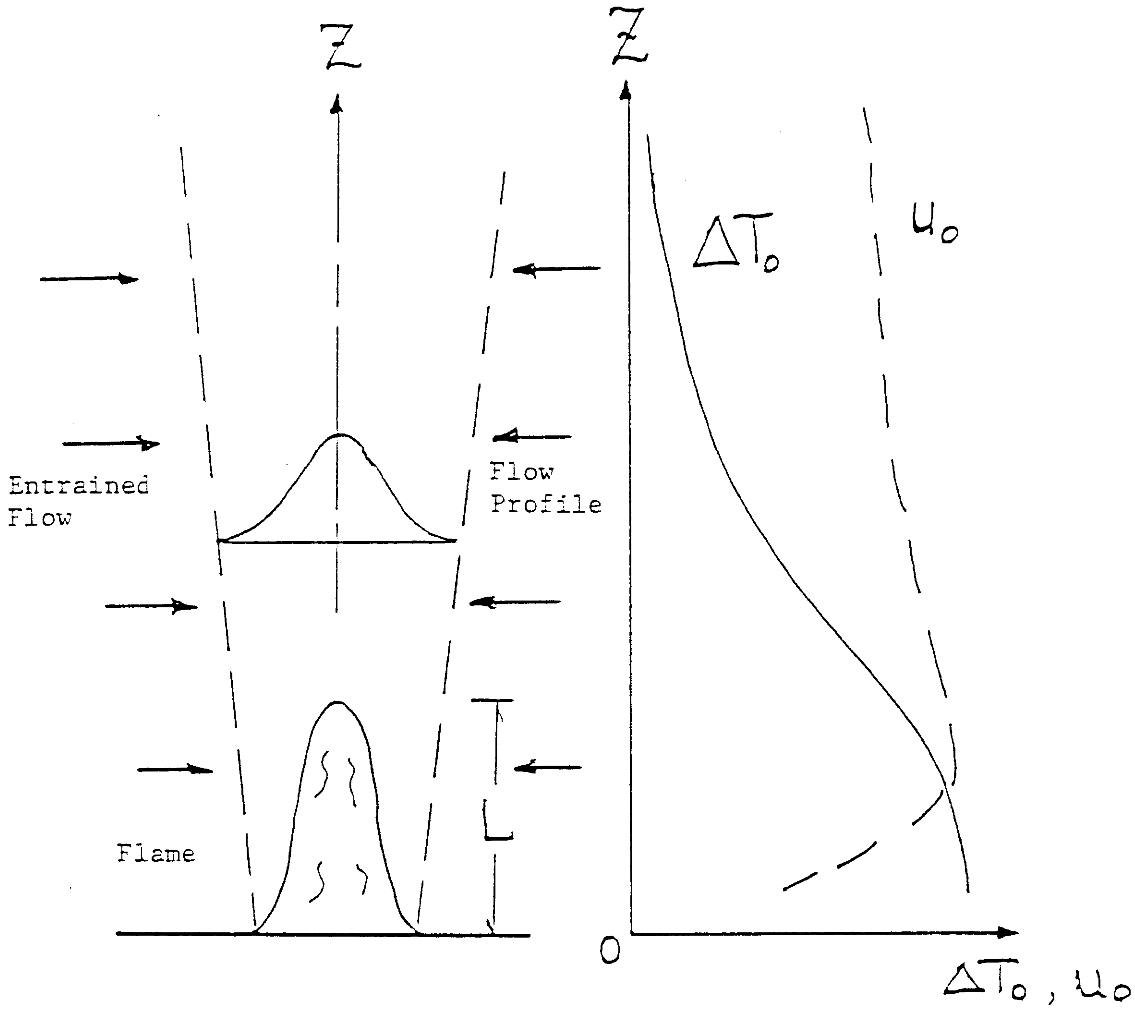


Figure 1. Some Features of a Fire Plume (Ref. 10)

Indeed, it has been reported that a turbulent fire plume is composed of three regions.[14] The first region is located at the base of the fuel source. It is usually a bright region characterized by a pulsation effect that is a function of the surface area of the fuel base.[15] The second region of the fire plume is the fully developed turbulent flame. The turbulence increases with the flame's height. Finally, the third region is located on top of the luminous parts of the flame, and extends to just below the upper control volume. This region is a non-luminous, non-reacting turbulent, composed primarily of unclear combustion products.

1.2 Fire Modeling

As Irwin Benjamin stated, ".....Being able to predict the growth of a fire in a room and its spread through a building should be as much a part of the fire protection engineers' design tools as predicting the flow of heated or cooling air through a building is the tool of the heating and ventilating engineer".[16] Prediction is the main thrust of enormous efforts required to obtain believable information that modeling can bring.[17] In this respect, fire models are the products of systematic design of physical phenomena aiming at the design of safer buildings.

Throughout the years, several fire modeling methodologies have been used.[18,19] These include the traditional experimental modeling which encompasses small-scale and full-scale replicas, and the more theoretical modeling, i.e., the mathematical modeling such as stochastic and deterministic models.[20]

1.2.1 Experimental Modeling

Experimental modeling is the most basic type of fire modeling. It presents advantages and disadvantages. It offers invaluable insight on fire phenomena, but it is usually extremely expensive and it replicates poorly. Experimental modeling can be designed for either full- or reduced-scale scenarios. In experimental modeling, two primary techniques are utilized, namely atmospheric (Froude) and pressure modeling.

1.2.1.1 Full-Scale Experimental Models

Experimental modeling conducted on a full-scale basis has no equal in investigating realistic fire scenarios. Indeed, it provides not only critical information about the fire behavior but also noetic communication about the structure housing the hostile fire.

The main advantage of full-scale experimental modeling is a realistic simulation of the fire behavior with reasonable accuracy in results. Yet, it is usually prohibitively expensive which reduces the likelihood of replications which in turn eliminates the possibility of having statistically significant results. In addition, full-scale experimentation requires substantial man-power and instrumentation. Also, full-scale experimentation has set the stage for fire tests to develop standard fire exposure conditions. These tests were intended to determine buildings' partitions fire resistance. Standard testing seems to be financially attractive since it does not require the use of whole structures, yet they are still relatively expensive to conduct. Therefore, full-scale experimentation modeling is an exploratory tool.

1.2.1.2 Small-Scale Experimental Models

Small-scale experimental modeling is the outcome of disadvantages of full-scale experimentations. Small-scale models are the product of studies attempting to obtain similar outputs through scale reduction, in geometric and thermophysical characteristics of fire scenarios. Even though small-scale experimental modeling is plagued by a myriad of problems, it has the distinct advantages of being relatively inexpensive and easier to manipulate in a laboratory setting.

Accurate scaling is difficult to achieve for variables such as linear dimensions, area reductions, volume reduction, etc. Some variables simply cannot be scaled, namely temperature, buoyancy, etc.

1.2.1.3 Techniques Used in Experimental Modeling

Two basic techniques have been used in experimental modeling. These are:

A. Atmospheric Modeling (known also as Froude modeling)[17], and

B. Pressure Modeling.[17]

Fluid dynamic scaling laws and diffusion flames are the basis of the two techniques.[17]

Obviously the former technique is desirable for large turbulent fires. Smoke and heat movements are applications of choice using Froude modeling as long as these fires do not exhibit viscous effects. One attraction of this technique is that it does not require sophisticated experiment nor structure.

The latter technique requires an environment where the pressure is higher than atmospheric. This environment induces a smaller buoyancy force to accommodate the reduced scale. Even though this technique offers the advantage of reduced cost, it still requires special pressure vessels to conduct fire tests.[18]

1.2.2 Mathematical Modeling

Through the efforts of estimating fire resistance ratings of fire protective materials from a single test, simple mathematical modeling was born. This type of modeling can also be viewed as prescriptive modeling. Recently greater efforts have been directed toward the mathematical modeling of fires in enclosures.[21]

Fire modeling varies in complexity depending on what information is desired from the models.[22] Some are constructed to determine the fire spread within a single enclosure.[23] Some other models forecast the spread of fires through multi-story buildings.[23] Two basic approaches have been used and these are:

A. Stochastic Modeling, and

B. Deterministic Modeling.

1.2.2.1 Stochastic Modeling

It is a computational approach that views fire growth and spread as well identifiable timely events. These events are systematically analyzed and quantified through a probabilistic evaluation. Even though this approach uses no fundamental physics nor fire chemistry, it takes into account fire principles when building models.[24,25,26]

In stochastic modeling two components can be recognized: the qualitative component which comprises the primary aspect of fire problem; and the quantitative component which focuses on those elements of the qualitative component that can easily be quantified.[27,28,29,30,31]

1.2.2.2 Deterministic Modeling

Primary because of the fact that stochastic models capitalize very little on known fact fire physics, it is perceived necessary to probe mathematical fire modeling in a deterministic fashion.[32] In this respect, from the late fifties to the mid-sixties, fire modeling was nascent in, respectively, Japan and in England (by Thomas).[33] By now, fire research efforts focused on the growth and spread of fire in terms of its physics and physiochemical properties.[34,35] In attempting to improve fire performance of structures, great attention has been directed to the expected maximum temperatures as they relate to time.

In the effort to gather information on conceptional fire behavior, two major methodologies have been undertaken. These methodologies can be better expressed as two types of models. These are commonly known as the field models and the zone models. The first type of model takes the "micro" approach, that is, it divides a well defined and limited space into a myriad of space elements.[34] To these spaces is then applied differential equations depicting physical phenomena. The second type of models takes the "macro" approach, that is, the total subject space is divided into only a few spaces known commonly as zones.[34] Because zones are indeed exaggerated space elements, only an approximate set of equations can be used to describe their fire related behavior. The following will detail the two types of models.

1.2.2.2.1 Field Models

Field models, sometimes known as field equation models, use partial differential equations applied to element spaces or fields to forecast fire variables such as temperature, smoke particles in space, etc. Field models in fire research provide an insight to intricate fire phenomena that other models cannot present.[36] They offer a different reaction to the view one would obtain when moving from a naked eye observation to a microscopic one. Both types of observations are informative. Obviously, field modeling falls in the "microscopic" observation category. In this category, field models can be either two-dimensional or three-dimensional. As expected, two-dimensional field models were developed first due to their relative simplicity. Yet, they still challenge the computing power of most existing hardware. This is primarily due to the required small time steps in order to obtain a desirable spacial resolution. The computation problem is worsened when the description of turbulence is added to fluid motion induced by the fire consideration. Figure 2 illustrates temperature contours for a two-dimensional field model.[34]

Indeed, the forecasting of turbulence, from fluid flow provoked by heat induced buoyancy, is a paramount problem for modern physics.[34,37,38] Similar comments can be stated about the three-dimensional field models which are currently being developed.

An ingenious experimental simulation has been used by a number of fire researchers[34] to model early development of fire plumes. This experiment consists of flowing colored salt water into colorless fresh water; this offers conditions where there are neither heat transfer to boundaries (tank wells of fresh water) nor thermal radiation (assuming salted and fresh water have some temperature).[34] In this experiment, the fresh water represents the ambient air, and the colored denser salt water represents the hot fire plume. Obviously, this experimental set-up needs to be visualized up-side-down in order to obtain the actual "mushrooming" effect of buoyant fire gases in an enclosure.

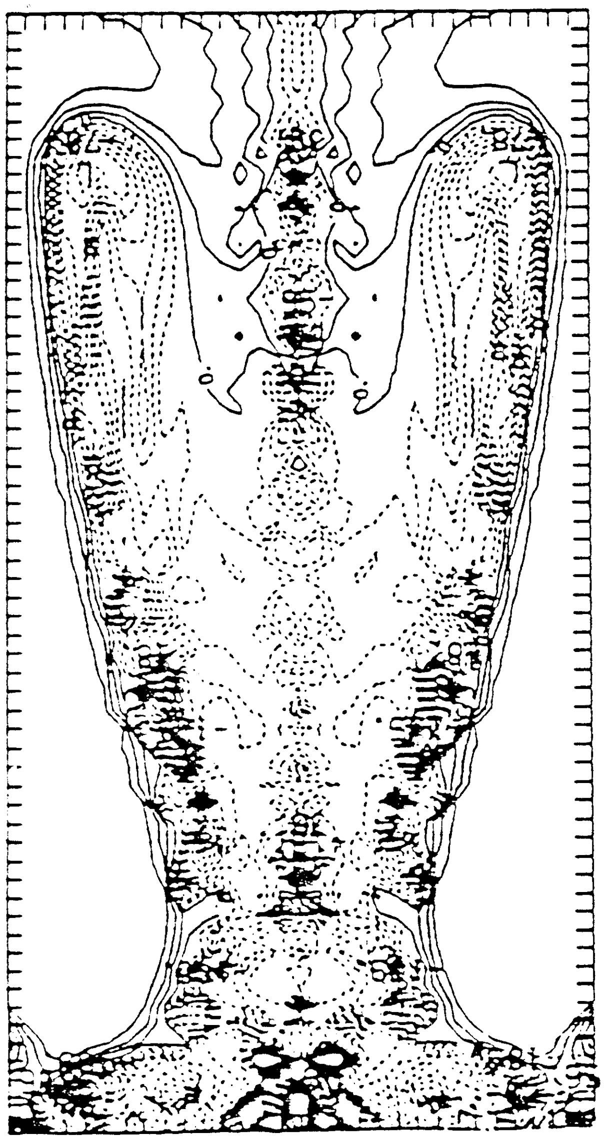


Figure 2. Temperature Contours for a Two-Dimensional Field Model

Field models can be utilized to assist in determining fire parameters at specific locations in an enclosure. Figure 3 illustrates sequential temperature contours. Note that dimensionless time and grid size are used. Figure 4 illustrates the effect of irregular enclosure dimensions on the temperature parameters.[34]

In addition to the fire growth aspect, Baum has addressed the smoke transport aspect in field modeling.[34] Figure 5 illustrates sequential tracking of smoke particles using the same dimensionless time and grid size as in Figure 3. Idealized smoke particles (assumed to be of homogeneous size) are tracked as they rise from the fire plume to the ceiling of the enclosure.

One can see that the potential application of field modeling is better understanding of the fire growth, fire plume, smoke transport, etc. Indeed, once the response function of a detector becomes known, then the criteria for determining smoke detection can be added to field modeling.

Field models provide insights of the dynamics of fire behavior which assist in the design of zone models. Zone models can be viewed as a predictive applied engineering tool, while field models are a basic predictive scientific instrument.[39]

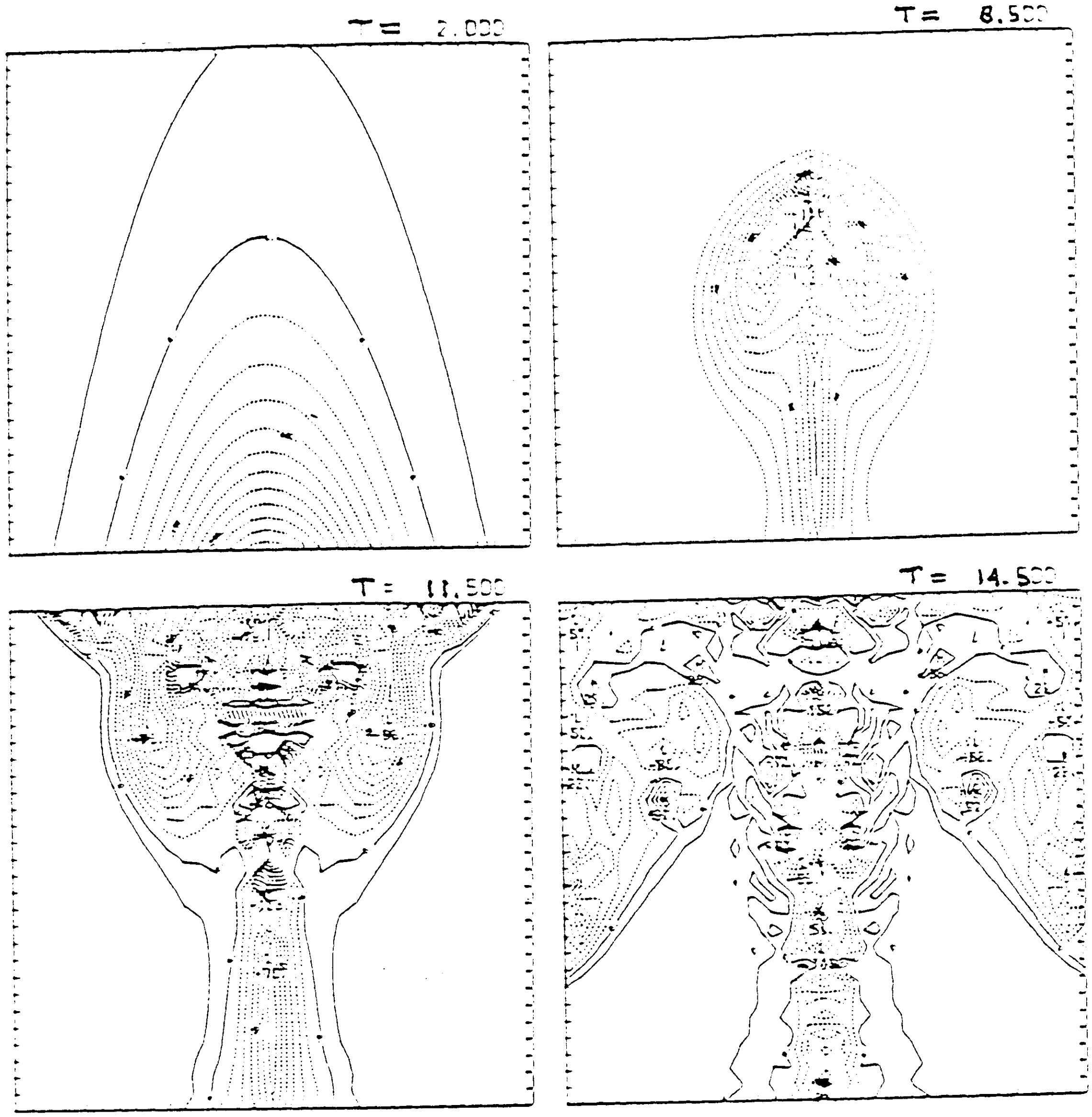


Figure 3. Sequential Temperature Contours for a Two-Dimensional Field Model

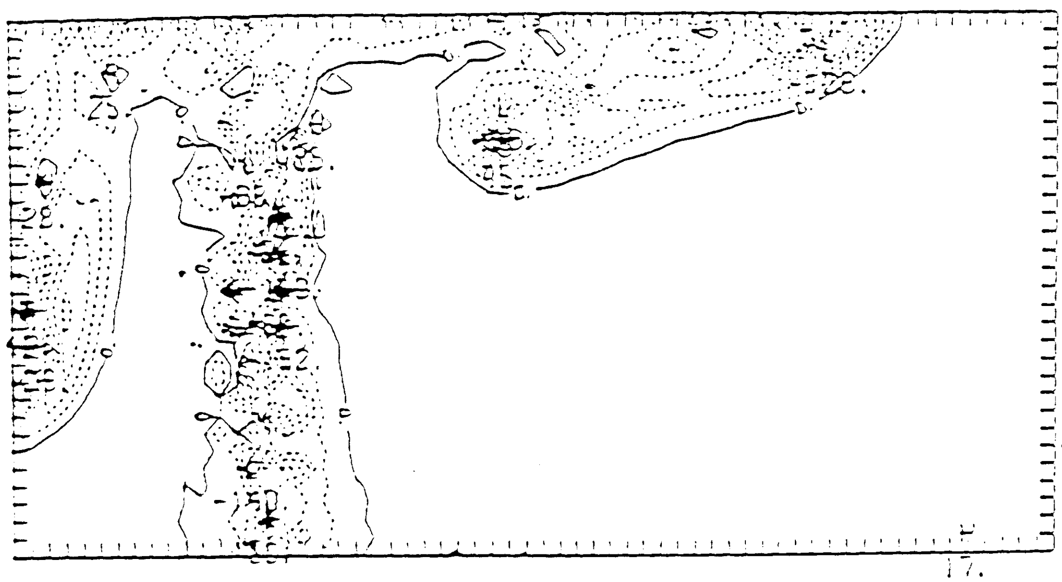


Figure 4. Effect of Irregular Enclosure Dimensions on Temperature

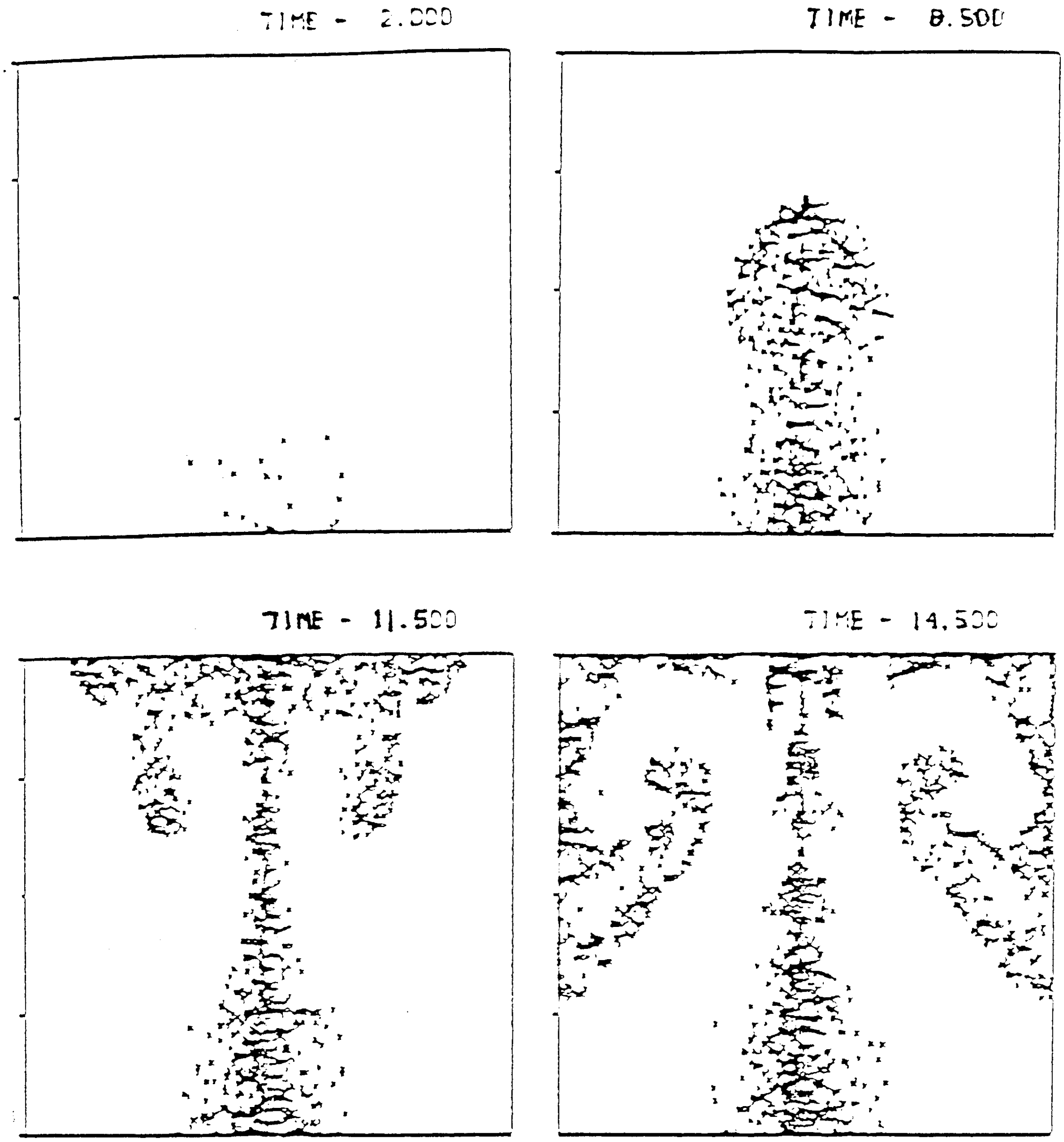


Figure 5. Sequential Tracking of Smoke Particles for a Two-Dimensional Field Model

1.2.2.2.2 Zone Models

Zone or control volume modeling takes the "macro" approach to the fire safety problem. A fire in an enclosure is characterized by two or more control volumes (zones) and a neutral plane demarkating the two zones. The upper zone is viewed as the hot zone, the lower is the cool one.[40] Figure 6 illustrates the above statements. Either algebraic or differential equations expressing the conservation of mass, momentum, and energy are used in zone modeling. Since zone models focus on indoor fires, vents or openings, to either the outdoors or to another enclosure(s), are either assumed or prescribed. Hence, smoke flow is a necessity to respect the conservation equations requirements because deflagrations are excluded. Both single and multicompartment fires are within the scope of zone modeling due to the relative simplicity of formulation.[41,42,43,44]

Due to the "macro" approach of the room fire problem, zone modeling recognizes two control volumes in which distinctive fire phenomena occur. These phenomena constitute the development and growth fire process. This calls for the assumption that a fuel is located in an enclosure, of reasonable geometrical ratios, and is ignited. Assuming a flaming fire, air is drawn to induce a heated rising plume. Soon, a hot gas layer starts forming at the ceiling, which in turn radiates heat back to fire bed. Depend-

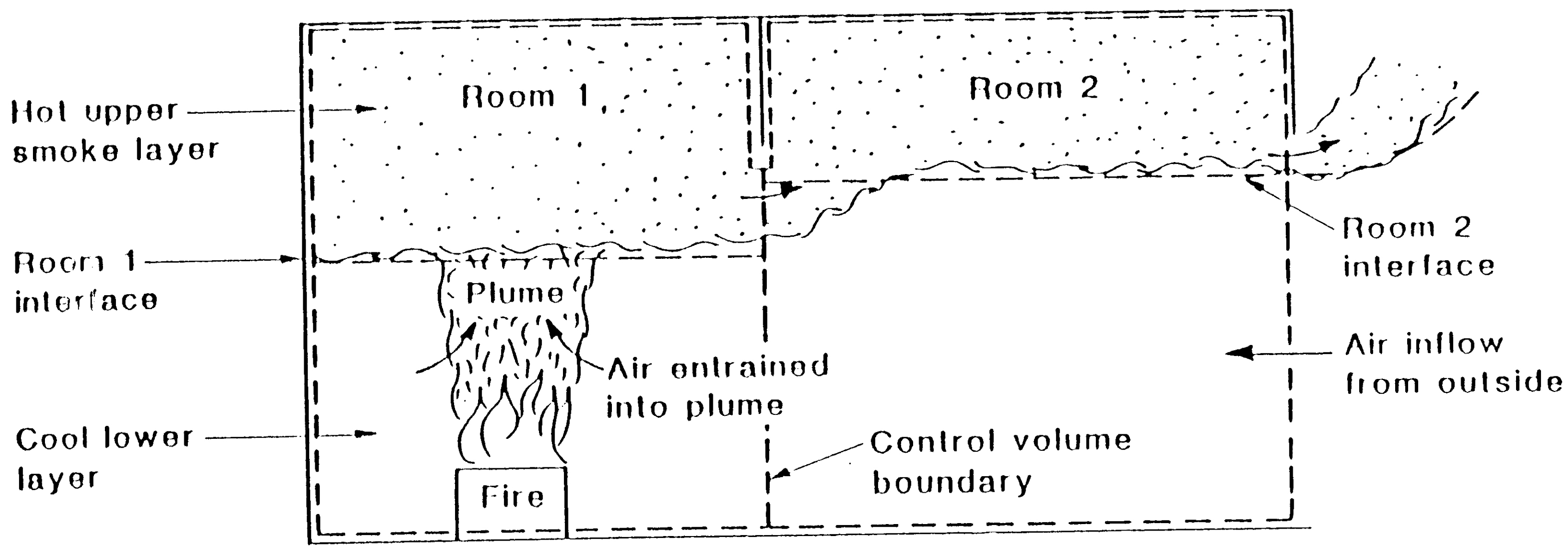


Figure 6. Schematic of Upper and Lower Control Volumes for a Zone Model

ing on the nature of the fuel, which plays an important role in the incompleteness of the combustion, the hot upper gas layer deepens and becomes visibly smoky. The existence of openings (doors, windows, etc.) will provoke the hot upper layer to flow out of the enclosure of origin. Meanwhile the upper layer was forming and impinging against the ceiling, a cool lower layer (largely unpolluted) shrinking in size, and constitutes the second control volume.[45,46,47,48]

One would realize that this is not a static phenomena but rather a highly dynamic one. In an attempt to reach equilibrium of the different interacting control volumes, an exchange of gases among the different zones takes place. A time dependent set of flow interchange equations, expressing the flow of hot gases from the enclosure of origin and the corresponding flow of "fresh" air into the enclosure, characterizes zone models.

Indeed, for a given enclosure there is a set of three equations in which four unknowns are identified. The first equation expresses the timely conservation of mass in which the first unknown is the mass of gas(es). The second equation describes the conservation of energy and from the first law of thermodynamics in which the temperature and gas volume are the unknowns. Finally, the third and last equation is the equation of state, which assumes the presence of an ideal gas, and contains the fourth unknown, the ambient pressure. The number of equations and their respective unknowns increase geometrically with the consideration of the number of zones, their interface, and the number of vents for each enclosure.[49]

In the late fifties, it was first recognized the instrumental relationship existing between both the fire and geometry of the events and the air flowing to and out of the enclosure. Indeed, the heated air in an enclosure rises while the ambient pressure decreases with height. Furthermore, as temperature in the enclosure increases, the thickness of the upper layer increases and the flow through vents increases also. This phenomena is accentuated with the nature of fire, fire plume, and the nature of the enclosure's boundaries.[45,46]

Fuel package(s) are assumed to be ignited or sustaining ignition. Yet for most models, they need to be specified as a type of fire or as a specified fuel and its respective burning rate. The above need for specification is relevant for the consideration of the interaction of the fire source with its environment. Indeed, whenever there is an energy source such as a fire, there are always thermophenomena such as radiation, convection and conduction, as Figure 7 illustrates. It turns out that the latter phenomenon plays little in the role of heat transfer process; hence, only radiation and convection are considered in zone modeling.

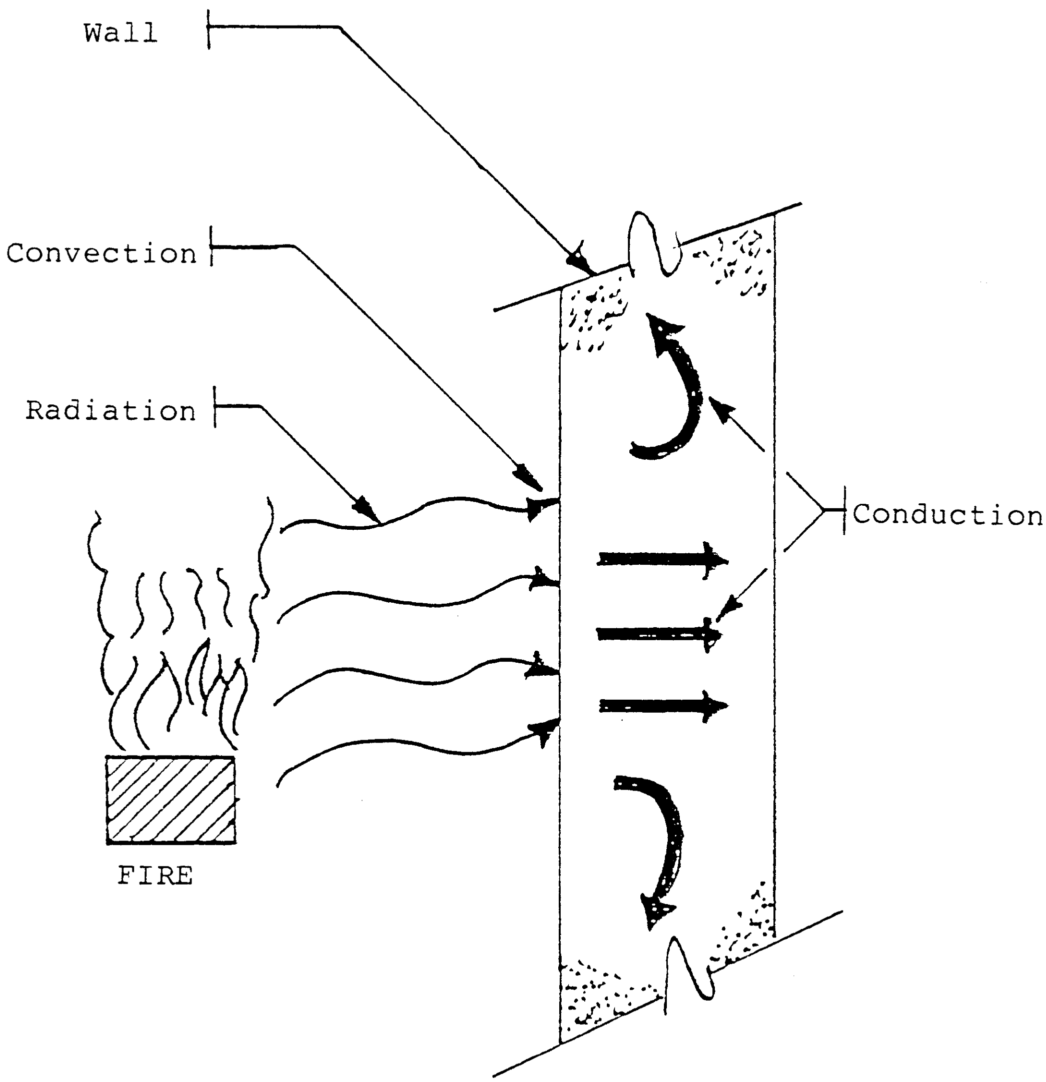


Figure 7. Radiation, Convection and Conduction Effects

The energy impact of these two factors are dependent on the geometrical characteristics of the enclosure and the nature of the fuel packages. In zone modeling, three types of fires have been utilized. These are gas burner fires, pool fires, and growing fires. The first type, the gas burner fire, is characterized by a fixed area fire, by a fixed burning rate, and by a known chemical composition. The second type, the pool fire, is identified by its fixed size and by a variable burning rate which depends on the fuel energy balance. The last type, the growing fire, which is the most complex, is one that requires a number of assumptions in order to simulate it. It requires an assumed circular fuel that increases in size due to heat flux to fuel surface as time progresses. As in pool fires, the burning rate for a growing fire is also dependent on the fuel surface heat balance.[50,51,52]

One very attractive predictive feature of most zone models is the relative concentrations of various toxic gases. In essence, only oxygen and carbon dioxide gases have been predicted with a satisfactory level of confidence. Carbon monoxide, on the other hand, has been difficult to predict accurately due primarily to the lack of full understanding of its production.[53]

Zone models address single compartments, multi-compartments, and multi-story fires.[41,46,49] In spite of the differences in scope of application, all zone models consider at least two control volumes in addition to basic conservation equations and interaction equations. They are all intended to be modular in scope and in application. It has been reported that some of them have been used as a tool to "reconstruct" hostile fires as part of an investigation process.[33,54,55] Zone models are relatively simple to use and most of the computational challenges have been overcome. Yet, because of the inherent lack of accuracy induced by necessary assumptions used to specify the type of fire, the number, size, and behavior of zones, etc., zone models need to be utilized with great caution.

Most users exercise fire models to assist them in predicting real life situations. Most of these situations involve hostile fires from which concerns for human lives, materials, and equipment exist. Hence, the stakes in attempting to investigate fire scenarios can be high. Therefore, providing guidelines and warnings to users when exercising fire models becomes important.[56,57]

In addition to sensitivity of input parameters information, disclosure of the relative comparison of experimental data to corresponding fire model output is also of paramount importance. This second need was achieved through a performance validation process.

1.3 Requirements of Fire Models Validation

As used in this document, "model validation" is the process of determining how appropriate a model is for possible use. In order to minimize biased model validation, the exercise is performed by an intellectually independent third party team. It has been reported that model evaluation and its need is increasing.[58] Much of the work reported in the literature is qualitative. Therefore, only directives on validation procedures were formulated. Gass believes that as long as models are used to either make public policy or engineering design decisions, there will be a need for evaluation.[59]

Five major components are commonly encountered in proposed model evaluation approaches.[56,57,58,60,61]

A. Documentation. This is an explanation of fundamentals on which the model is based. It also includes full nomenclatures of variables used in the computer code. The process of documenting a model requires the modeler(s) to provide information that would allow users to evaluate its capabilities and limitations. Documentation is intended to provide critical information about the model; without it the model would be perceived as a "black-box".

B. Verification. This process is composed of two parts. One part requires determination of the appropriateness of relationships describing the physics of the model, as well as the accuracy of the mathematical calculations. The other part is the numerics the model uses. The reader should realize that without sufficient documentation, the verification process would be limited or impossible. Verification is designed to check model structures, consistency and accuracy.

C. Performance Validation. This is the process of comparing model predictions against experimental data. Performance validation contributes to the unveiling of relative errors in prediction.

D. Sensitivity Study. This is the process of imposing changes on input parameters while observing model response(s). Sensitivity analysis not only benefits users, but it can also benefit modelers.

E. Usability. This is the process of establishing potential model users and their technical ability to use them. It also consists of determining the applications for which the model is best suited.

This report emphasizes model validation in the broader sense of the term. It simply implies that the fifth component of the evaluation process was omitted. Therefore, it is inferred that a validation process is comprised of a minimum of four components; namely documentation, verification, sensitivity analysis, and performance validation. Due to insufficient documentation of the model, the investigator conducted only limited and unstructured verification of the model.

2. GENERAL SCOPE

Constrained by the above limitation, two generic methodologies for sensitivity analyses and performance validation process for zone models have been applied. Reasonable background of the two methodologies preceded illustrations of the respective techniques used to arrive at functional formats.

Section 3 presents the process of performing a sensitivity analysis on a deterministic fire model. Results, as well as major difficulties encountered, are included in this section. In Section 4, performance validation is presented. It includes fire model simulations and graphical results of test statistics. It also illustrates graphical comparisons of the data to a sample model output.

A summary of general conclusions and recommendations from both sensitivity analysis and performance validation are presented in Section 5.

Only incidental and limited verification process was performed on the fire model FAST[45] due to the model's inadequate documentation. Most inferences stated are based on the users point of view as well as limited full understanding of physics/numerics of the fire model. Therefore, the model was assessed as a "semi-black box".

3. PARAMETRIC SENSITIVITY ANALYSIS

3.1 Introduction

In situations where either safety or unreasonable expenditures, or both, are of concern, when assessing the sensitivity of a mathematical model, an alternative methodology is called for to answer the "what if" questions.[62] Indeed, the sensitivity analysis probes the effect of change in input parameters on the response of the model. Since there is no practical analytical solution, investigations are possible only through computer experiments. This process is also known as computer simulation process.[63,64,65]

The expected benefits of the suggested analysis are three-fold.

A. Warning the user(s) of the model about the required care to be taken when exercising the model,

B. Raising questions about the model's "building blocks", and

C. Providing directives to which parameters should be closely monitored during full-scale fire experiments.

Whenever a mathematical model is built, it is "common" to investigate the model's sensitivity. This is true for either a deterministic or a stochastic model. A widely accepted statistical methodology is known as a (full) factorial experiment.

However, one of the limitations with full factorial designs is the rapid increase (geometrical) of measurements with the number of factors (input parameters or independent variables) considered. This drives the analysis to a prohibitive requirement of time and effort. The large number of required measurements in a full factorial can be reduced to a reasonable number of measurements utilizing the methodology of a fractional factorial, also known as a fractional replicates.

The alternative solution, a fractional factorial analysis, is acceptable by virtue of an intrinsic characteristic of factorial design, known as "confounding". Indeed, as the terminology implies, a number of experimental situations (treatments) are redundant, that is they are confounded with other treatments. For an in-depth understanding and appreciation of fractional factorial designs, the reader(s) should consult the works of Box-Hunter and Hunter, Davies, and Daniel.[62,66,67]

Most factorial analyses include interactions (groups) of factors of interest. It is a way of looking at the possible effect of a group acting in a synergetic way.

It is generally agreed the fact that interactions (contributions) involving higher order interactions can be neglected because of:

A. Lack of physical meaning of the interaction(s), and/or

B. The difficulty of interpretation of the results.

Fractional factorial methodology seems to be adequate to obtain information on the main effects and as many of the interactions as appear necessary and meaningful. Hence, third or higher order interactions are rarely considered.

In this particular study, the number of factors selected for analysis has been limited to 16. Their selection was aided by the investigator (relative familiarity) of the problem of fire behavior in multi- compartments as well as an overall knowledge of the model's operations, requirements, and constraints.

The specific design utilized is composed of 16 factors with 1/256th replication requiring 256 measurements or computer runs. A full factorial experiment for 16 factors would have required 2^{16} or 65,536 replicates of runs, while this specific design reduces the total number of computer runs to only 256. Hence, one could notice that fractional factorial design leads to saving 65,280 computer runs.

The fractional factorial designs at two levels imply that each of the selected factors has been allowed to embrace either one of two chosen values, that is a low or high level value. These two levels have been selected with the rationale that they would represent two different scenarios. A complete description of the selected factors can be found in the next section.

A prescribed partial plan, portraying the synchronized levels for the 16 factors, has been extracted from the literature[68] and a portion of it is shown in Appendix A. The partial plan considers blocking which is not relevant in this type of experimentation. Therefore, the plan has been viewed as a string of 256 independent observations.

It is important to note that discussed sensitivity analysis is for unreplicated fractional factorial since the model to be investigated is a deterministic one. Therefore, no variations in output can be obtained from two identical runs. This implies that there is no value representing the common standard error. However, one could provide such an estimate if certain assumptions are made. In particular, if most or all higher order interactions would measure differences emanating from experimental error, one could provide an appropriate reference measure for the remaining effects.

3.2 Experimental Design

The model to be investigated requires a large number of input parameters. After careful consideration of possible influences some parameters have on the outputs of the model, 16 have been selected for statistical analysis. For each factor (input parameter) two levels were chosen to depict forecasted extreme, yet physically possible situations. The selected 16 parameters are external as opposed to being internal to the model. External parameters are those which the model's user can easily manipulate as inputs.

Internal parameters are those with which the model demands appreciable familiarity of its structure. Indeed the study of internal parameters could provide an insight on how well the physics the model utilizes reflects fire behavior. This research aspect could be the focus of another sensitivity analysis of the model's structure. This would be achieved by manipulating internal parameters while holding external parameters constant and proceeding with the sensitivity analysis methodology.

External parameters can be grouped into three categories;

A. Geometrical Data,

B. Fire Specifications, and

C. Thermophysical Properties.

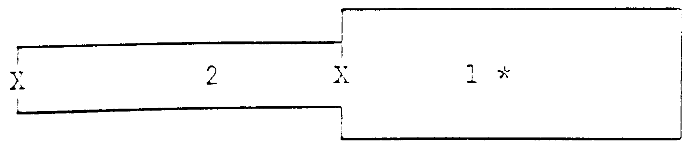
The first category, geometrical data, describes the enclosures or compartments basic physical dimensions as well as vents or openings connecting adjacent enclosures. Compartment dimensions include widths, heights, and depths. Vents are described by their widths, heights, and sills. Only the case where one vent connecting two compartments has been considered. The mentioned dimensions for the "low" and "high" level have been chosen in such a way that the surface area and the enclosure's volume doubles, respectively, as shown in Table 1. The low level values for the compartment geometries have been selected with an attempt to describe a compromising typical "hotel/motel" room. The high level values seem to describe remote yet possible room geometry. The author likes to remind the readers that those high/low values reflect some realism, yet they seem to embrace some extremism. Note that the high level values are simply twice the low level values, respectively.

Also, potential users of the model should note that the model is insensitive, by design, to the lateral location of vents; it only recognizes the vertical location. In other words, the model will not acknowledge whether a vent is located in a compartment's corner or in the middle of one of its walls.

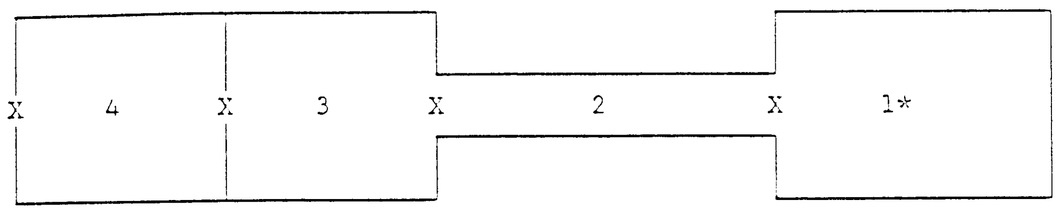
Figure 8 illustrates a schematic floor plan view of the multi-compartment scenarios. On the same figure a schematic shows how vent's dimensions are described to the model.

Table 1. Experimental Parameters

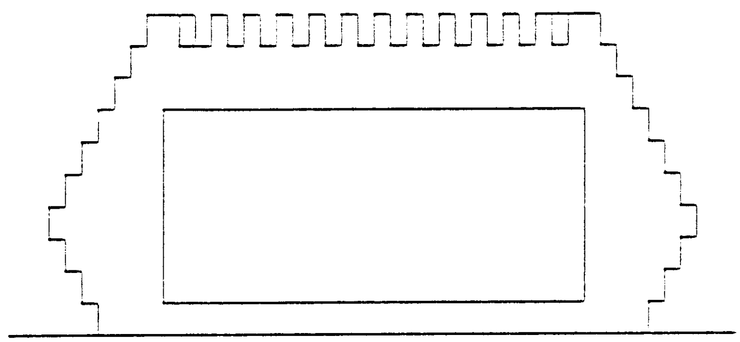
CODE	NAME	VALUE LOW	VALUE HIGH
	Geometrical Data		
A	Compartment Width (m)	3.5	7.0
B	Compartment Depth (m)	4.0	8.0
C	Compartment Height (m)	2.5	5.0
D	Number of Compartments	2	4
E	Vent Width (m)	1.0	2.0
F	Vent Height (m)	1.5	2.5
G	Vent Sills (m)	0.0	1.0
	Fire Specifications		
H	Heat of Combustion (KJ/kg)	25,000	50,000
J	Fuel Mass Rate (Kg/s)	0.002	0.004
K	Fire Position	Center	Corner
L	Ambient Temperature (K)	273	330
	Thermophysical Properties		
M	Conductivity (KW/mK)	$0.18 x 10^{-3}$	$5 x 10^{-3}$
N	Specific Heat (kJ/kgK)	0.9	1.9
O	Density (kg/m^3)	790	2200
P	Emissivity	0.3	0.9
S	Thermal Properties (Walls/Ceilings/Floors)	Existent	Nonexistent



8-a. Two-Room Scenario



8.b. Four-Room Scenario



8.c Vent-Room Scenario

where:
X symbolizes a vent connecting 2 adjacent compartments
* symbolizes fire compartment location

Figure 8. Schematic Floor Plan View of Multi-Compartment Scenarios

The rationale behind the two-room and four-room scenario is the simulation of a partially simplified architectural layout of a hotel/motel arrangement. The two-room scenario (Figure 8-a) represents a single room connected to a corridor, while the four-room scenario (Figure 8-b) represents a room (numbered one) and a suite (numbered three and four) both connected to a corridor (numbered two). One may note that in Figures 8-a and 8-b the corridor location is different from what one may usually find in hotel/motel settings. There are two reasons for that discrepancy. First, the model has no capability in differentiating the corridor location in relationship to the enclosure's location. It only requires that different rooms be connected by vents. Second, Figures 8-a and 8-b, as shown, have been drawn for sake of clarity.

The second category, fire specifications, is composed of the heat of combustion and the fuel mass rate as shown in Table 1. Arbitrarily, 25MJ/kg and 50MJ/kg have been selected for the low and high level values, respectively. It was assumed a constant fuel mass loss rate as opposed to an increasing mass loss rate up to a peak followed by a symmetrical decrease. In other words, the hypothetical situation simply means that the structure will not run out of fire energy. Obviously, this situation is not only unrealistic, but also extreme; yet the advantage from it seems that one could uncover some anomalies by "pushing" the model beyond its limits. Also, the ambient temperature parameter has been included in the study and has been allowed to vary from a very cold day to a hot one.

The third category, thermophysical properties, is composed of the thermophysical of the compartments' interior boundaries, such as conductivity, specific heat, density, and the emissivity of walls, floors, and ceilings. An extreme situation has also been included, which is the perception of no heat loss through the compartment's boundaries. It is a situation similar to considering the compartment as a "thermos" bottle.

3.3 Methodology

Because of the relatively large number of computer runs required (256), it seemed necessary to develop a scheme aiding the investigator not only to minimize input error, but also to increase the overall efficiency of the study. In this respect the following was achieved:

A. A computer code providing the essence of fractional factorial for two-level 16 factors encompassing 256 experiments was created. The output of this code was named "ZEROS" and a sample can be found in Appendix B.

B. A computer code capitalizing on the output of the above code "ZEROS" to generate the corresponding 256 input files readily acceptable to the source code (the model) was completed. A sample of it is illustrated in Appendix C.

C. It was decided that among the numerous output strings of information, two variables would be most useful in assessing the model's behavior. These are the upper layer temperature and the upper smoke layer. It was, therefore, necessary to manipulate the output format in the source code in order to obtain a compact output format describing fire behavior. This process was important to achieve because of the constraints the computing hardware was imposing. Over 9,400 records of output were expected, and that would constitute a large file; which is not desirable. This new format was designed to provide upper layer temperature and smoke layer every ten seconds of the total 360 seconds simulation time in each compartment. A sample of a typical format (for a four compartment scenario) can be found in Appendix D.

D. A computer code was created to determine the sensitivity coefficients for each of the 16 factors. This task was necessary since there is no commercial statistical software package capable of processing a fractional factorial experiment with 16 factors. The section entitled "Difficulties Encountered" reveals more details on this challenge.

Each of the four above tasks is discussed in the remainder of this methodology section. Some of the information used or deduced originated from extensive literature and the reader(s) will be directed to the original documentation, as necessary. However, it was attempted to provide as much information as possible to keep readers not only interested, but also aware of the pitfalls the investigator encountered.

Most reasonably, after deciding that only a fractional factorial is feasible and informative to perform sensitivity analysis on a complex deterministic model, the next step, leading to the first task, is to design a plan to do it.

Indeed, a fragmented plan was luckily located in the literature search.[68] This plan provided the combination of the high and low levels for the 16 factors for the first eight experiments and the first experiment of the rest of the 33 sets composing 248 experiments. Therefore, it was necessary to develop a computer code generating the missing 231 experiments for the 16 factors at two levels each. This code creates an image recognized by most statistically oriented readers as a form of factorial design. In this code the value "1" symbolizes the high value, and the value "0" symbolizes the low value for each factor. The output of this code, termed "ZEROS", can be viewed as a two-dimensional matrix of 16 by 256.

The second task was the development of a computer code which utilizes "ZEROS" to generate output matching exactly the required format the model needs to be exercised. Outputs from this code become input files for the source code. Therefore, 256 input files were produced. These are called RUN001 to RUN256. Because of the large number of runs, it seemed helpful to create an intermediary computer code through which the 256 runs can be submitted to the mainframe computer in a few steps. The intermediary computer code is called "RUNALL". The output of this code is a sequential series of dependent variables tabulated where the first column is the 37 time steps (first time step are the prescribed initial conditions of each run). The second column through the ninth are the dependent variables as they relate to the possible four different compartments. The output of "RUNALL" is called "NEWDATA" and can be perceived as a two-dimensional matrix formed by 9 by 9472.

Finally, task three utilizes matrix "ZEROS" and matrix "NEWDATA" through a computer code, to generate sensitivity coefficients for each of the 16 factors. In Appendix E a brief and simple methodology illustrates how one may obtain sensitivity coefficients or effects of each factor.

3.4 Results

As stated earlier, the goal of the sensitivity analysis is to determine the relative sensitivity of the chosen 16 input parameters for FAST.[45]

Indeed, the results of this section includes plots of the 16 main effects as a function of the simulated time for the respective two dependent variables (upper smoke layer depth and upper layer temperature) which are associated with four possible compartments. Therefore, for each dependent variable and compartment, respectively, one would access information from a total of 64 plots. That total of 64 (16 x 4 = 64) was obtained by plotting the 16 parameters for each of the four compartments.

Relative comparison for practical evaluation of the results is desirable. For example, by being able to view the sensitivity behavior of parameters of interest, one would be capable of comparing and ranking the sensitivity of those parameters. It followed that for each compartment the sensitivity of all 16 parameters are plotted as a function of simulated time on the same graph. Hence, for each of the four compartments, four plots can be found portraying the sensitivity behavior over the simulated time. These plots are illustrated in Figures 9 to 12 and in Figures 13 to 16. Because plots of sensitivity over simulated time are not always very conclusive, it was believed helpful to determine a discrete average sensitivity value for each parameter. That value is simply the arithmetic average of sensitivity coefficients over simulated time. Figures 17 and 18 illustrate averages of sensitivity coefficients over simulated time for each of the 16 parameters. The information one could extract from Figures 17 and 18 is a mean of confirming or questioning behavior of sensitivity for any particular parameter. Whenever the sensitivity of a parameter is pronounced over the simulated time, the average sensitivity is noticeable also.

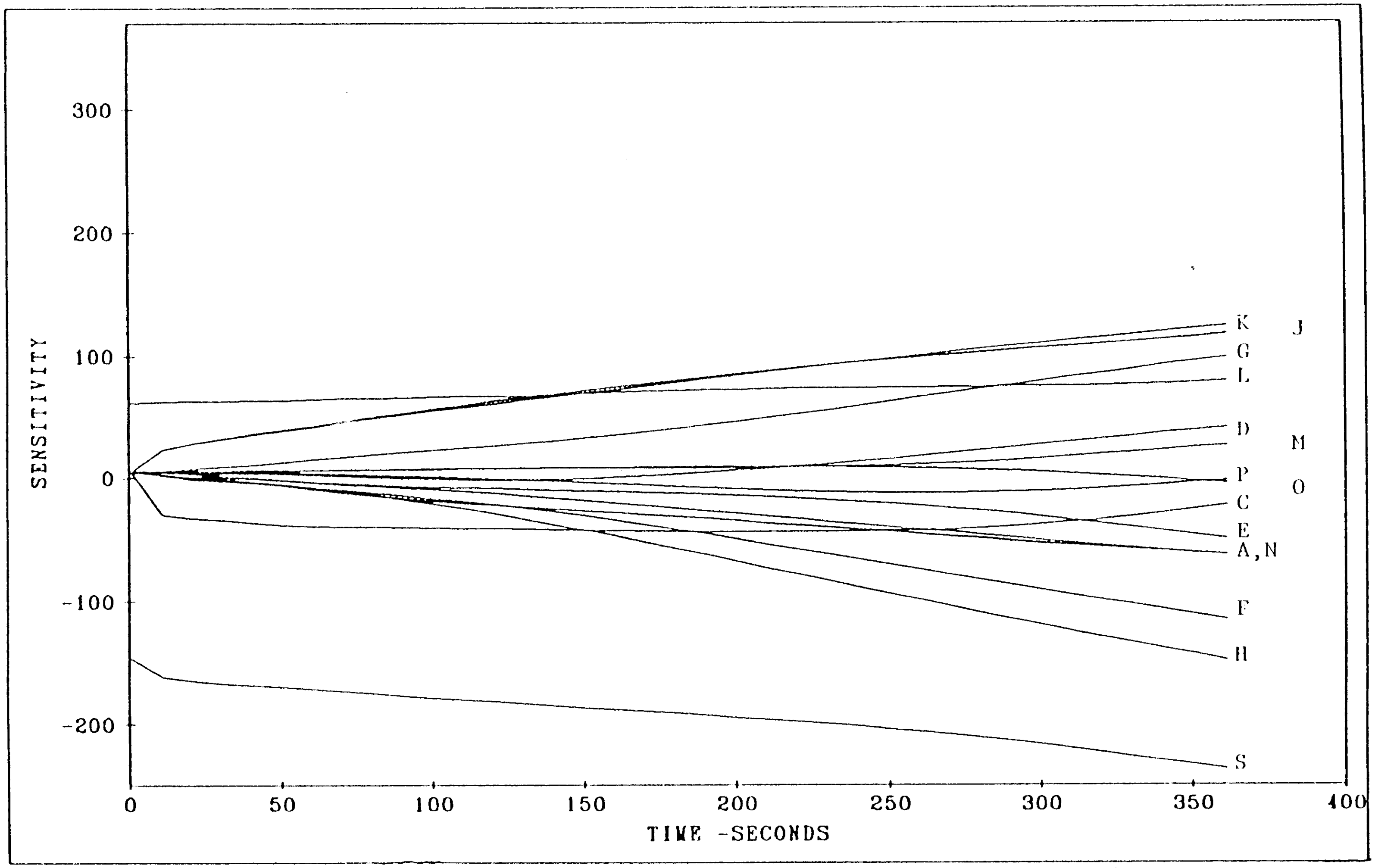


Figure 9. Upper Layer Temperature Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 1

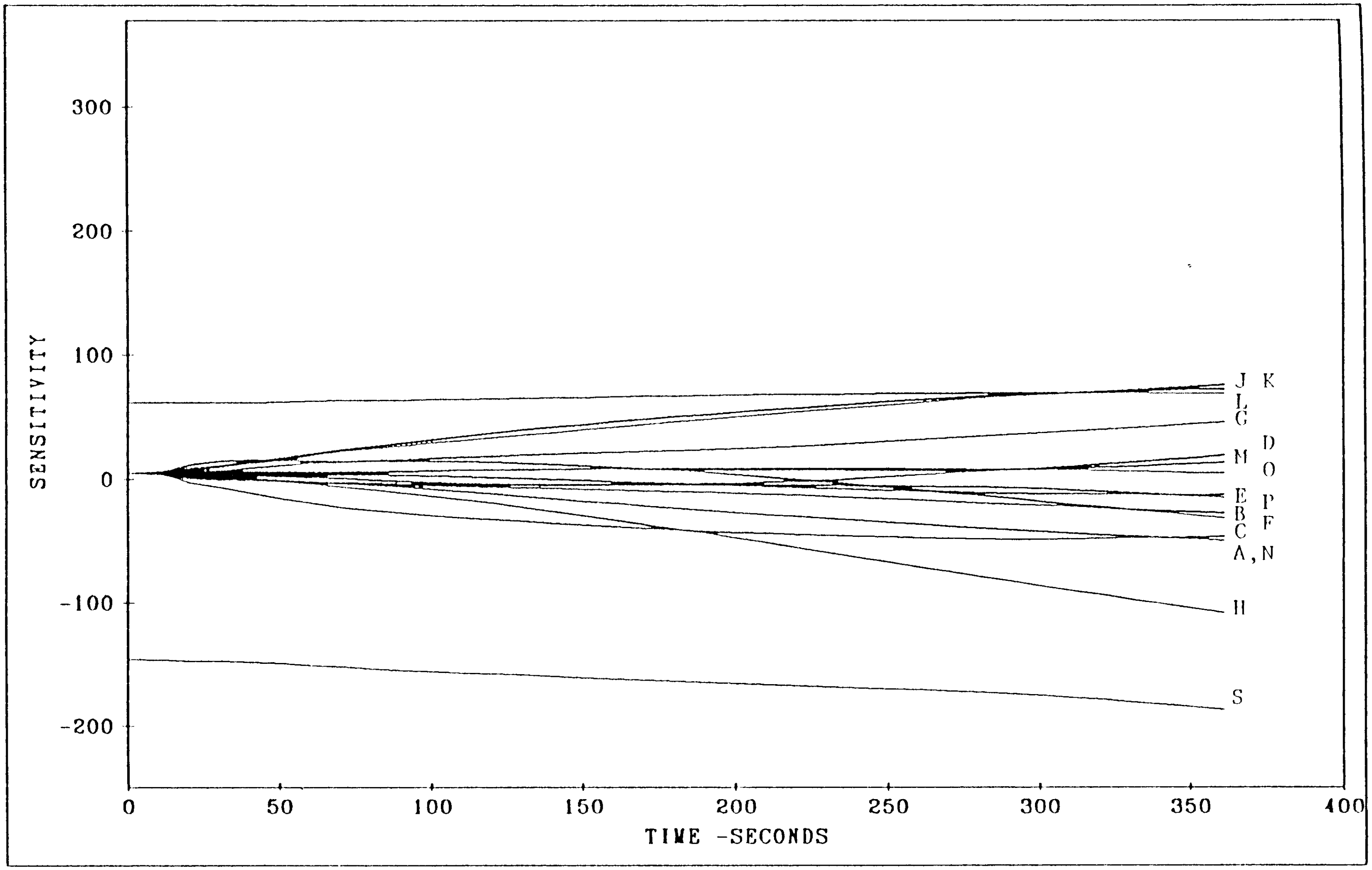


Figure 10. Upper Layer Temperature Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 2

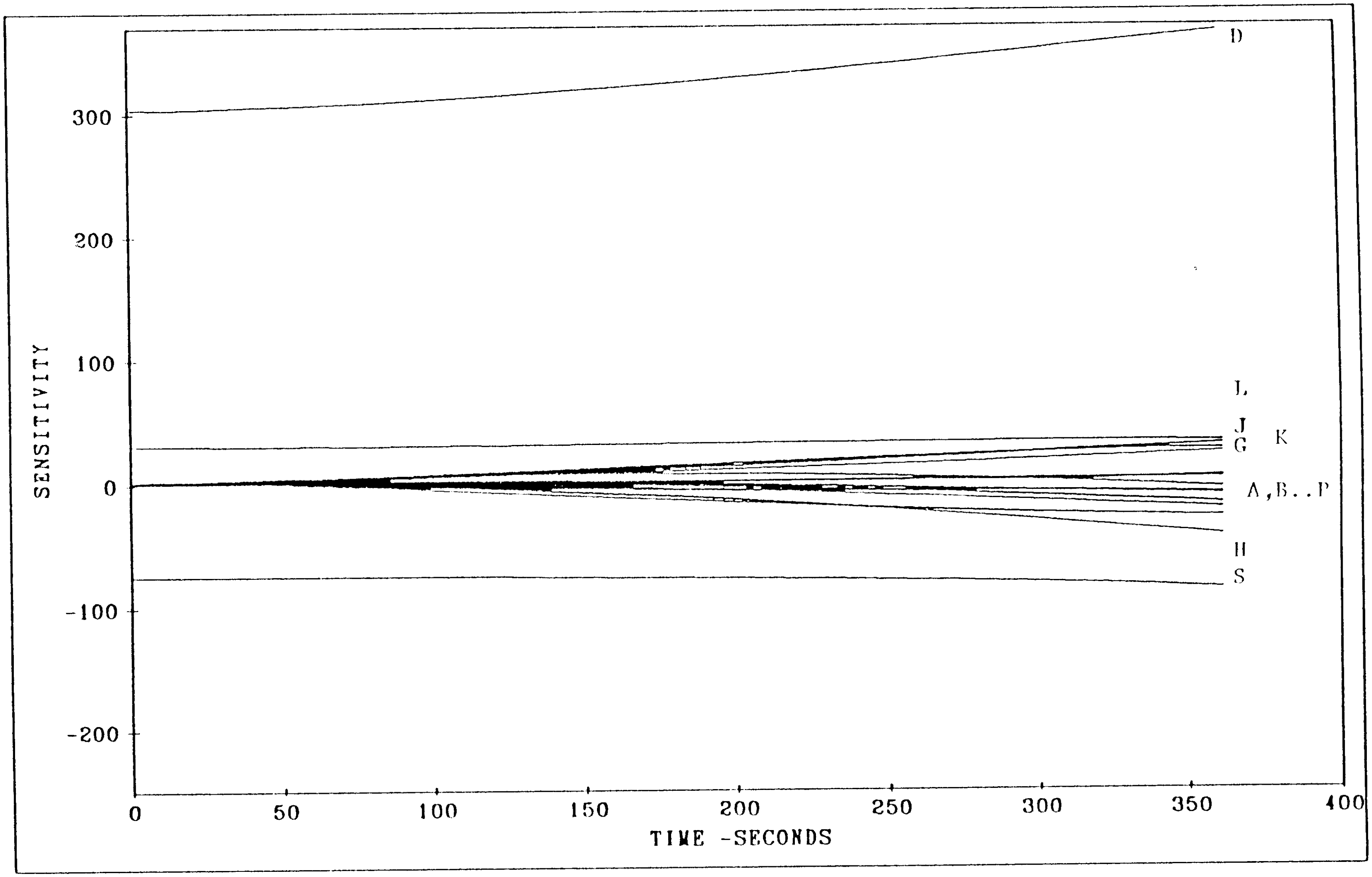


Figure 11. Upper Layer Temperature Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 3

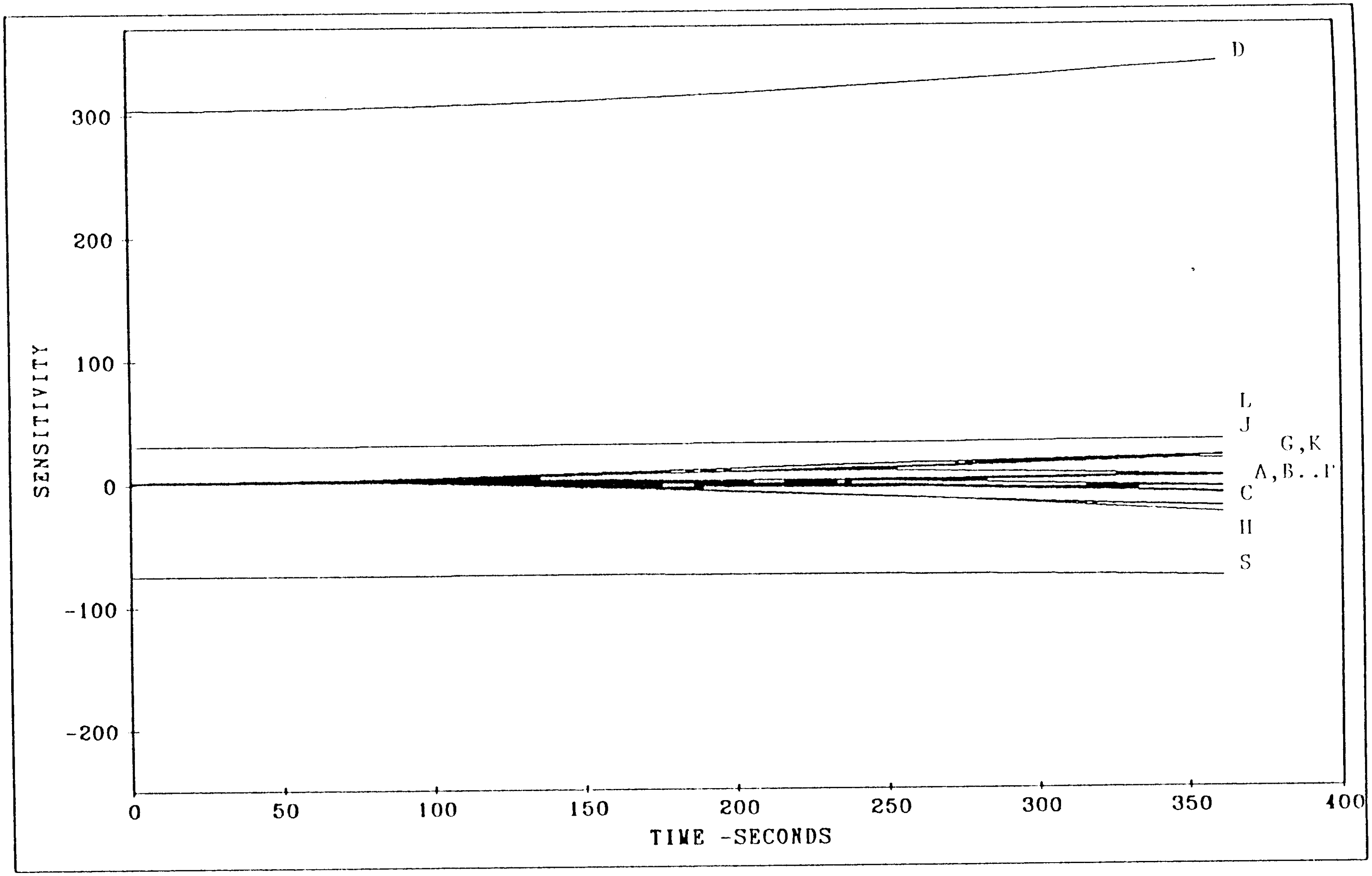


Figure 12. Upper Layer Temperature Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 4

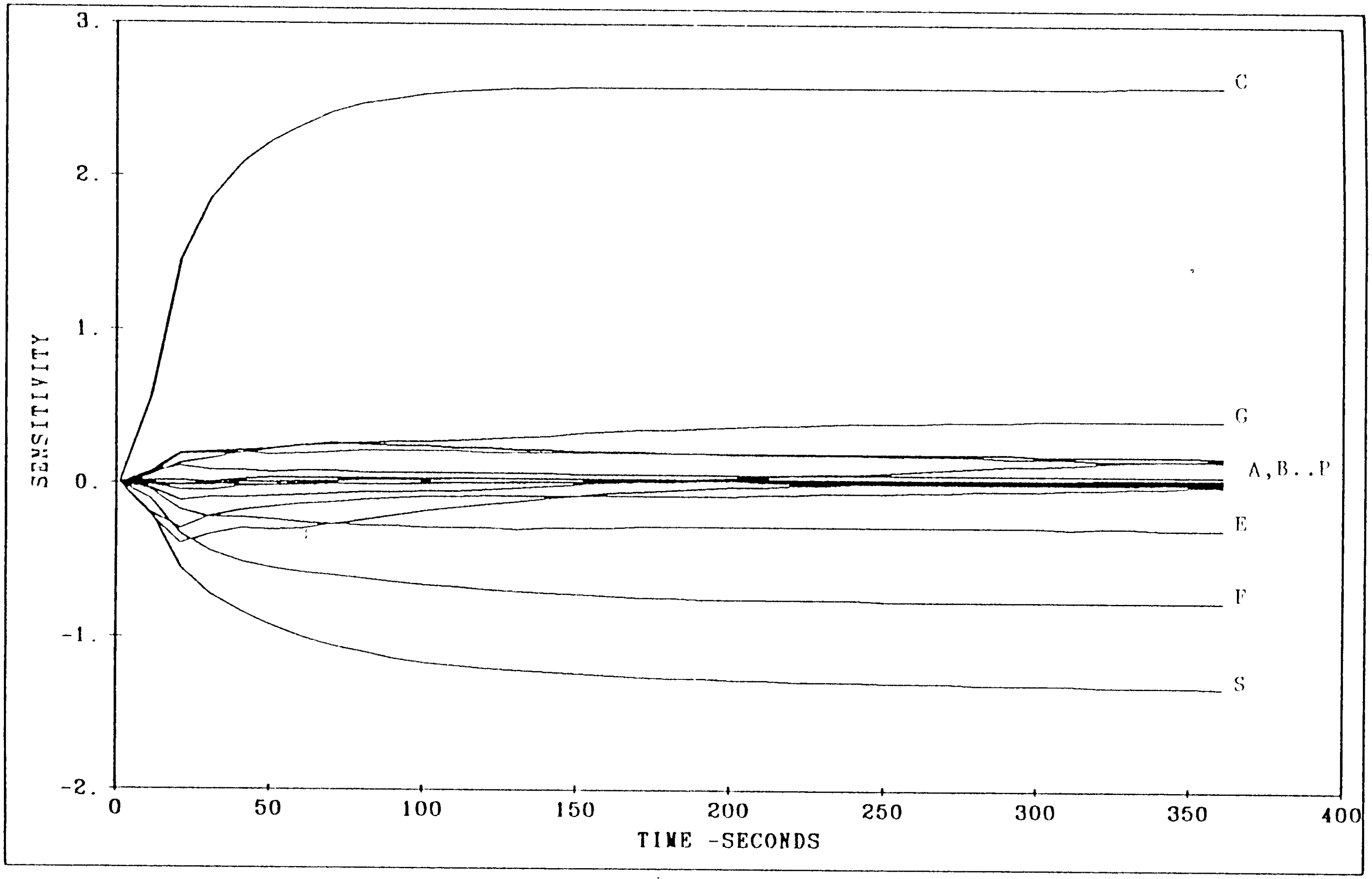


Figure 13. Upper Layer Depth Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 1

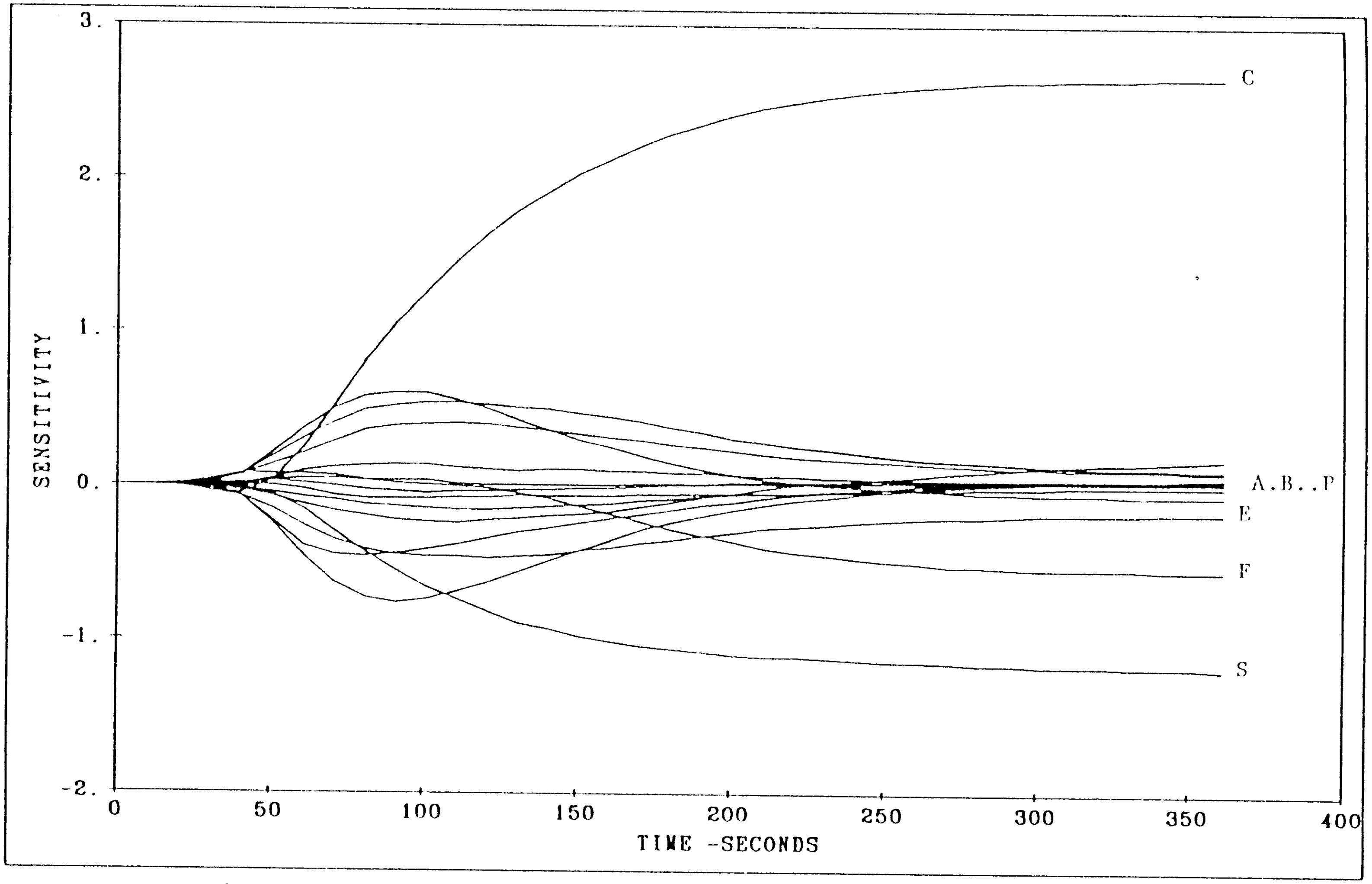


Figure 14. Upper Layer Depth Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 2

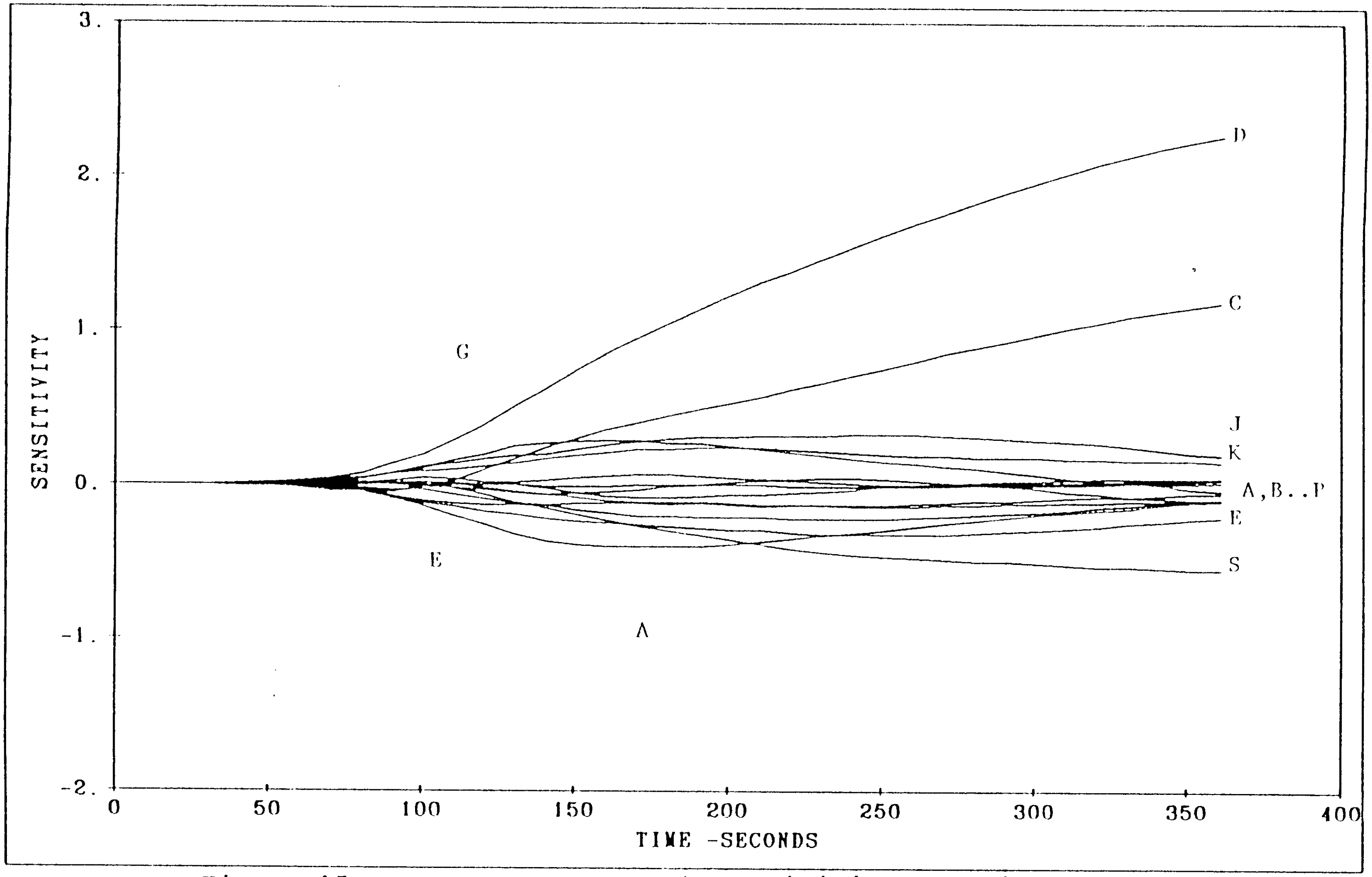


Figure 15. Upper Layer Depth Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 3

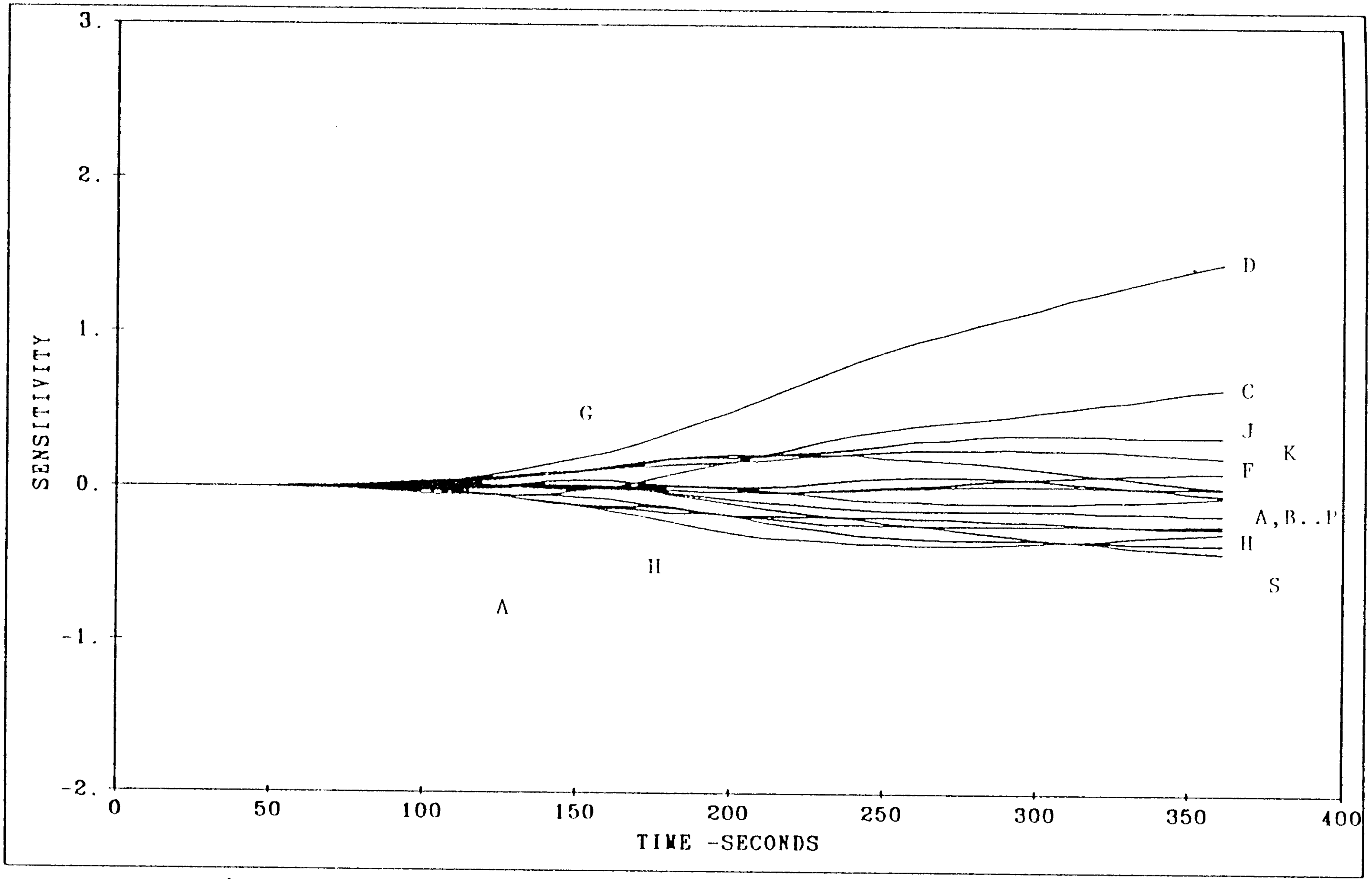


Figure 16. Upper Layer Height Sensitivity Functions of Each Parameter (A, B, C,...S) for Compartment 4

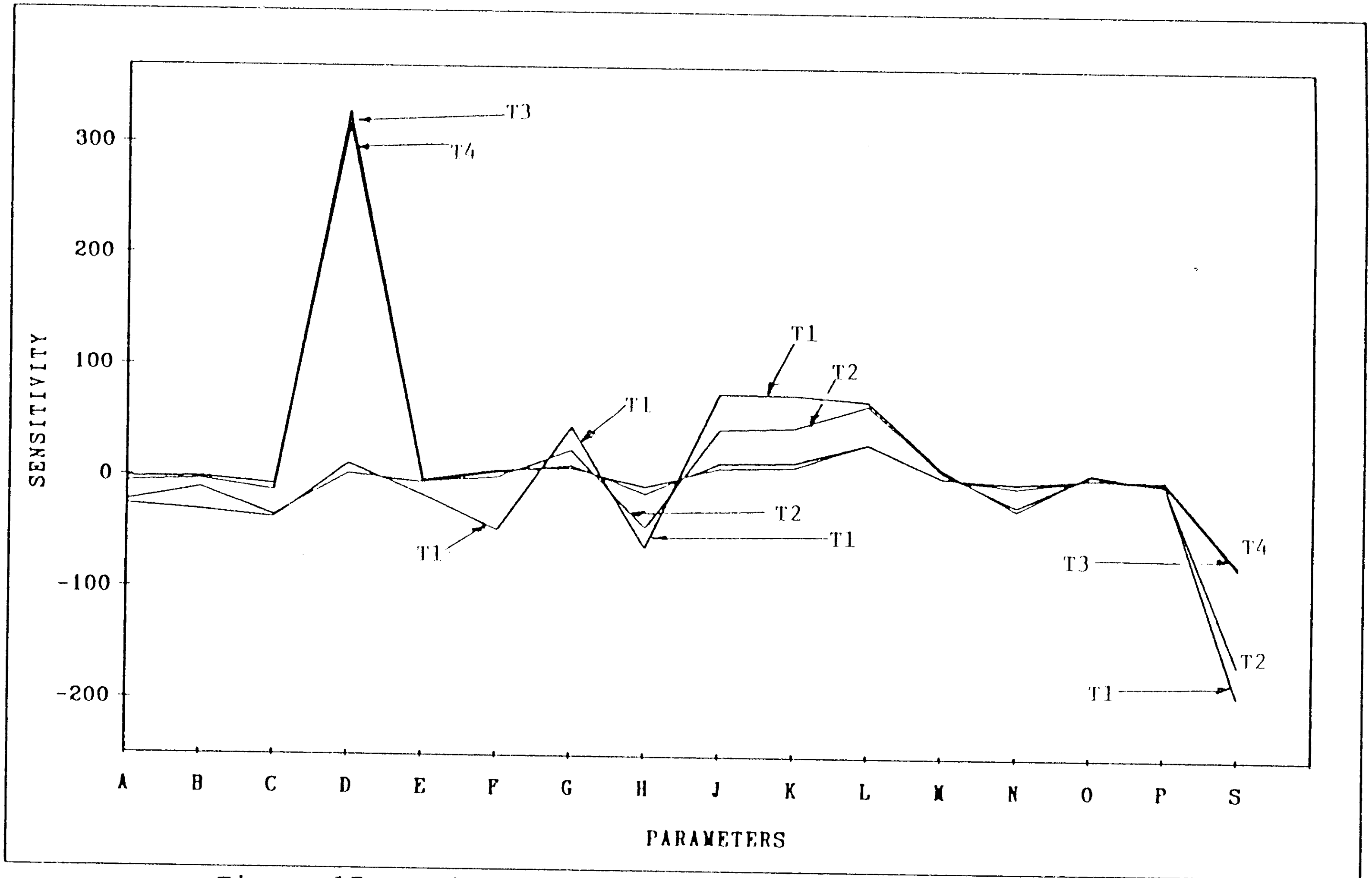


Figure 17. Discrete Upper Layer Temperature for All Compartments (1, 2, 3, and 4) For Each Parameter

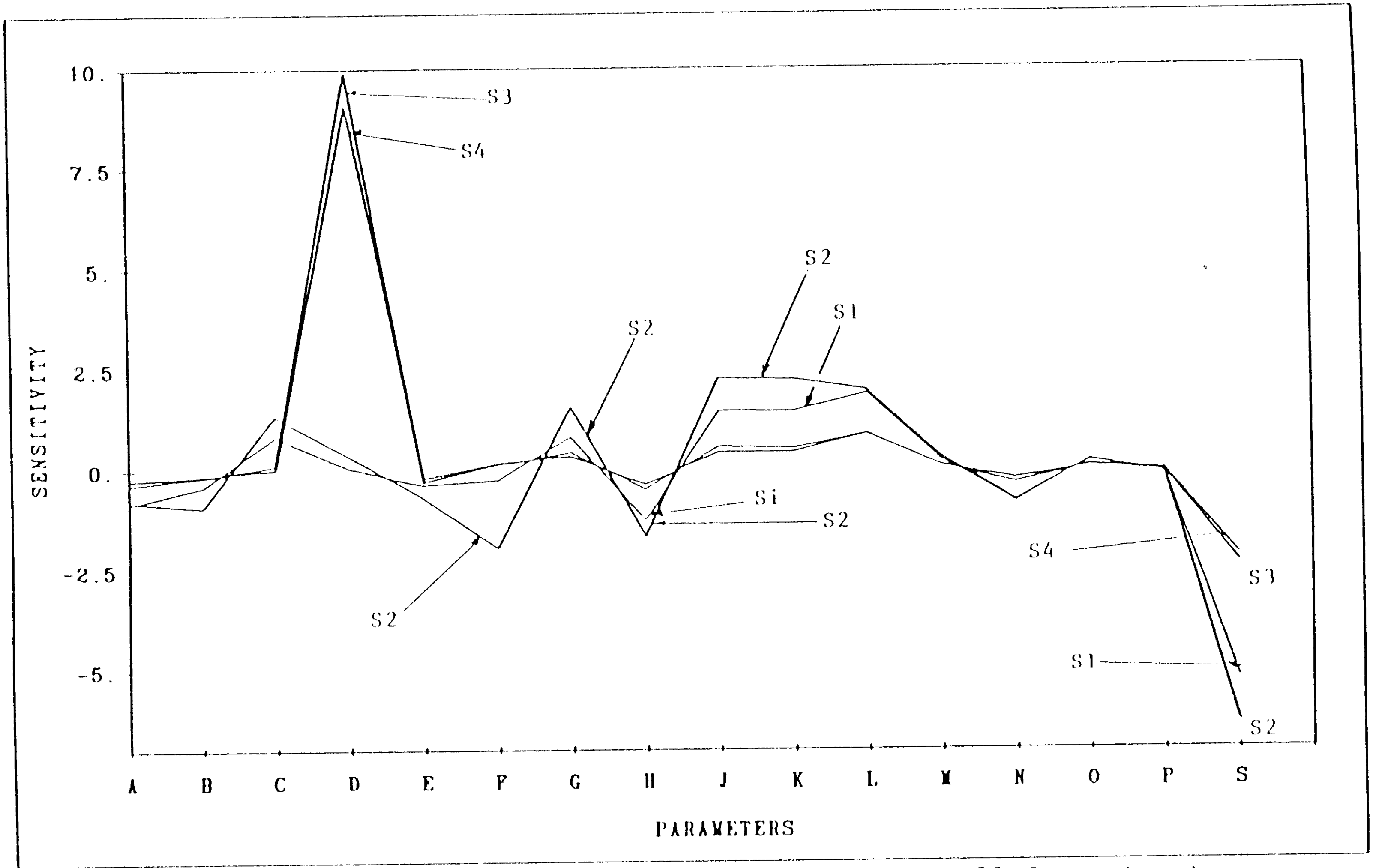


Figure 18. Discrete Upper Layer Depth for All Compartments (1, 2, 3, and 4) for Each Parameter

One would note that the sensitivity behavior of the simulated time, for the upper layer temperature seems to fan out. On the other hand, one would observe the sensitivity coefficient behavior for the upper layer depth seems to exhibit a bulge, which appears to grow and fan out over the simulated time. One may notice that sensitivity coefficients, in general, show similar behavior in compartments one and two. The same remark applies for compartments three and four. The reason for this involves the binary characteristic of factorial design at two-level. Indeed, only two situations are possible. These are situations where a structure has two or four compartments.

3.5 Conclusions

From the plotted results in Figures 13 to 18, a number of critical conclusions could be drawn. By virtue that the sensitivity analysis has been undertaken as a function of two separate, "unrelated" dependent variables, upper layer temperature and upper depth, two parallel sets of conclusions would be expected. The first set is composed of Conclusions 1 and 2; the second set comprises Conclusions 3 and 4. These are the following:

1. General conclusions for the upper layer temperature sensitivity coefficients over the simulated time for the respective four com-

partments,

2. General conclusions for the upper layer depth sensitivity coefficients over the simulated time for the respective four compartments,
3. General conclusions for the average upper layer temperature sensitivity coefficient for each parameter for the respective four compartments, and
4. General conclusions for the average upper layer depth sensitivity coefficient for each parameter for the respective four compartments.

Once the set of conclusions is formulated one would be able to perceive the trend of the sensitivity behavior of each parameter over simulated time. In addition to the preceding effort, one could compare the deduced trend of sensitivity to the averaged sensitivity coefficients. This exercise should either solidify or question concluding sensitivity statements. It is expected that whenever agreement between the first and second general conclusions exists, the confidence in the conclusions is qualitatively increased.

1. General conclusions for the Upper Layer Temperature sensitivity coefficients over the simulated time for the respective four compartments.

Using Figures 9, 10, 11, and 12, one would deduce the following:

a. Parameter S (thermophysical properties existence) appears to be very sensitive throughout the simulation period for all compartments.

b. Parameter L (Ambient Temperature) seems to be considerably sensitive throughout the simulated time but more so in the first two compartments than the last two.

c. Parameters G, H, J, and K (sill height, heat of combustion, fuel mass rate, and fire position) show sensitivity behavior during most of the simulation duration in the first two compartments.

d. Parameter D (number of compartments) seems to be very sensitive for the two last compartments, as would be expected.

One should note that the shape of the sensitivity function of parameters over the simulated time fans out more for the two first compartments than the last two. There is no other apparent peculiarity noticeable from the plots.

2. General conclusions for the Upper Layer Depth of Smoke sensitivity coefficients over the simulated time for the respective four compartments.

Using Figures 13, 14, 15, 16, and 18, one would deduce the following:

a. Parameter D (number of compartment) appears to be very sensitive in the third and fourth compartment.

b. Parameters C, E, F, and S (compartments' height, vent's width and height, and thermo-physical properties existence) seem to be quite sensitive.

c. Parameters J, K, and L (fuel mass rate, fuel position, and ambient temperature) show moderate sensitivity.

One should note the peculiarity of these plots. A noticeable bulge is displayed during the first 50 seconds of the simulated time in the compartment of origin. In the adjacent compartment (second compartment), the bulge grows in size and moves to the range of 50 to 150 seconds of the simulated time. On the third and fourth compartment the bulge is still showing, but it tends to fan out with increasing simulation time. Preceding the bulges is a period of complete insensitivity behavior. These inactivity periods correspond to periods where the fire event is still in the former compartment.

Since the sensitivity of some parameters varied over the simulated time, it would be desirable to support or question the above conclusions. Therefore, parallel to the first and second general conclusions, the following is a set of comparisons of parameters' sensitivity behavior. This comparison exercise emanates from the comparative sensitivity function over the simulated time (Figures 9 to 12 and Figures 13 to 16) and from the discrete sensitivity function of all 16 parameters (Figures 17 and 18).

First, let us state the third and fourth general conclusions.

3. General conclusions for the average upper layer temperature sensitivity coefficient for each parameter, for the respective four compartments. Figure 17, illustrates sensitivity value of each of the 16 parameters for the four compartments, for upper layer temperature.

   Figure 17 seems to infer the following:

   a. Parameter S (thermophysical properties existence) appears to be sensitive for all compartments.

   b. Parameters G, H, J, K, and L (vent sills, heat of combustion, fuel mass rate, fire position, and the ambient temperature) seem to be moderately sensitive for the first two compartments.

   c. As expected, parameter D (number of compartments) is highly sensitive for the two last compartments.

These three conclusions seem to be in agreement with the first general conclusions drawn. Therefore, continuous sensitivity behavior seems to be equivalent to discrete sensitivity behavior.

4. General conclusions for the average upper layer depth sensitivity coefficient for each parameter, for the respective four compartments.

Figure 18 appears to support the following observations and conclusions.

a. Parameter S (thermophysical properties existence) shows acute sensitivity behavior for all four compartments.

b. Parameter D (number of compartments) expresses definite sensitivity behavior for the third and fourth compartments.

c. Parameters C, F, G, H, J, K, L, and N (compartment height, vent's height, vent's sill, heat of combustion, fuel mass rate, fire position, ambient temperature, and specific heat) seem to be mildly sensitive for the first two compartments.

Again, there seems to be a fair agreement between the general conclusions for the upper layer depth over the simulated time and the corresponding conclusions of discrete sensitivity representation of the parameters of interest.

The sensitivity analysis applied to FAST reveals persistent sensitivity of the existence of thermophysical properties of walls, ceilings, and floor combination. The number of compartments is also quite a sensitive parameter. Though unexpected, the ambient temperature showed consistent sensitivity behavior.

3.6 Recommendations

The reader should keep in mind that only two dependent variables have been utilized to investigate the sensitivity of 16 input parameters. The subject model, FAST, expresses its behavior through more than two dependent variables (upper layer temperature and upper layer depth of smoke). It follows that this study could be expanded to determine sensitivity using different dependent variables as well as other input parameters of interest.

Indeed, while utilizing the same methodology one could replace insensitive parameters by new ones. The present study for example, indicates strongly that the parameter of thermophysical properties of compartment boundaries is sensitive. The existence or nonexistence of thermophysical properties infer the walls, ceiling, and floor, simultaneously. Therefore, one would not be able to point to which part(s) (ceiling, walls, or floor) of the compartment boundaries to which the sensitivity is due. Hence, it would be desirable to determine specifically which element(s) of the boundaries is responsible for the strong sensitivity behavior. This demonstrates the need for probing further into the investigation of FAST.[45] This process would only increase the users level of confidence in the model's performance.

4. QUANTITATIVE PERFORMANCE VALIDATION STUDY

4.1 Introduction

When doing research one should always provide reasonable and appropriate means supporting the accuracy of either measurements or estimations. In the process of assessing the validity of a deterministic model, one should quantify findings in terms of the level of confidence in these findings. Indeed, the quantification of the fire model validation through statistical inference is the focus of this report. Of course, any statistical inference is only as believable as the reasonableness of the statistical assumptions postulated.

Whenever statistics are desired to confirm and support a hypothesis, one needs to be concerned with the statistical data characteristics. These characteristics usually are the number of replications of experimental conditions, and the randomness of the data collected. The former characteristic, if large enough, infers the possibility of obtaining a data distribution function. This would lead to a parametric inference test. This characteristic is seldom encountered in large-scale fire tests. Due to the high cost of the test the latter characteristic, alone, for small samples demands the use of nonparametric statistics which are sometimes called distribution-free statistics.

A number of practitioner statisticians have contributed to developing tests for distribution-free inferences and nonparametric inferences.[69,70,71,72] Indeed, depending on the nature of the data, one of the two approaches offers attractive methodologies associated to reasonably valid assumptions. The distribution-free statistical methodologies do not require specific distribution characteristics. On the other hand, nonparametric statistical methodologies are associated with the type of hypothesis to be tested. For practical purposes, nonparametric methodologies use general assumptions and techniques are applied to samples. Such general assumptions would be that the population is a continuous function.[70] Null hypothesis statements are similar for parametric and nonparametric techniques, but they differ distinctively in the specificity of assumptions supporting them. Parametric methods are based on specific assumptions about the population sampled. On the other hand, nonparametric methods do not require such specificity in assumptions.

There are a number of key terms characterizing the process of model validation. These are "accuracy", "fit", "agreement", etc.; which are usually preceded by a qualifier such as good, reasonable, acceptable, etc. Associated with the variety of model validation processes is the many versions of rigorousness in model validation procedures. These different versions are differentiated by the embrace of different attitudes in the perception of the most informative way to apply the validation ranging from subjective to partially quantitative. There is a presumption that the more subjective a validation process is, the less supportive the conclusion on how valid is the model is under scrutiny. Based on the stated presumption, the author adopted the most quantitative validation process, given some limiting validation data attributes. The significance level of acceptance or rejection of the null hypothesis would reflect the degree of agreement quantitatively. It is not because one can quantify how accurate the estimation of a particular population parameter is that the process becomes an absolute validation of the model. Indeed, the reliability of a statistical decision depends on the accuracy of the experimental data.

In general, when data is statistically infeasible to postulate specific distribution behavior, a nonparametric technique would become a very useful methodology since it does not require specificity in assumptions.

Literature clearly shows the more nonparametric a methodology is the more chance to reject the null hypothesis.[72] In fire safety research no evidence was found supporting a practical quantitative methodology for performance validation fire safety models.

4.2 Assumption of Model Validation Process

There are two major assumptions that need to be stated and explained, and they are as follows:

1. Validation data is (experimental) randomized
2. Model is perfectly deterministic. It is exhibiting a sample mean or median equaling model population mean or median and variance equaling zero for both cases.

The validation experiments described below were randomized by design.[68] That was achieved by considering and arranging parameters such as length of time between each experimental burn, the ambient environmental conditions, and the physical experimental layout, etc. More comments will follow on the nature, size, and limitations of the validation data.

The second assumption may not seem to be one because the characteristics of a deterministic model is intrinsic to all deterministic models; that is there is no variation in output among runs for the same input information.

Note however, most complex deterministic models are built on two major structural blocks of information. These are scientific physics concepts and empirical physical phenomena. The former concepts, governed by mathematical formula are still deterministic by nature. The second one possesses inherent variability. This variability is very rarely exhibited in a deterministic model's output. This statement is not advocating the inclusion of variability in a deterministic model. Note that if it was so, the product would be a model partially stochastic and partially deterministic. Therefore, for each time step and for each parameter of the subject simulation, the model provides values reasonably perceived as means with all variances being equal and null. Variation on the model also stems from variability on the output parameters. This characteristic of the subject model, apriori could be viewed as a penalty against it. But, it could also be viewed that the model is subject to a stringent criteria for statistical rejection.

Having stated and elaborated on the assumptions meanings, requirements and validation procedures will be discussed next. There are three aspects to the model validation process, namely, validation data, model simulation, and statistical model selection and application.

4.3 Experimental Data for Validation Purposes

This section is comprised of the experimental physical layout and data acquisition. The purpose of the data is to develop a generic methodology for model evaluation. Description of instrumentation used in fire burns along with relevant information of the statistical state of the data are the subjects of this section.

A number of scientists at the Center for Fire Research (NBS) labor hard to generate useful and reliable information on fire behavior and its boundaries interactions. Monitored and recorded information such as temperatures, smoke heights, smoke/air movement, etc. was provided by the Center for Fire Research, Fire Performance and Validation Group.[73]

Under a prescriptive fire burns program, a number of different large-scale fires were designed, instrumented, recorded, and followed by a data transformation procedure. This procedure transformed "raw" data to "engineering" readable information. That is information originating as electrical impulses is transformed, after proper instrument calibration, into temperature units, densities, etc. The data is then standardized and basic statistics are generated. These statistics are means and standard deviations for various experimental output variables. Note that the transformation of raw data to engineering readable information is, in essence, obtained through a mathematical model.

Figure 19 illustrates the burn room - corridor - target room configuration as well as the location of different monitoring instrumentation. Instrumentation for full-scale burns comprises the following:

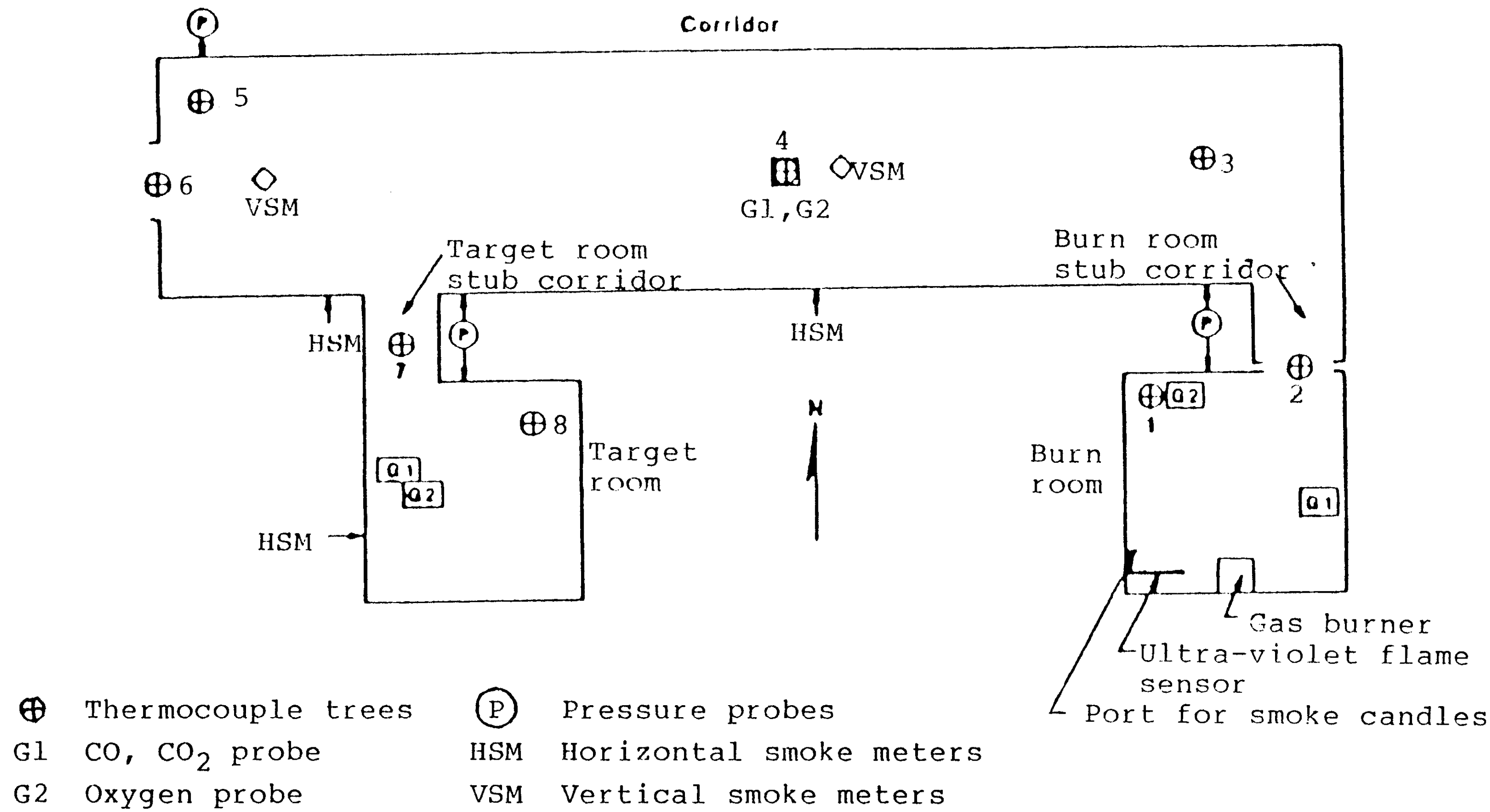


Figure 19. Experimental Layout and Instrumentation Configuration for Corridor Gas Burner Tests (Ref. 73) (Not to Scale)

A. Data Loggers

These are automated instruments which amplify an electrical signal emanating from a sensor probe at a prescribed rate of instantaneous reading. Data loggers collected data averaging over 1/60 of a second to minimize the existing 60 Hz noise.

B. Thermocouples

Extremely reliable and inexpensive, thermocouples are widely used in fire research. The several purposes they are used for include mass flow calculation and heat release rate in doorways. Of course, they are also utilized to measure ambient conditions. Therefore, there are seven locations for thermocouple "trees" as is illustrated in Figure 19.

C. Pressure Transducers

These are instruments to measure air movement. High sensitivity is a must to be effective at detecting air movement of 1 m/s or less. These instrument probes are found at the burn room, corridor, and target room as is illustrated in Figure 19.

D. Smoke Photometers

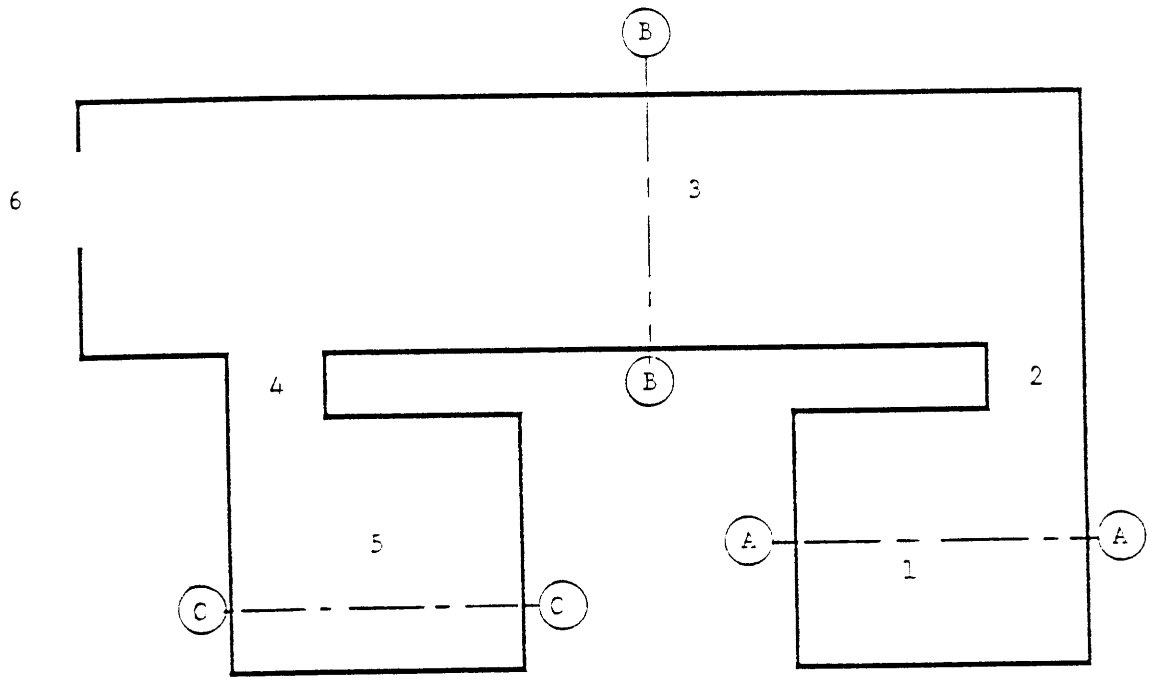
Smoke photometers are used to estimate relative smoke obscuration. Referred to as a smoke meter, a smoke photometer is composed of light sources, focused on a light detector using optical techniques. These instruments were installed in the corridor and the target room as can be seen on Figure 19.

E. Combustion Gas Analysis

The knowledge of the precise composition of combustion products is very desirable. Present gas analysis techniques synchronized with existing instruments for the analysis do not allow reliable information on combustion products toxicity.

However, most information provided included standard deviations. Therefore, a user may either choose to consider the information reliable enough for validation purposes; or may choose to add a "safety factor" to the given data.

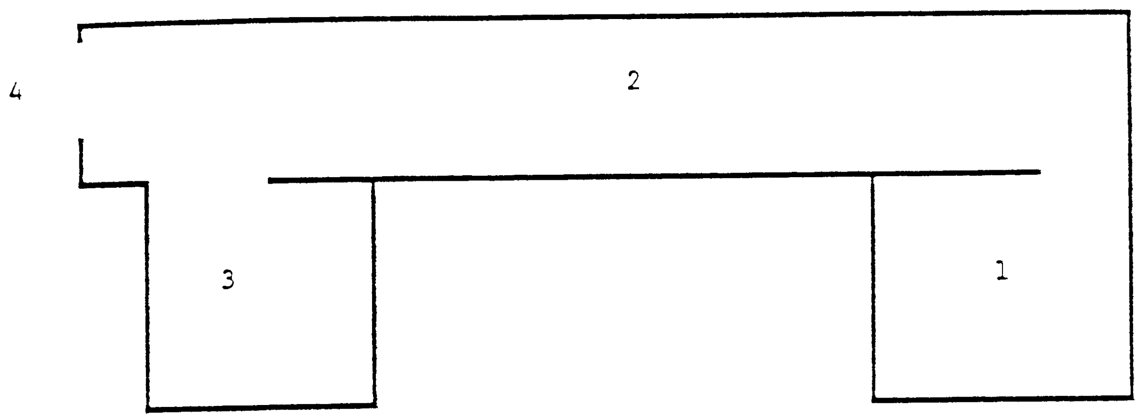
As in Figure 19 where instrumentation was the major focus, Figures 20 and 21 differentiate two physical layouts of the experimental set up. A five room arrangement as illustrated in Figure 20. Similarly a three room arrangement is depicted by Figure 21. The actualization of a three room set up was possible because of the perception that the burn room stub corridor and the target room stub corridor as part of the corridor, physically. This was achieved by substantiating the volume of the stub corridor and stub target room by an equivalent longer corridor dimension. It followed the alteration of the corridor height as can be seen on Table 2.



LEGEND:

1 is the Burn Room
2 is the Burn Room Stub Corridor
3 is the Corridor
4 is the Target Room Stub Corridor
5 is the Target Room
6 is the Outside Burn Structure.

Figure 20. Physical Layout of Full-Scale Fire Burn Structure - Five Room Set Up (Not to Scale)



LEGEND:

1 is the Burn Room
2 is the Corridor
3 is the Target Room
4 is the Outside Burn Structure

Figure 21. Physical Layout of Full-Scale Fire Burn Structure - Three Room Set Up (Not to Scale)

Table 2. Physical Dimensions of Full-Scale Fire Burn Structure - Two and Three Room Set Up

LOCATION*	WIDTH(m)	DEPTH(m)	HEIGHT(m)	SILL(m)
1	2.34	2.34	2.16	NA
2	1.02	1.03	2.00	NA
3	2.44	12.19	2.44	NA
4	0.79	0.94	2.04	NA
5	2.24	2.22	2.43	NA
1 - 2	0.81	NA	1.60	0.0
2 - 3	1.02	NA	2.00	0.0
3 - 4	0.79	NA	2.04	0.0
4 - 5	0.79	NA	2.04	0.0
3 - 6	1.02	NA	2.03	0.0

*Refer to Figure 20

LOCATION*	WIDTH(m)	DEPTH(m)	HEIGHT(m)	SILL(m)
1	2.34	2.34	2.16	NA
2	2.44	12.58	2.56	NA
3	2.24	2.22	2.43	NA
1-2	0.81	NA	0.79	0.0
2-3	1.60	NA	2.04	0.0
2-4	1.02	NA	2.03	0.0

**Refer to Figure 21

NA = NOT APPLICABLE

The input of the model to be validated not only requires the rooms' physical dimensions but also the thermophysical characteristics of the rooms boundaries. These boundaries are the ceiling, walls, and floor. Their corresponding thermophysical properties are the thermal conductivity, the specific heat, the materials density, the thickness and emissivity, for each slab constituting that boundary.

Figures 22, 23 and 24 illustrate a sectional view revealing the different slabs representing ceiling, walls and floor for each different location. This type of information assists in predicting the expected "heat loss" to the "surroundings". Note that the burn room boundaries are made of materials which tolerate several burn experiments with little damage.

Thermophysical Properties of Burn Room Boundaries

NATURE	CALCIUM SILICATE	CERAMIC FIBER	FIRE BRICK
Conductivity (kW/m.K)	0.000117	0.000164	0.00039
Specific Heat (kJ/kg.K)	1.38	1.04	1.04
Density (Kg/m^3)	720	128	750
Thickness(m)	0.0127	0.050	0.1130
Emissivity	NA	0.97	0.80

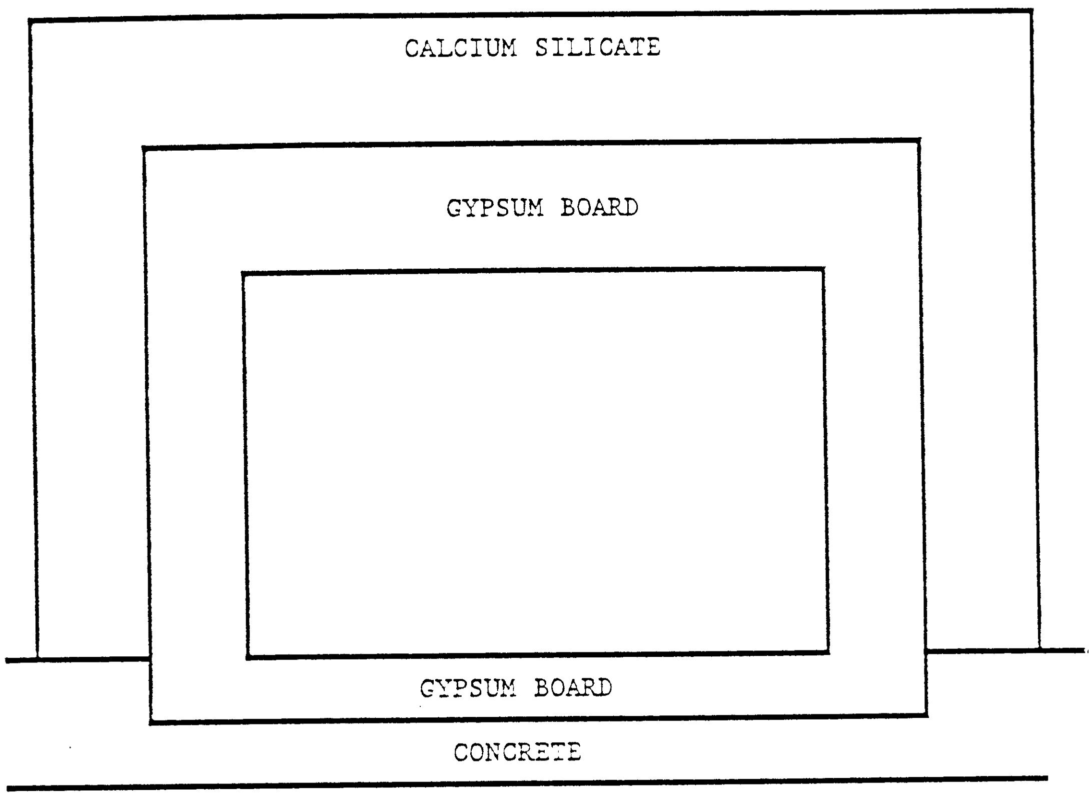


Figure 22. Sectional View (A-A) of the Burn Room Illustrating its Thermophysical Properties (Not to Scale

Thermophysical Properties Of Corridor Boundaries

NATURE	CALCIUM SILICATE	GYPSUM BOARD	CONCRETE
Conductivity (kW/m.K)	0.000117	0.00017	0.00182
Specific Heat (kJ/kg.K)	1.38	1.09	1.04
Density (Kg/m^3)	720	930	2280
Thickness (m)	0.0127	0.0127	0.102
Emissivity	NA	0.90	0.90

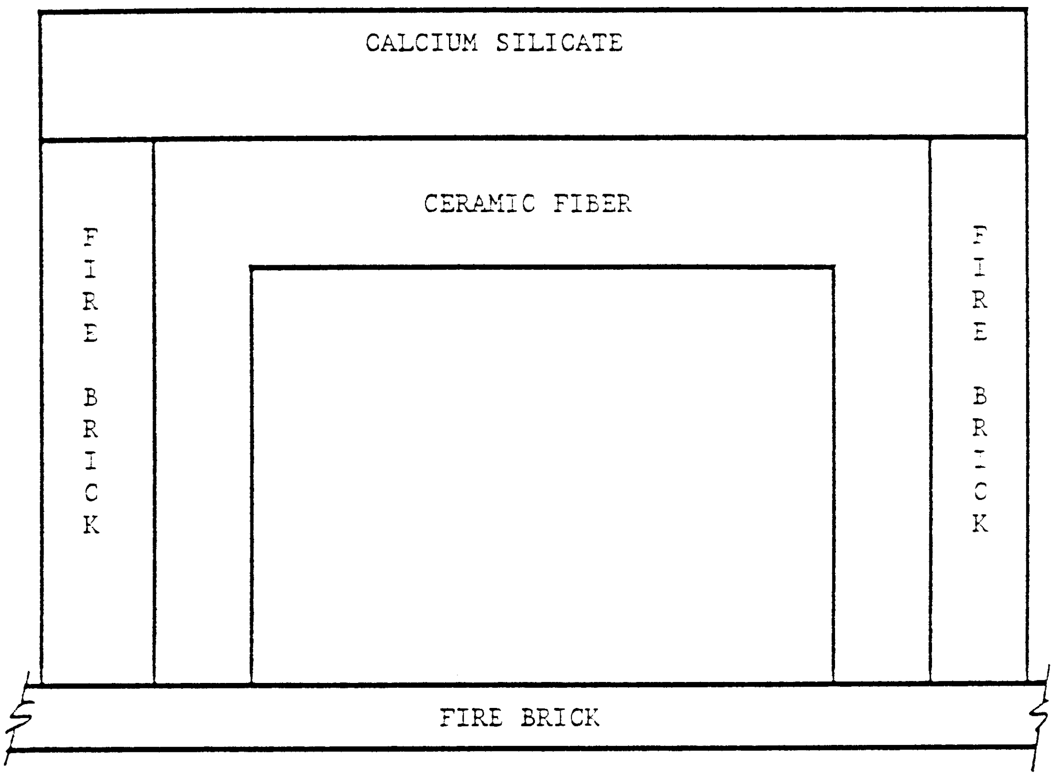


Figure 23. Sectional View (B-B) of the Corridor Illustrating its Thermophysical Properties (Not to Scale)

Thermophysical Properties of Target Room Boundaries

NATURE	GYPSUM BOARD	CONCRETE
Conductivity (kW/m.K)	0.00017	0.00182
Specific Heat (kJ/kg.K)	1.09	1.04
Density (Kg/m^3)	0.0127	0.102
Thickness (m)	930	2280
Emissivity	0.90	0.90

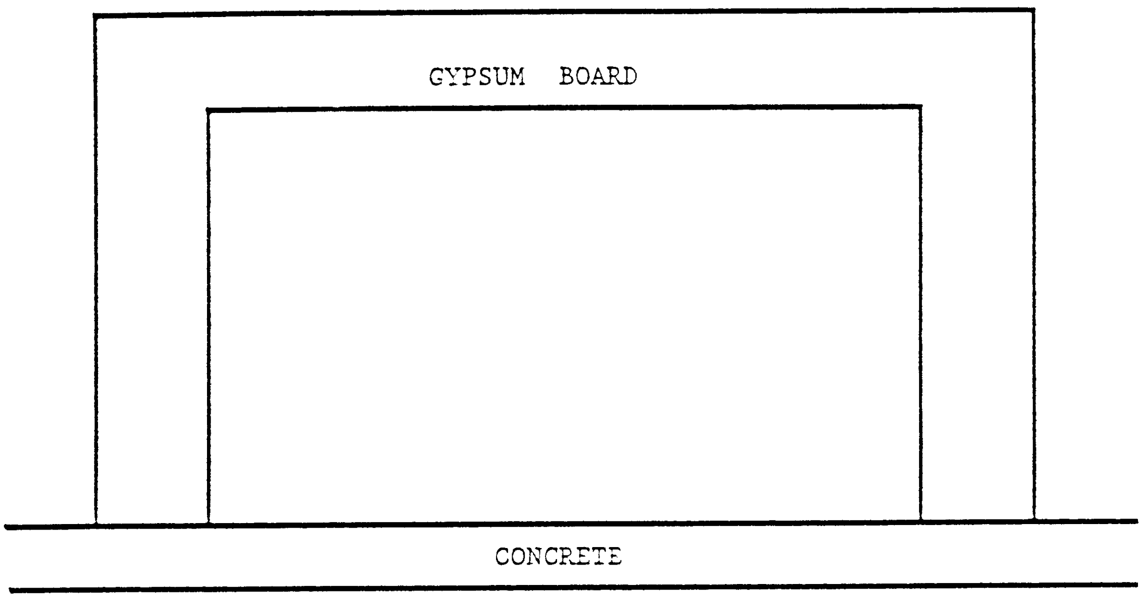


Figure 24. Sectional View (C-C) of the Target Room Illustrating its Thermophysical Properties (Not to Scale)

The actual full-scale fire burns were undertaken for three (3) different fire sizes, namely 100, 300 and 500 kW. For almost each fire size, two different physical configurations of the layout were utilized. Referring to Figure 19, one would imagine the use of a door to segregate diverse compartment. With the burn room present and open to the remaining of the structure, the following matrix illustrates the physical layouts achieved.

		CORRIDOR	
		OPEN	CLOSED
TARGET ROOM	CLOSED	1, 5, 8	2
	OPEN	4, 6, 9	3

In total and among the three fire sizes, nine sets of different physical configurations were performed with varied replication as it can be seen on Table 3.

Table 3. Summary of Eight Sets of Fire Tests for Three Fire Gases and Different Configurations

SET NO.	FIRE SIZE	CORRIDOR DOORWAY	TARGET ROOM	NUMBER OF REPLICATES
1	100kW	Closed	No	4
2	100kW	Closed	Yes	5
3	100kW	Open	Yes	8
4	300kW	Open	No	3
5	300kW	Closed	Yes	2
6	300kW	Open	Yes	3
7	500kW	Open	No	5
8	500kW	Open	Yes	3

For each burn experiment, a procedure determining the initiation and the completion of the experiment. This procedure is composed of the following:

A. Pilot light period of approximately 300 seconds,

B. Main burn period of approximately 600 seconds, and

C. Cool down period of approximately 300 seconds.

Even though the period of interest is the main burn period, the two (2) others play important roles. The pilot light period is necessary to stabilize monitoring instruments. In order to insure that the instrumentation is still sensitive enough to be used in another test, the cooling down period was used. Data was recorded during the three burn periods.

As Table 3 indicates, set 1 possesses the largest number of replicates, but not large enough to construct a rough distribution of a chosen variable. This important limitation practically rules out parametric treatment of the data.

4.4 Statistical Experimental Design for Performance Validation

With the statistical nature of the validation fire data in mind, the most appropriate statistical test to validate the model is known as the Wilcoxon's test.[70,71,72,69,74] Wilcoxon's test is called a "distribution free" test because there is no need to define/know the distribution of the populations or samples. In this case, these two samples are the experimental data and model data samples. From paired samples, inferences are made for their respective populations.

Again, the major reason for selecting the nonparametric test (Wilcoxon's test) is based on the inherent robustness of its general assumptions and the lack of a priori knowledge of the type of distribution representing the sample data. This test is designed primarily to be a test detecting location differences. This could be the difference of two medians of two different samples (experimental and model samples).

The Wilcoxon's test will be presented through its attributes, such as ranking properties and related distribution properties of linear ranking statistic.[74] In essence, the test succeeds to quantitatively describing the degree of acceptance that the median of sample A is different than the median of sample B. This is done through the ranking of the values of sample A and B. The difference in ranks between samples A and B would reflect the acceptance or rejection of the hypothesis.

Formally stated, two independent random samples, A_1, A_2, A_3,...A_n and B_1, B_2, B_3,... B_m emanate from two populations with continuous cumulative distribution functions F(A) and F(B), respectively. The combined samples A and B then become a sample of n+m (n+m=N) elements to be ranked from 1 to N.

Mathematically stated, the new ranked sample can be represented by a vector Z. In this context, elements of samples A and B, are viewed as having binary properties, i.e., zero (0) or one (1). Hence, vector Z can be written as $Z = (Z_1, Z_2, Z_3, \ldots Z_N)$, where $Z_1, Z_2, Z_3, \ldots Z_N$ could be either 0 or 1. In other words, the Z vector becomes the rank-order statistic which leads to a class of statistic, called the linear rank statistic. The linear rank statistic is usually defined as

$$W_N = \sum_{i=1}^{N} a_i Z_i; \quad 1 \leqslant a \leqslant N$$

where Z_i is defined as the indicator random variable.

In the following the mean and variance of W_N can be computed as:

$$\text{Mean} = \frac{m(N+1)}{2}$$

$$\text{Variance} = \frac{mn(N+1)}{12}$$

the minimum value of W_N is: $\sum_{i=1}^{m} i = \frac{m(m+1)}{2}$

the maximum value of W_N is: $\sum_{i=N-m+1}^{N} i = \frac{m(2N-m+1)}{2}$

Once the linear rank statistic is determined, one needs to refer to the appropriate table for a given n and m and record the probability value for rejecting the null hypothesis.

Having some background for the theory of the Wilcoxon's test, let us illustrate its utility using a numerical example.

4.4.1 Typical Application of Wilcoxon Test

Data has been collected from two groups of industrial output for a specific product. Among numerous factors affecting the quality of the product, one attribute has been investigated. The first group of eight products, treated group, was produced by a new manufacturing process. The second group, control group, was produced by the old manufacturing process.[74] The correspondance of treated and control groups parallel model and experimental data, respectively.

There are two assumptions to be reasonably met. These are:

A. Two random samples taken independently of each other, and

B. The two populations have roughly the same probability distribution.

Data: Quality attribute of control and treated products for day 1.

Treated Group	Control Group
2.6	1.2
2.0	1.8
1.7	1.8
2.7	2.3
2.5	1.3
2.6	3.0
2.5	2.2
3.0	1.3
	1.5
	1.6
	1.3
	1.5
	2.7
	2.0
$n_1 = 8$	$m_2 = 14$

The treated group sample is merged with control group sample, ordered and ranked, as illustrated below:

TREATED & CONTROL SAMPLES ORDERED	RANKED	
	CONTROL	TREATED
1.2	2	
1.3	3	
1.3	3	
1.5	5.5	
1.5	5.5	
1.6	7	
1.7		8
1.8	9.5	
1.8	9.5	
2.0	11.5	
2.0		11.5
2.2	13	
2.3	14	
2.5		15.5
2.5		15.5
2.6		17.5
2.6		17.5
2.7	19.5	
2.7		19.5
3.0	21.5	
3.0		21.5

Sum of Ranks = 126.5

If the medians of the two samples were equal, the sum of ranks calculated would equal the average value of the Wilcoxon statistic. This value is calculated by n(m+n+1)/2, where n is the number of observations in the treatment sample and m is the number of observations in the control sample. By comparing W_{avg}, the average Wilcoxon statistic, to the calculated sum of Rouk, W_{calc}, there are three possible inferences. They are:

A. If $W_{calc} > W_{avg}$, a number of observations from the treatment sample are large in magnitude.

B. If $W_{calc} < W_{avg}$, a number of observations from the treatment sample are small in magnitude.

C. If $W_{calc} = W_{avg}$, all observations from the treatment sample are equal to the median of the control sample.

The average value W_{avg} is then 8(8+14+1)/2 = 92, while the calculated sum of ranks is W_{calc} = 126.5.

The results of the test statistic include a point estimate for the difference between treated and control medians, as well as a confidence interval for that point estimate. These are illustrated below.

Two independent random samples from two populations have medians $_1$ and $_2$, respectively. The appropriate null hypothesis can be stated as follows:

H_o : $\eta_1 = \eta_2$, against the non-null hypothesis

$H_1 : \eta_1 \neq \eta_2$.

It should become clear to the reader that the statistical hypothesis is expressing the median location problem.

Using the data from the previous example, the two sample rank procedure yielded to the following results. Note that these results have been obtained through a pre-packaged statistical routine.[46]

Treatment N = 8 Median = 2.5500

Control N = 14 Median = 1.7000

A point estimate for $_1$ - $_2$ is 0.7000

A 94.% confidence interval for $_1$ - $_2$ is (0.2000, 1.2000)

Test $\eta_1 = \eta_2$ vs. $\eta_1 \neq \eta_2$

W = 126.5

The test is significant at 0.0204.

Typically, the Mann-Whitney test determines medians of the two samples. One can observe that these are different, but in addition, the significance level of the test leads to the rejection of the null hypothesis. One is 95% confident that the chance of observing two samples having different medians when in fact the two populations have the same median is only 2.04%.

Therefore, one would confidently conclude that from the evidence of day 1, the new manufacturing process did, indeed, affect the quality of the product. In order to be persuaded that the new manufacturing process affects the quality of the product over time, one needs to collect data in days 2, 3, 4, etc. and perform the Mann-Whitney test and display respective significance levels as depicted in Figure 25.

4.5 Methodology

The methodology for the performance validation study consists of exercising the fire safety model "FAST" to simulate similar experimental conditions for which full-scale data exist. The model simulation is designed to emulate output most relevant in describing the behavior of the model that reveals its performance agains real fire data.

4.5.1 Model Simulation

The subject model in this exercise known as FAST version 17[45] is a deterministic, multicompartment, two zone fire model. The model is based on a number of assumptions; the most important one requires that two distinct control volumes for each compartment or room exist.

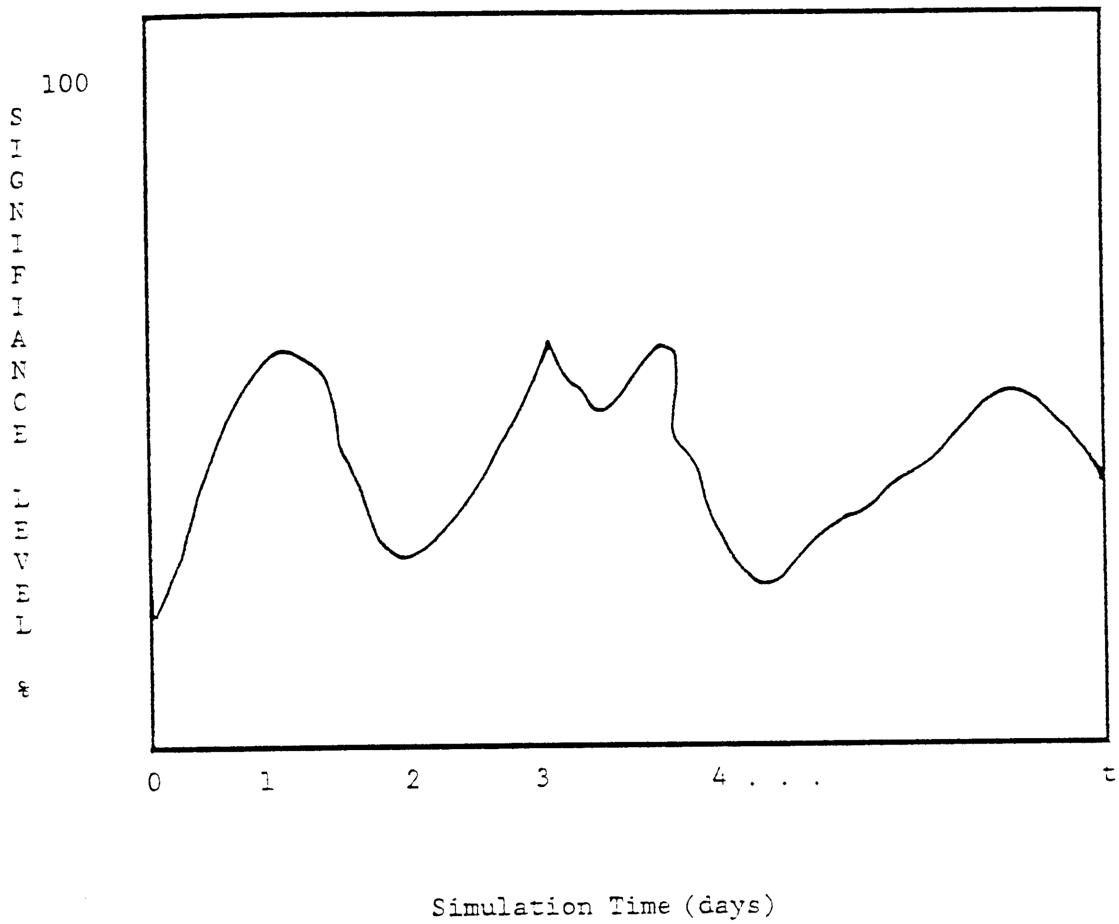


Figure 25. Significance Level of the Wilcoxon Test for Variable of Interest Over Time

There are four input categories to be considered in executing the model. These are: 1) simulation time and time-step, 2) configuration and floor plan data, 3) thermo-physical properties of the compartment boundaries, and 4) fire specifications.

A. Simulation time and time step

This entry requires the length of the fire simulation and how often a printout is wanted. To match the experimental output records, 600 seconds are needed as the simulation time with a 10 second time step.

B. Configuration and floor plan data

This part requires the number of rooms, their dimensions and the size of their connections. The ambient temperature is also needed. The model assumes ambient pressure. Table 3 provides most of the required input for this category.

C. Thermophysical properties of the compartment boundaries

There are five properties composing the thermo-physical characteristic of the boundary. Namely these are conductivity, specific heat, density, thickness, and emissivity of each slab constituting an element of the compartment boundaries. There are three elements comprising each compartment; the ceiling, walls and floors. The five properties, for each slab, must be inputed moving from the inside of the compartment to the outside. For example, from Figure 22 which illustrates a cross sectional view of the burn room. For the walls, one would input the ceramic fiber thermophysical properties data before the firebrick properties data.

D. Fire specifications

FAST is a model that uses a prescribed fire. Indeed, it needs to be told the heat of combustion of the fuel, its location, and combustion efficiency. One advantage in dealing with a prescribed fire is having the flexibility to manipulate the heat output rate. One could also choose between a growing, decaying fire or a steady fire.

The fire energy the model requires is expressed in terms of the total calorific value of the fuel (heat of combustion) for a given scheme of time intervals, associated with the respective fuel mass loss rate. Figure 26 illustrates the input information as the model format requires it, for a 100kW size fire with the burn room and corridor configuration, for a two room scenario. (recall Figure 21). For this pilot study, the statistics for two output variables will be analyzed, the upper layer temperature and the smoke layer thickness. The graphical output can be seen on Figure 27 and Figure 28 for the upper layer temperature and the smoke thickness, respectively, for the burn room.

```
VERSN    17 SET 1 OF 205      100KW,CD DOOR OPEN
TIMES     600 10 10 0 0 .1
NROOM     2
NMXOP     1
TAMB      293
HI/F      0.0  0.0
WIDTH     2.34  2.44
DEPTH     2.34  12.80
HEIGH     2.16  2.44
HVENT     1  2  0.81  1.60  0.0
HVENT     2  4  1.02  2.03  0.0
CEILI
COND  .000164/.000117 .00017/.000117
SPHT  1.04/1.38    1.09/1.38
DNSTY  128./720.     930./720.
THICK  .05/.0127    .0127/.0127
EMISS   .97            .90
WALLS
COND  .000164/.000398 .00017/.000117
SPHT  1.04/1.04     1.09/1.38
DNSTY  128./750.    930./720.
THICK  .050/.113    .0127/.0127
EMISS   .97           .90
FLOOR
COND  .000398 .0017/.000182
SPHT  1.04     1.09/1.04
DNSTY  750.  930./2280.
THICK  .1130    .0127/.102
EMISS   .80            .90
LFBO       1  ROOM OF ORIGIN
LFBT       1  TYPE OF FIRE
LFPOS      1 CENTER OF ROOM
CHEMI      1.0  0.0  .75  .25  0.0  50630. 293.
LFMAX      1
FTIME      600.
FMASS      .00205 .00205
FHIGH       .5 .5
```

Figure 26. FAST Input File as Required by the Model Format for 100kW Fire in Burn Room - Corridor with Corridor Doorway Open

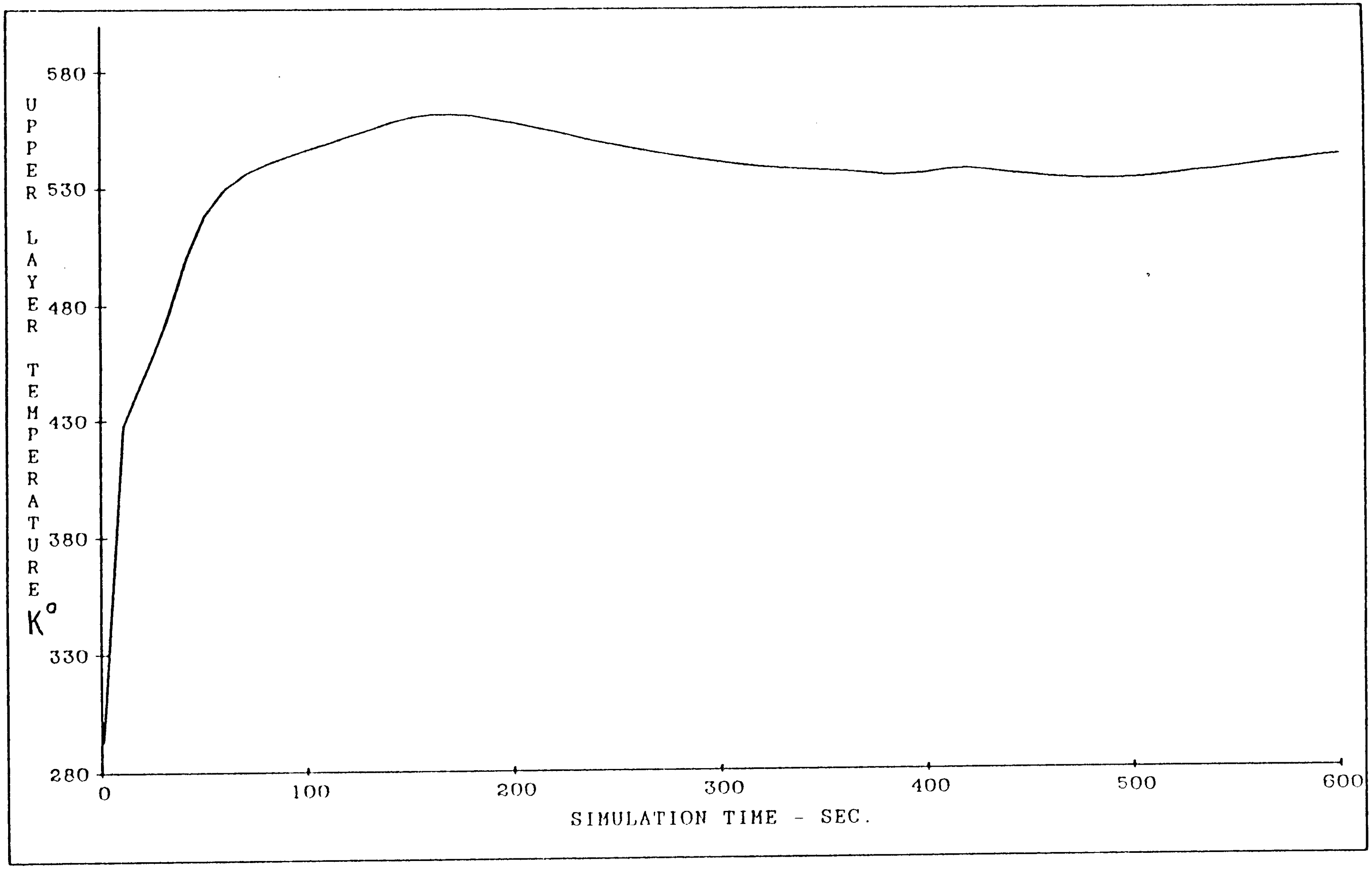


Figure 27. Upper Layer Temperature Versus Simulation Time for a Two Room Configuration (Burn Room)

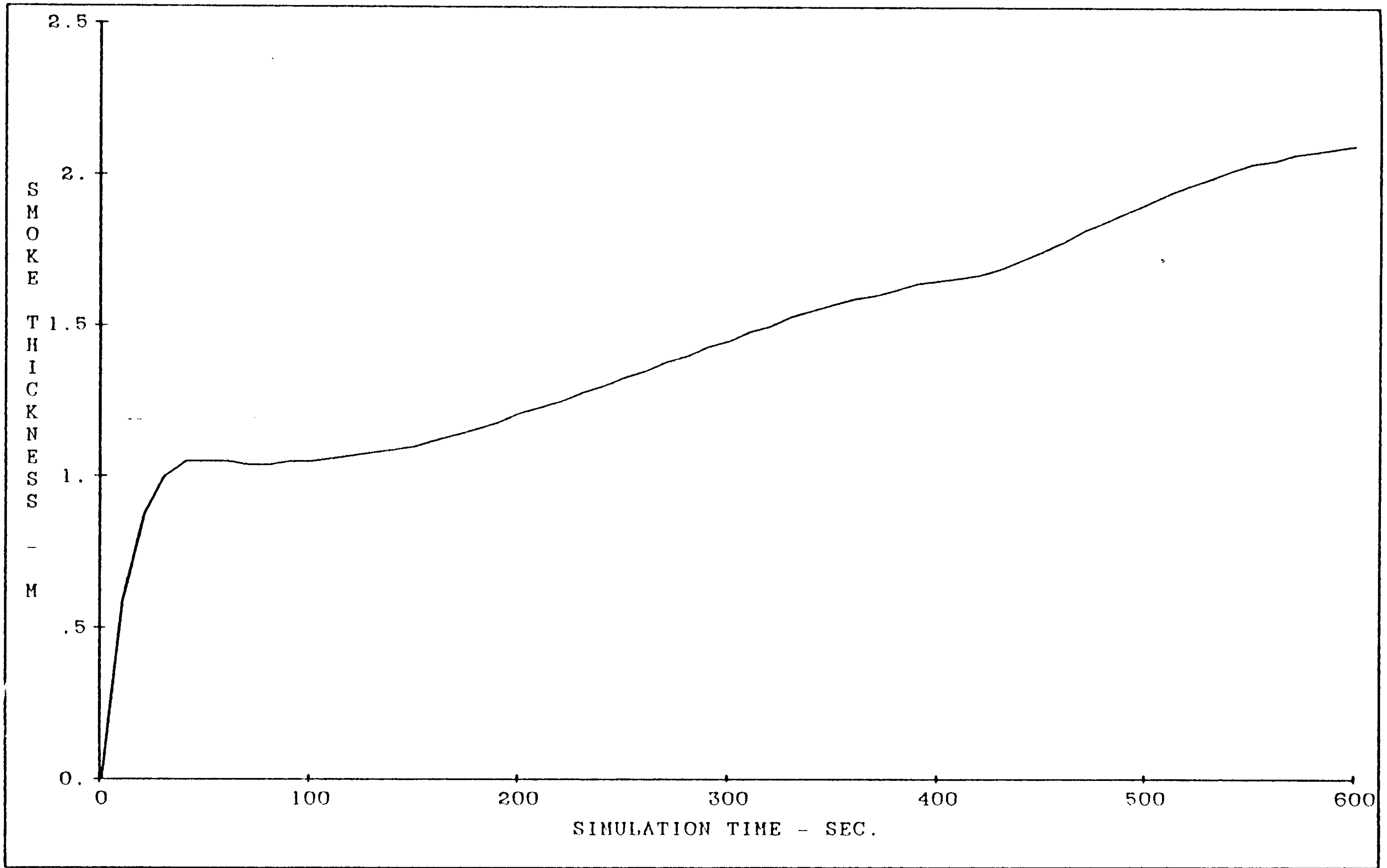


Figure 28. Smoke Thickness Versus Simulation Time For a Two Room Configuration (Burn Room)

Model simulation is simply the process of gathering the appropriate data from the full-scale experimental set up, and obtaining for each time-step and variable,one single value representing the sample of the model.

Having the first statistical sample through model simulation, the next step is to prepare the two samples for the statistical model application.

4.5.2 Statistical Model Application

This section will illustrate the application of the Wilcoxon test (Mann- Whitney Test) using samples from the model and the experiment. For each time step selected, data elements (treatment sample) and experimental sample (control sample) are prepared for analysis. For each output variable of interest, a set of samples is set up for statistical analysis. A numerical example will partially illustrate the Mann-Withney test methodology. Finally, the numerical example results will be briefly discussed.

Among the numerous output variables, two were selected from the point of view of a user as opposed to a scientist or modeler(s). These are the upper layer temperature, and the smoke layer thickness. A modeler would be interested in flows of air and smoke, energy balances, etc. Investigating these other output variables would certainly shed some light on weaknesses of either the physics of the model or its numerics. Yet when one, as a user, is concerned with fire safety and life safety of a real fire scenario, these selected two output variables could be reasonably informative to assist the user to assess the hazards of that scenario. Therefore, for each time step and each output variable a statistical test will be performed.

For each fire size simulated, either 240 (60 time steps times four (4) output variables in simulation of set 1 or 540, (60 times steps times six (6) output variables in simulation of set 3 and 4 pairs of samples are produced, (model and experimental). One can see how the number of samples reached substantially large proportions.

For each variable and location, a pair of samples for each time step will be generated. As an example, a 100kW fire for a configuration excluding the target room and keeping the corridor doorway open, will illustrate the Mann-Whitney statistical treatment. The time steps selected are 10, 20, 40, and 60 second state of events.

4.6 Performance Validation Results

The results presented in this section are not intended to validate the FAST model per se, but rather they are the product of detailed procedures necessary to validate any fire model. It is a fact that the deterministic fire model utilized in this study is FAST version 17. Since FAST is presently (December 1986) under review by a number of special committees, it is not appropriate to use these results to form an opinion on the performance validity of the model. Therefore, a systematic performance validation exercise would be neither meaningful nor productive at this time.

With the above statement in mind, the 100kW fire size became the focus of the applied performance validation procedure. The 100kW fire was selected because it is the case where all possible scenarios were treated, as Table 4 illustrates.

Table 4. Validation Data Sets Characteristics

Characterization	Set 1	Set 2	Set 3	Set 4
Fire Size (kW)	100	100	100	100
Number of Replications	9	4	5	8
Corridor Doorway	OPEN	CLOSED	CLOSED	OPEN
Target Room	NO	YES	NO	YES

Similarly to the sensitivity study, results are presented graphically because of sheer volume of output. For each compartment or room in the simulation statistical output for the chosen two variables are plotted.
Figure 29 through Figure 32 illustrate the statistical treatment of time dependent calculations. These calculations depict how experimental and model samples performed and probable inferences on the their respective populations.

Detailed tabular data and statistical results follow Figures 29 through 32 to illustrate the nature of the range of statistical significance of the test. This range includes both underprediction and overprediction situations for selected time - steps and key parameters in the burn room of Set 1.

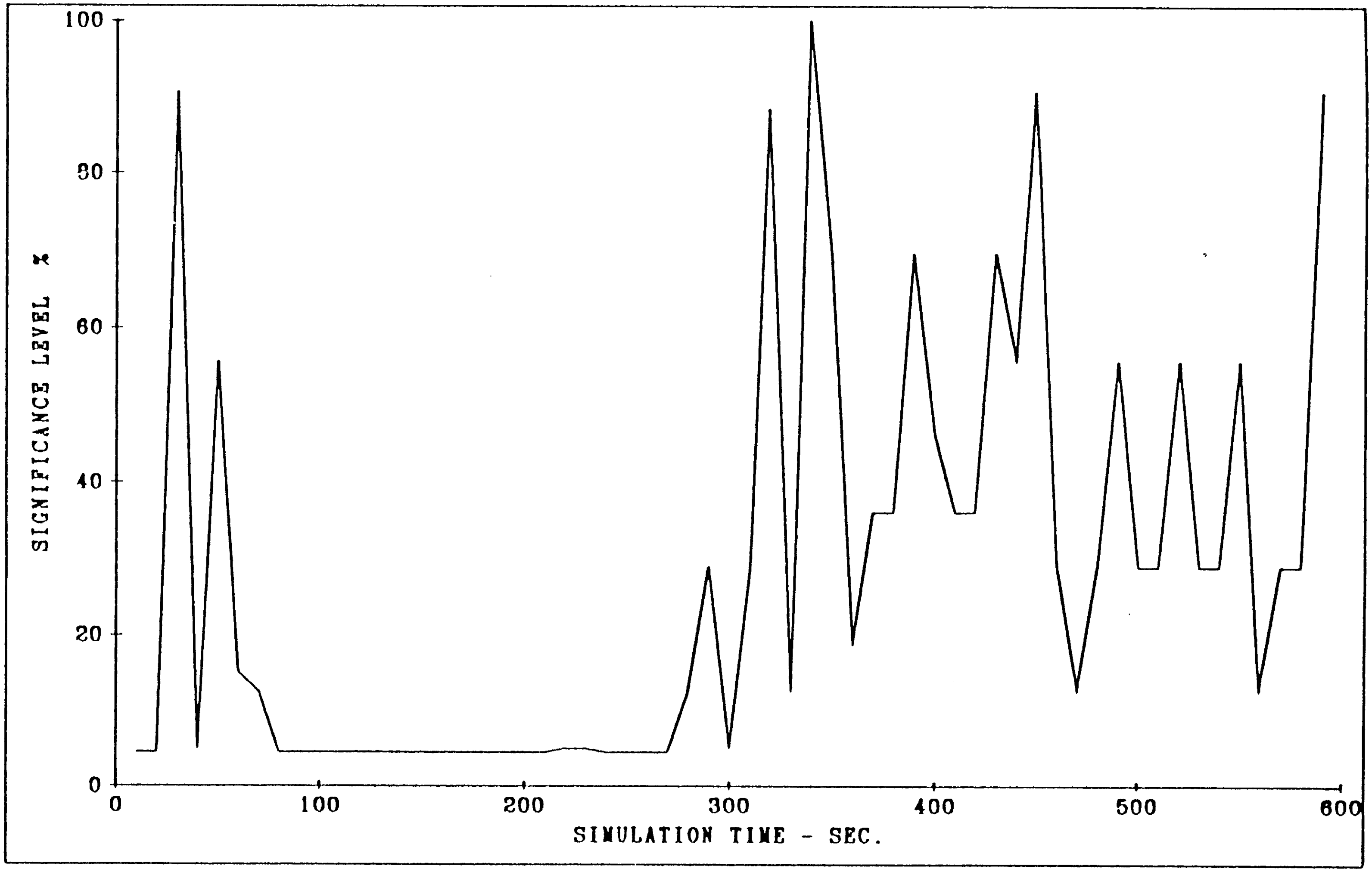


Figure 29. Statistical Significance Level of Rejection of the Null Hypothesis for the Upper Layer Temperature in the Burn Room of Set 1

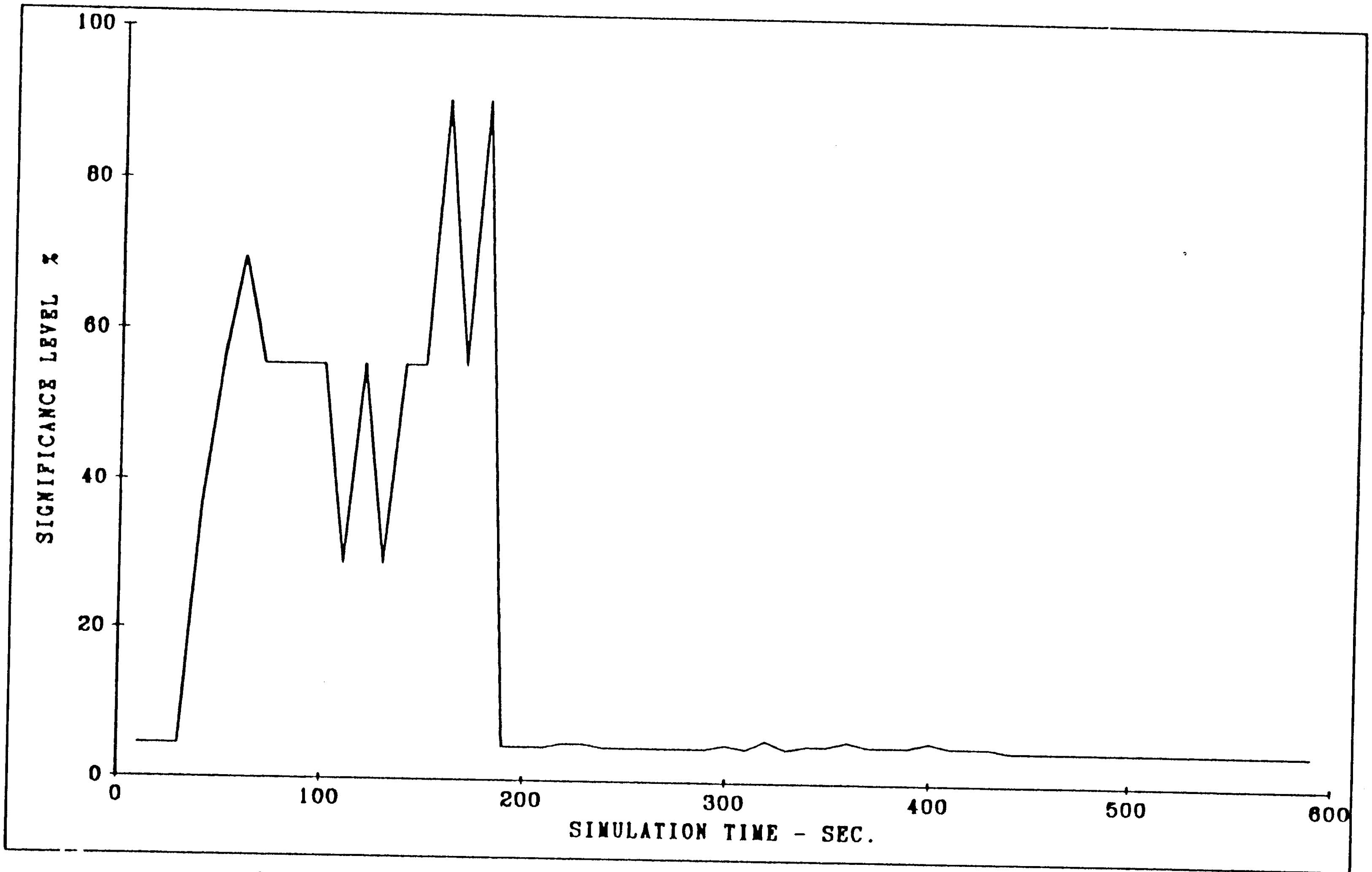


Figure 30. Statistical Significance Level of Rejection of the Null Hypothesis for the Upper Layer of Smoke in the Burn Room of Set 1

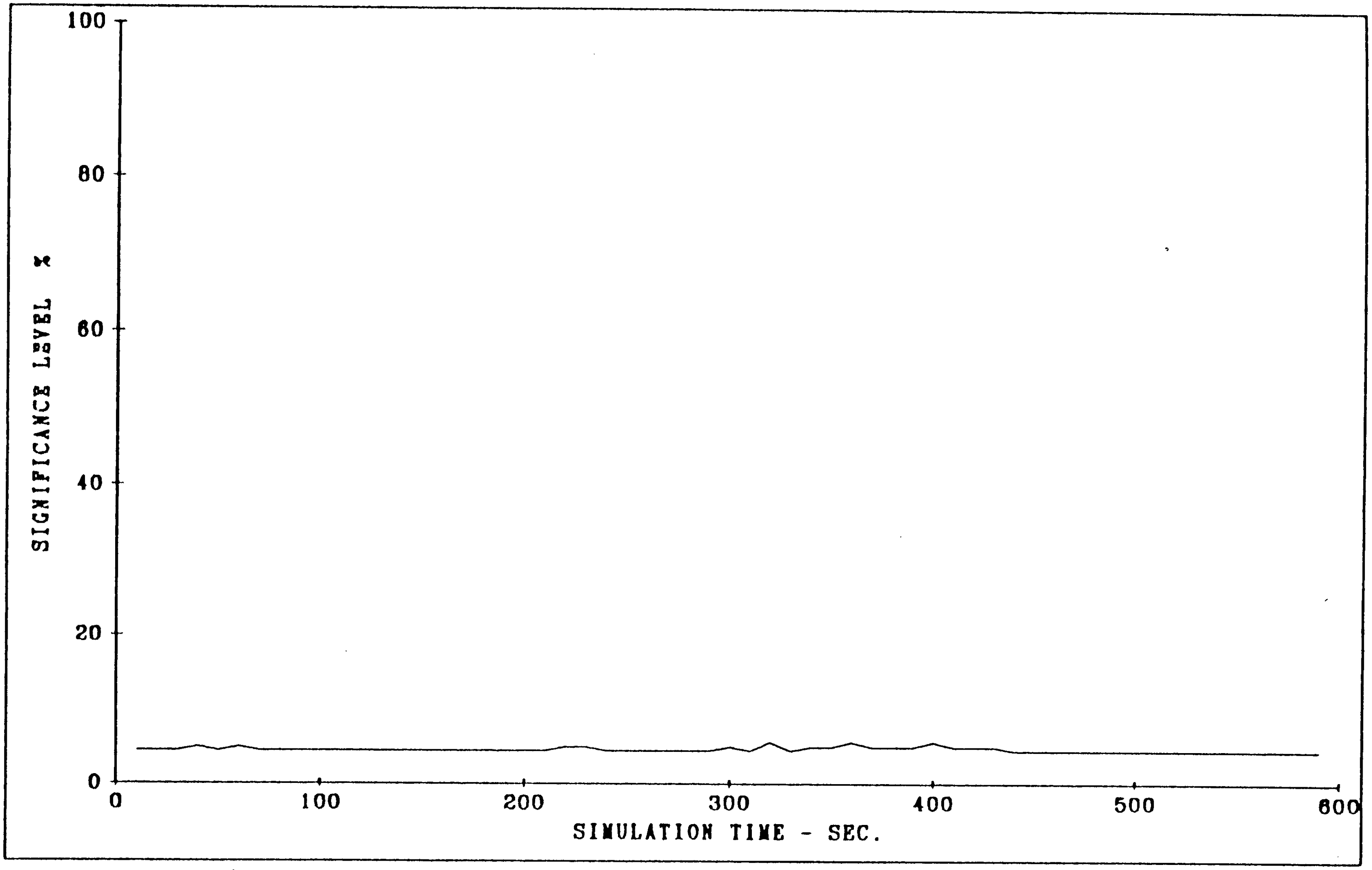


Figure 31. Statistical Significance Level of Rejection of the Null Hypothesis for the Upper Layer Temperature in the Corridor of Set 1

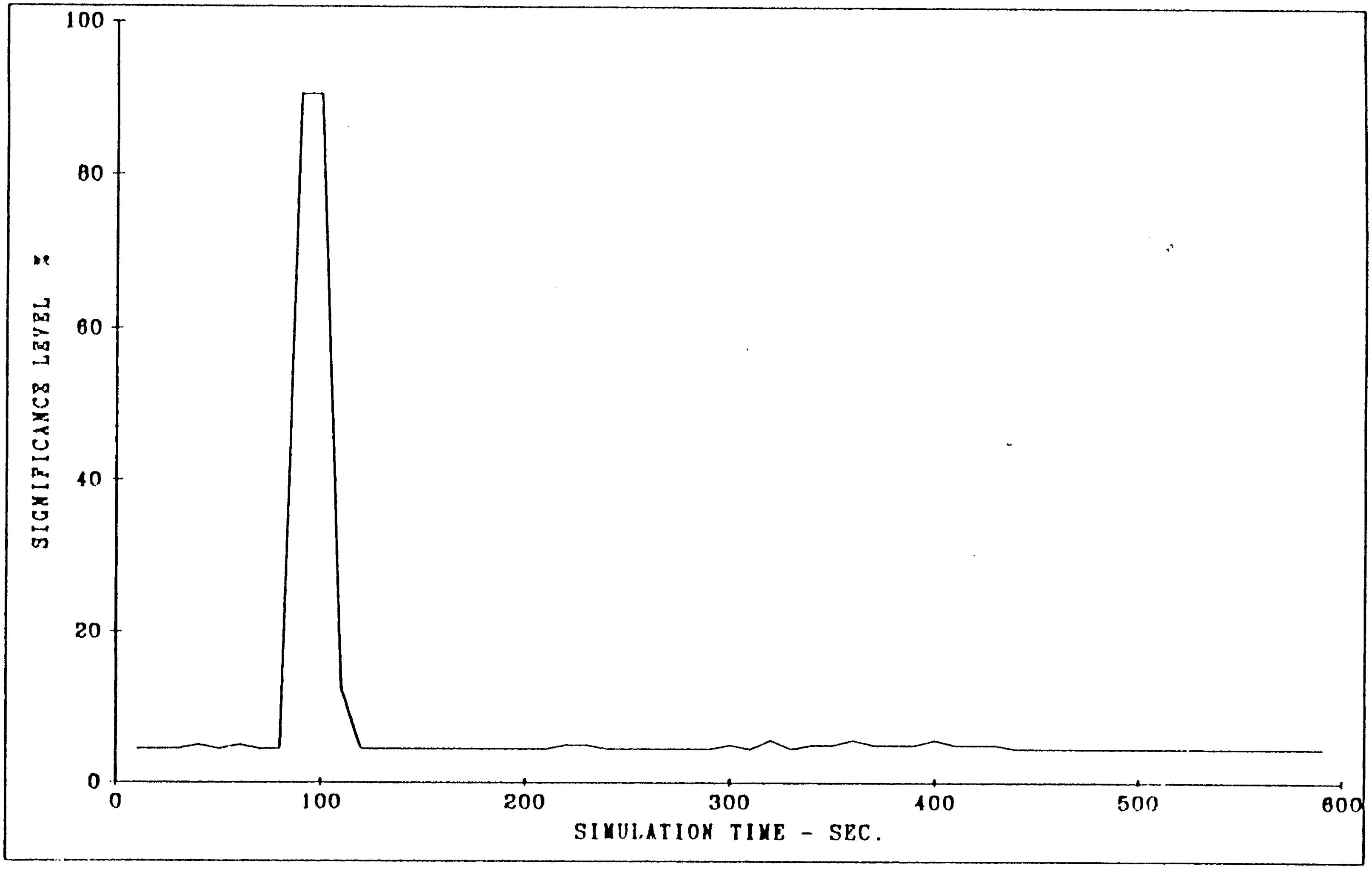
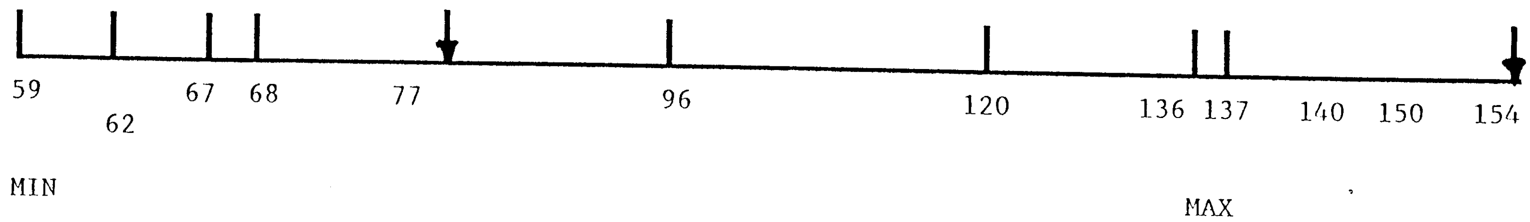


Figure 32. Statistical Significance Level of Rejection of the Null Hypothesis for the Upper Layer of Smoke in the Corridor of Set 1

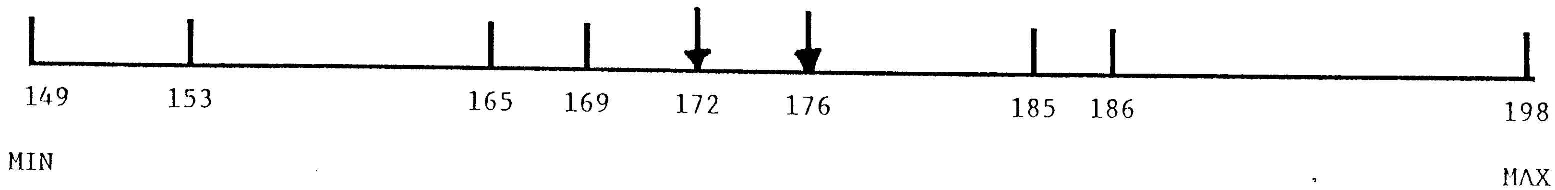
Table 5. Statistical Results for Upper Layer Temperature in the Burn Room of Set 1 at Time Step 10 Seconds



Row	EXP	MOD	MOD + EXP	MOD + EXP RANKED	MOD + EXP ORDERED
1	137.72	154.4	154.40	10.5	59.06
2	62.88	154.4	154.40	10.5	62.88
3	59.06		137.72	9.2	67.16
4	136.65		62.88	2.0	68.37
5	77.82		59.06	1.0	77.82
6	120.76		136.65	8.0	96.37
7	96.37		77.82	5.0	120.76
8	67.16		120.76	7.0	136.65
9	68.37		96.37	6.0	137.72
10			67.16	3.0	154.40
11			68.37	4.0	154.40

```
MTB > MANN-WHITNEY ON DATA EXP MOD
    EXP        N =  9     MEDIAN =      77.82
    MOD        N =  2     MEDIAN =     154.40
    A POINT ESTIMATE FOR ETA1-ETA2 IS  0.0000000
    A 95.0 PERCENT C.I. FOR ETA1-ETA2 IS  (  0.000000,    0.000000)
    W =       45.0
    TEST OF ETA1 - ETA2  VS.  ETA1  N.E.  ETA2
    THE TEST IS SIGNIFICANT AT     .0451
*ERROR * COMPLETION OF COMPUTATION IMPOSSIBLE
*ERROR * ALL VALUES IN COLUMN ARE IDENTICAL
```

Table 6. Statistical Results for Upper Layer Temperature in the Burn Room of Set 1 at Time Step 20 Seconds

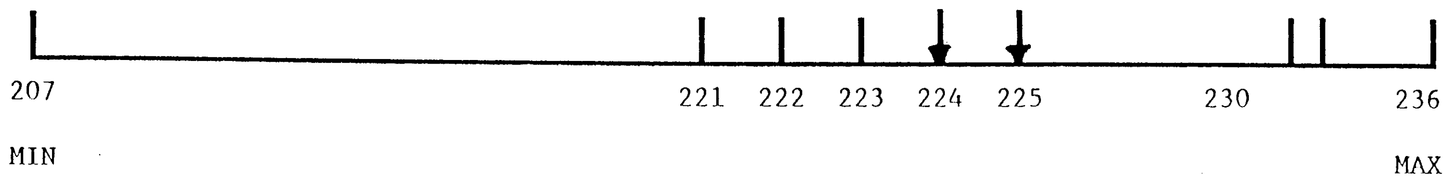


Row	EXP	MOD	MOD + EXP	MOD + EXP RANKED	MOD + EXP ORDERED
1	198.38	176.5	176.50	6.5	149.35
2	153.04	176.5	176.50	6.5	153.40
3	172.59		198.38	11.0	165.59
4	185.69		153.04	2.0	169.42
5	188.08		172.59	5.0	172.59
6	169.42		185.69	9.0	176.50
7	149.35		188.08	10.0	176.50
8	165.59		169.42	4.0	177.16
9	177.16		149.35	1.0	185.69
10			165.59	3.0	188.08
11			177.16	8.0	198.38

```
MTB > MANN-WHITNEY ON DATA EXP MOD
    EXP        N =  9     MEDIAN =       172.59
    MOD        N =  2     MEDIAN =       176.50
    A POINT ESTIMATE FOR ETA1-ETA2 IS  0.0000000
    A 95.0 PERCENT C.I. FOR ETA1-ETA2 IS  (  0.000000,    0.000000)
    W =       53.0
    TEST OF ETA1 - ETA2  VS.  ETA1  N.E.  ETA2
    THE TEST IS SIGNIFICANT AT     .9062
    CANNOT REJECT AT ALPHA = 0.05

*ERROR * COMPLETION OF COMPUTATION IMPOSSIBLE
*ERROR * ALL VALUES IN COLUMN ARE IDENTICAL
```

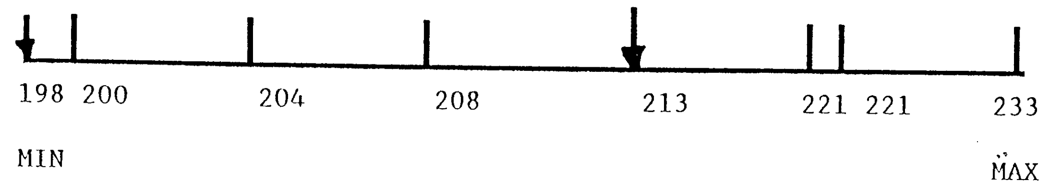
Table 7. Statistical Results for Upper Layer Temperature in the Burn Room of Set 1 at Time Step 40 Seconds



Row	EXP	MOD	MOD + EXP	MOD + EXP RANKED	MOD + EXP ORDERED
1	224.37	225.5	225.50	7.5	207.69
2	222.79	225.5	225.50	7.5	221.29
3	223.96		224.37	5.0	222.79
4	233.54		222.79	3.0	223.96
5	221.29		223.96	4.0	224.37
6	207.69		233.54	10.0	225.31
7	225.31		221.29	2.0	225.50
8	232.46		207.69	1.0	225.50
9	236.18		225.31	6.0	232.46
10			232.46	9.0	233.54
11			236.18	11.0	236.18

```
MTB > MANN-WHITNEY ON DATA EXP MOD
    EXP        N =  9     MEDIAN =      224.37
    MOD        N =  2     MEDIAN =      225.50
    A POINT ESTIMATE FOR ETA1-ETA2 IS  0.0000000
    A 95.0 PERCENT C.I. FOR ETA1-ETA2 IS  (  0.000000,     0.000000)
    W =      51.0
    TEST OF ETA1 - ETA2  VS.  ETA1  N.E.  ETA2
    THE TEST IS SIGNIFICANT AT     .5557
    CANNOT REJECT AT ALPHA = 0.05
*ERROR * COMPLETION OF COMPUTATION IMPOSSIBLE
*ERROR * ALL VALUES IN COLUMN ARE IDENTICAL
```

Table 8. Statistical Results for Upper Layer Temperature in the Burn Room of Set 1 at Time Step 70 Seconds



Row	EXP	MOD	MOD + EXP	MOD + EXP RANKED	MOD + EXP ORDERED
1	213.84	198	198.00	1.5	198.00
2	213.43	198	198.00	1.5	198.00
3	204.37		213.84	7.0	200.45
4	220.75		213.43	6.0	204.37
5	233.63		204.37	4.0	208.15
6	200.45		220.75	8.0	213.43
7	208.13		233.63	10.0	213.84
8	221.03		200.45	3.0	220.75
9			208.15	5.0	221.03
10			221.03	9.0	233.63

```
MTB > MANN-WHITNEY ON DATA EXP MOD
    EXP         N =  8     MEDIAN =       213.63
    MOD         N =  2     MEDIAN =       198.00
    A POINT ESTIMATE FOR ETA1-ETA2 IS  0.0000000
    A 95.0 PERCENT C.I. FOR ETA1-ETA2 IS  (  0.000000,    0.000000)
    W =        52.0
    TEST OF ETA1 - ETA2  VS.  ETA1  N.E.  ETA2
    THE TEST IS SIGNIFICANT AT      .0502
    CANNOT REJECT AT ALPHA = 0.05
*ERROR * COMPLETION OF COMPUTATION IMPOSSIBLE
*ERROR * ALL VALUES IN COLUMN ARE IDENTICAL
```

4.7 Conclusions

Due to the nature of the experimentation, three possible situations become apparent. These are:

A. Prediction of the model falls within the range of experimental data. This situation will be termed, arbitrarily, as the accurate prediction region, or

B. Prediction of the model falls to the left of the experimental data. This situation will be termed, arbitrarily, as the underprediction region, or

C. Prediction of the model falls to the right of the experimental data. This situation will be termed arbitrarily as the overprediction region.

If one could obtain additional experimental data and perform statistical analysis, it would be expected to encounter a shift from one prediction region to another. Therefore, it would be conceivable that a major data change would reverse the present conclusions. In addition, it should be stressed that it is not the spread of data that influence the significance level but rather the rank of individual observations. For example, suppose that originally the rank of the experimental median was 5.5, while the rank of the model median was 6.5 which induced a significance level of 80%. Now, if additional experimental values were provided, both experimental and model medians would change which may or may not change, the significance level. However, the significance level would increase if experimental and model median ranks get closer. Similarly, the significance level would decrease if the experimental and model median ranks get farther apart.

The criteria for performance validation of a deterministic model seems to be lenient, in regard to how well the fire model performed against experiments of full-scale testing. Indeed, a deterministic model would not be under binary constraints of a pass/fail basis. In light of the scheme of under, accurate, and overprediction of the fire model, Tables 9, 10, 11 and 12 illustrate the time-varying behavior of chosen parameters for respective locations and sets of data. Note that the point estimate and the respective confidence estimate interval are both null for all analyses. This is due to the nature of observations of the model sample, that is, they are all identical.

From Tables 5, 6, 7, and 8, one may conclude the following.

A. Burn room-corridor with corridor doorway open exhibits reasonably accurate prediction for primarly the burn room.

B. Burn room-corridor with closed corridor doorway exhibits general underprediction.

Table 9. Summarized Conclusions of Statistical Treatment of Set 1

LOCATION	PARAMETER	BEHAVIOR PARAMETER THROUGH SIMULATION TIME (SECONDS)	REMARKS
Burn Room	Upper Layer Temperature	Fluctuation of under predicting to accurate prediction during the first 80 seconds. Over prediction from 80 to 380 seconds. From 380 seconds to the end accurate prediction.	N.A.
Burn Room	Upper Layer of Smoke	Starting with underprediction for the first 30 seconds, it shrinks to accurate prediction to around 200 seconds. It then overpredicts.	Overprediction range of 0.30 to .50 meters
Corridor	Upper Layer Temperature	General overprediction of the model over the model over experimental results.	Overprediction range of 5 to 25°C.
Corridor	Upper Layer of Smoke	Starting with an underprediction for the first 80 seconds then peaking to very good accuracy followed by a general overprediction.	Overprediction range of 0.20 to 0.50 meters.

Table 10. Summarized Conclusions of Statistical Treatment of Set 2

LOCATION	PARAMETER	PARAMETER BEHAVIOR THROUGH SIMULATION TIME (SECONDS)	REMARKS
Burn Room	Upper Layer Temperature	General underprediction	Underprediction range of 40 to 60°C.
Burn Room	Upper Layer of Smoke	General underprediction	Underprediction range of 0.60 to 1.0 meters.
Corridor	Upper Layer Temperature	General underprediction	Underprediction range of 50 to 70°C.
Corridor	Upper Layer of Smoke	General underprediction	Underprediction range of 1.0 to 2.0 meters.

Table 11. Summarized Conclusions of Statistical Treatment of Set 3.

LOCATION	PARAMETER	BEHAVIOR OF PARAMETER THROUGH SIMULATION TIME (SECONDS)	REMARKS
Burn Room	Upper Layer Temperature	General accurate prediction.	Short underprediction between 40 to 60 sec.
Burn Room	Upper Layer of Smoke	Ranging from a short underprediction to to adequate accuracy to some overprediction overrules.	
Corridor	Upper Layer Temperature	Excluding a change from under to accurate prediction, overprediction overrules.	Overprediction range of 5 to 10°C.
Corridor	Upper Layer of Smoke	Underprediction in the first third of the simulation followed by an acurate prediction (100 sec) than underprediction (100 sec), accurate prediction (80 sec) then overprediction.	N.A.
Target Room	Upper Layer Temperature	Prediction (100 sec) then underprediction (100 sec), accurate prediction (80 sec) then finally overprediction.	N.A.
Target Room	Upper Layer of Smoke	Starting underprediction, the accurate prediction to overprediction back down to accurate and finally overpredicting.	Underprediction - 5 - 10°C. Overprediction - 10 - 20°C.

Table 12. Summarized Conclusions of Statistical Treatment of Set 4.

LOCATION	PARAMETER	SIMULATION TIME (SECONDS)	REMARKS
Burn Room	Upper Layer Temperature	Underprediction of first 50 to 100 seconds, the rest is accurate prediction.	N.A.
Burn Room	Upper Layer of Smoke	Unprediction during the first 50 seconds then accurate prediction for the rest of simulation.	
Corridor	Upper Layer Temperature	Underprediction for the first 30 seconds then relative accurate prediction for up to 200 seconds, followed by overprediction.	Underprediction range of 5 to 15°C.
Corridor	Upper Layer of Smoke	General Underprediction.	Underprediction range of 1.0 to 0.2 meters
Target Room	Upper Layer Temperature	Underprediction (0-160 sec), then accurate prediction, followed by a general overprediction.	Underprediction range of 8 - 10°C. Overprediction range of 8 - 15°C.
Target Room	Upper Layer of Smoke	General Underprediction.	Underprediction range of 1.2 to 0.2 meters

C. Burn room-corridor-target room with corridor doorway closed exhibits a reasonable accuracy for the burn room. The remaining locations go through an underprediction phase (100-150 sec), followed by a brief accuracy phase (50-100 sec), finally a substantial overprediction phase (200-400 sec).

D. Burn room - corridor - target room with corridor doorway open exhibits reasonable accuracy for the burn room. The remaining locations portray general underprediction.

In general, one could conclude that there is a reasonably accurate prediction at the burn room, for all scenarios. Scenarios where the corridor doorway is closed exhibit more underprediction than overprediction. Similarly, scenarios where the corridor doorway is open exhibit more underprediction and overprediction but with less deviation.

4.8 Recommendations

To enhance the robustness of the statistical methodology for performance validation, one would need to consider the following recommendations:

A. As expected, an increase in the number of replication of experiments is highly desirable. A range of 12 to 15 replications would make the experiment more informative. This would also increase the accuracy of the model against reasonable experimental data. Because of expenditure and effort required in full-scale burns, it is suggested to focus on extreme fire sizes. It is suggested to generate an experimental data base that would focus on small fires and large size fires. For example, 100kW and 500kW fires with respectively larger replication numbers would have more benefit than gathering data from 100, 300, and 500kW fires characterized by relatively fewer replications.

B. Once timely data are obtained, it would be very helpful and informative to do a preliminary analysis through descriptive statistics. This exercise could potentially assist in selecting proper statistical methods to treat data.

C. Because of the clear trend of poor accuracy of the model beyond the burn room, it is necessary to verify the model assumptions and equations. In particular, flow entrainment appears to be a major influence on temperature and smoke density predictions beyond the burn room. Therefore, either a systematic or a selective verification could reveal potential changes needed to improve predictions of the model.

5. GENERAL CONCLUSIONS

In order to further fire science and to encourage the use of fire models, users should be aware of the sensitivity of input parameters. Users also should be informed of the level of accuracy for variables of interest.

The general conclusions, from both in-depth studies, namely validation studies, are summarized below.

Users should exercise care when exercising fire model (FAST version 17) for the following input parameters.

A. Thermophysical properties of boundaries of enclosures,

B. Fuel and its characteristics. Fire location is also included, and

C. Attributes of physical height of rooms and eight openings. Increasing the number of rooms is discouraged.

The level of accuracy in predicting behavior of fire attributes in a multi- compartment structure is dependent upon the physical configuration considered.

For a comparatively small gas-burner fire (100kW), the fire model did reasonably and accurately predict upper layer temperature and smoke thickness in the burn room. Beyond the burn room, the fire model prediction of both upper layer temperature and smoke thickness were poor.

6. GENERAL RECOMMENDATIONS

To improve the quality of fire models and to address the urgent needs of the paramount problems of fire safety in this nation, the following recommendations must be stated and acted upon.

Parallel to the studies undertaken, two sets of recommendations will follow. The first set of recommendations focuses on the nature of the sensitivity analysis. The second set addresses issues on the consequences of the performance fire model validation.

Once more, it must be stressed that it is extremely important to provide complete and sufficient documentation as well as conducting a verification exercise of the fire model under scrutiny. In addition, the following must be considered:

A. Focus on the apparent sensitive input paramenters such as the thermophysical properties of the enclosures' boundaries.

B. Determine a proportionality relationship of those establihed sensitive input parameters.

C. Investigate input paramenters not considered in this present study and perform the above two tasks.

Since the zone model utilized to conduct the performance validation has been the subject of a re-evaluation of its basic assumptions, physics, numerics, it would be useful to initiate one or two options.

The first option is to "retire" the present zone model ad focus on the development of an "improved", well documented, verified zone model. This improved model would be based upon the present model with the inclusion of the state-of-the-art fire research findings. This model would ideally integrate functional building features such as atrium, smoke detection, heat ventilation air conditioning (HVAC) systems and sprinkler systems.

The second option would be to solidify the present zone model by providing complete and sufficient documentation, verifying it, and by fixing its physics and/or numerics so that it predicts what is theory, it was supposed to predict accurately.

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APPENDICES

APPENDIX A

This appendix illustrates the partial plan for fractional factorial using 16 factors. This plan has been extracted from a Government publication. The plan was labeled 256.16.8 which symbolizes 1/256 replication of 16 factors in 32 blocks of 8 units each.

Factors: A, B, C, D, E, F, G, H, J, K, L, M, N, O, P, S.

Completely
Randomized: All two-factor interactions except CE, CE, CF, CK, EF, EK, FK are measurable.

Blocks:

1 (1) bdghjlmn cefgjklmops bcdefhknops acdefhklmp abcefgjknp adghjos ablmnos	2 bcefghkl 5 abcdefghjklmn 8 adlo 11 cdegjno	3 jlmno 6 adjmn 9 cdeglm 12 bdfhjklno	4 bcefghjkmno 7 abcdefghko 10 bdfhkm 13 abfhjkn
14 aegjln	15 abfhklmo	16 acegmo	17 cfglmnp
18 bekmnp	19 efgop	20 behjklop	21 abdehjkp
22 acdfgjlp	23 abdehklmnop	24 acdfgmnop	25 defnp

26	27	28	29
bcdghklnp	defjmop	bcdghjkmop	abcghjkmp
30	31	32	
aefjp	abcghknop	aelnop	

NOTE: a) The symbol (1) is used to specify that all factors are at low level

b) The presence of a letter indicates the high level of that factor; its abscence denotes the low level. For example, in block 32 (aelnop) treatment aelnop indicates that A, E, L, N, O, and P are set at high-level; and B, C, D, F, G, H, J, K, M, and S are set a low-level.

APPENDIX B

From the plan illustrated in Appendix A, 256 treatments or run scenarios have been generated and a sample from it follows.

Note that there is no blocking involved in this study; the labeled blocks were used for convenience only. Each block is comprised of eight (8) runs. The following Appendix (Appendix C) is the result Block 21, RUN2, for the high/low levels assignment, as it is stated at the end of RUN021.

Block 20

0	1	0	0	1	0	0	1	1	1	1	0	0	1	1	0
1	1	1	0	0	1	0	1	1	0	1	0	0	0	0	1
1	0	0	1	1	0	0	0	1	1	1	0	1	1	1	0
1	1	0	0	1	0	1	1	0	1	0	1	0	1	1	0
0	0	0	0	1	0	1	1	0	1	1	0	1	0	1	1
0	1	0	1	1	0	0	0	1	1	0	1	0	0	1	1
0	0	1	0	0	1	0	1	1	0	0	1	1	1	0	0
0	1	1	1	0	1	1	0	0	0	1	0	0	1	0	0

Block 21

1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	0
0	1	1	1	0	1	0	1	1	0	0	0	0	1	0	1
0	0	0	0	1	0	0	0	1	1	0	0	1	0	1	0
0	1	0	1	1	0	1	1	0	1	1	1	0	0	1	0
1	0	0	1	1	0	1	1	0	1	0	0	1	1	1	1
1	1	0	0	1	0	0	9	1	1	1	1	0	1	1	1
1	0	1	1	0	1	0	1	1	0	1	1	1	0	0	0
1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0

Figure B-1. Partial Output of File "ZEROS"

APPENDIX C

From the generated computer file (ZEROS) a computer program was designed to produce the respective 256 runs. Those runs have been set up in such a way that they include required system commands (CYBER 205) followed by the required format the model needs to be exercised. Capitalizing on the planned modularity of the number of created files, a set of complex system commands has been completed to run all of the 256 runs using a two step procedure. Also, individual runs can be selected to produce any output of interest.

```
VERSN     017 MULTIPLE CONNECTED COMPARTMENTS
TIMES     360 60 L0 0 0 .1
NROOM     4
NMXOP     1
TAMB      273
HI/F      0..  0.  0.  0.
WIDTH     7.0 7.0 7.0 7.0
DEPTH     8.0 7.0 8.0 8.0
HEIGHT    2.5 2.5 2.5 2.5
HVENT     1 2 2.0 1.5  .0
HVENT     2 3 2.0 1.5  .0
HVENT     3 4 2.0 1.5  .0
HVENT     4 5 2.0 1.5  .0
CEILI
COND      .00018 .00018 .00018 .00018
SPHT        .9   .9   .9   .9
DNSTY      790   790   790   790
THICK     .015  .015  .015  .015
EMISS       .9   .9   .9   .9
WALLS
COND      .00018 .00018 .00018 .00018
SPHT        .9   .9   .9   .9
DNSTY      790   790   790   790
THICK     .015  .015  .015  .015
EMISS       .9   .9   .9   .9
FLOOR
COND      .00018 .00018 .00018 .00018
SPHT        .9   .9   .9   .9
DNSTY      790   790   790   790
THICK     .015  .015  .015  .015
EMISS       .9   .9   .9   .9
LFBO     1  ROOM OF ORIGIN
LFBT     1  TYPE OF FIRE
LFPOS    1
CHEMI    1.0 0.0 0.0 0.0 0.0 50000 300
LFMAX    1
FTIME    900
FMASS     .004  .004
FHIGH    .1 .1
CO  .02
OD  .02
A SUMMARY OF BLOCK 21 RUN  2  (SEE FILE RUN 162)
 A B C D E F G H J K L M N O P S
 0 1 1 1 0 1 0 1 1 0 0 0 0 1 0 1
```

Figure C-1. Input File - Run #162

APPENDIX D

The following is a typical output that has been modified to form an eventual matrix (ALLDAT) composed of nine columns, and these are the following:

A. Column 1 represents the simulation time steps with ten (10) second increments up to 360 seconds,

B. Columns 2, 4, 6, and 8 are the upper temperature values for rooms 1, 2, 3, and 4, respectively, and

C. Columns 3, 5, 7, and 9 are the upper layer values for rooms 1, 2, 3, and 4, respectively.

Note that time step starts with the number "1" which symbolizes the initial simulation conditions that is time-step zero (0).

Figure D-1 illustrates a complete output for a two-compartment scenario, followed by the start of an output for a four-compartment scenario.

1	273.0	0.00	273.0	0.00				
11	334.8	0.16	273.0	0.00				
21	347.5	0.55	273.0	0.00				
31	360.0	0.84	273.1	0.00				
41	368.8	1.00	273.1	0.00				
51	371.0	1.04	279.5	0.01				
61	376.1	1.11	292.3	0.03				
71	380.9	1.17	298.5	0.08				
81	385.6	1.21	302.8	0.14				
91	390.6	1.25	306.5	0.21				
101	396.8	1.28	310.8	0.33				
111	403.9	1.31	314.7	0.47				
121	411.2	1.32	317.9	0.63				
131	418.4	1.33	321.2	0.80				
141	425.5	1.33	324.0	0.98				
151	432.3	1.33	327.9	1.13				
161	439.0	1.34	333.4	1.22				
171	445.6	1.34	339.0	1.28				
181	452.0	1.35	344.5	1.32				
191	458.2	1.36	350.3	1.34				
201	464.4	1.37	355.9	1.35				
211	470.4	1.38	361.7	1.36				
221	476.1	1.38	367.8	1.36				
231	481.8	1.38	373.8	1.36				
241	487.3	1.38	379.8	1.36				
251	492.4	1.39	386.1	1.36				
261	497.4	1.38	392.2	1.36				
271	502.1	1.38	398.3	1.35				
281	506.5	1.38	404.5	1.35				
291	510.7	1.38	410.4	1.35				
301	514.6	1.38	416.2	1.34				
311	518.2	1.38	422.2	1.34				
321	521.7	1.38	427.7	1.33				
331	524.8	1.38	433.1	1.33				
341	527.7	1.37	438.6	1.33				
351	530.4	1.37	443.6	1.32				
361	532.9	1.37	448.5	1.32				
1	330.0	0.00	330.0	0.00	330.0	0.00	330.0	0.00
11	417.0	0.13	328.7	0.00	329.3	0.00	329.3	0.00
21	428.4	0.47	328.7	0.00	329.3	0.00	329.3	0.00
31	438.5	0.73	328.7	0.00	330.0	0.00	329.3	0.00
41	448.0	0.95	328.7	0.00	330.0	0.00	329.3	0.00
51	451.1	1.01	330.0	0.00	330.0	0.00	329.9	0.00
61	456.1	1.10	346.3	0.05	330.0	0.00	329.3	0.00
71	463.6	1.22	360.5	0.24	330.0	0.00	329.3	0.00
81	469.5	1.30	367.5	0.54	329.3	0.00	329.3	0.00
91	474.1	1.35	371.4	0.87	329.3	0.00	329.3	0.00
101	475.7	1.37	372.6	1.01	330.0	0.00	329.9	0.00
111	477.3	1.39	374.5	1.13	332.6	0.02	329.3	0.00
121	480.5	1.43	379.9	1.26	337.6	0.13	329.3	0.00
131	483.2	1.47	384.6	1.32	339.8	0.29	329.3	0.00
141	485.5	1.50	388.3	1.35	341.2	0.45	329.3	0.00
151	487.3	1.54	391.2	1.36	342.3	0.60	329.3	0.00

Figure D-1. Complete and Partial Output for Two- and Four-Compartment Scenarios, Respectively

APPENDIX E

The output from the 256 runs stored in a file (NEWDATA) in conjunction with file ZEROS lead to the calculation of the sensitivity coefficients. For illustration purposes a fictitious simple example is utilized to illustrate how to generate those coefficients for a two level factorial experiment.

Let us consider a given system where among its numerous parameters, four are the focus of a sensitivity analysis study. These parameters or factors are A, B, C, and D, respectively, and serve as inputs to the system (model) of interest. In addition to the four parameters, two interactions are to be investigated. This illustrative example is for 16 treatments or runs as shown on Table E-1.

Followed by Table E-1 are two typical calculations of main effects and interactions to determine sensitivity coefficients.

Table E-1. Factorial Matrix and Response of System

	FACTORS				INTERACTIONS						
Treat-ment	A	B	C	D	AB	BD	ABC	ABD	ACD	ABCD	Re-sponse
1	0	0	0	0	1	1	0	0	0	1	71
2	1	0	0	0	0	1	1	1	1	0	61
3	0	1	0	0	0	0	1	1	0	0	90
4	1	1	1	0	1	0	0	0	1	1	82
5	0	0	1	0	1	1	1	0	1	0	68
6	1	0	1	0	0	1	0	1	0	1	61
7	0	0	1	0	0	0	0	1	1	1	87
8	1	1	0	0	1	0	1	0	0	0	80
9	0	0	0	1	1	0	0	1	1	0	61
10	1	0	0	1	0	0	1	0	0	1	50
11	0	1	1	1	0	1	1	0	1	1	89
12	1	1	1	1	1	1	0	1	0	0	83
13	0	0	1	1	1	0	1	1	0	1	59
14	1	0	0	1	0	0	0	0	1	0	51
15	0	1	0	1	0	1	0	0	0	0	85
16	1	1	0	1	1	1	1	1	1	1	78

NOTE:

1 Symbolizes high level value allocation for respective factors and interactions

0 Symbolizes low level value allocation for respective factors and interactions

Calculation of main effect B:

(-71-61+90+82-68-61+67+80-61-50+89+83-59-51+85+78)/8=24.00

Similarly, the calculation of interaction effect ABCD:

(+71-61-90+82-68+87-80-61+50+89-83+59-51-85+78)/8=-0.25

Because of the absence of an estimate of standard error, interactions ABC, ABD, ACD, and ABCD have been selected to be used to obtain an estimate of standard error, assuming that the three and four-factor interactions are negligible. This estimate is a measure of the differences emanating primarily from experimental error.

Table E-2 summarizes the effects of single factors and their interactions, followed by Table E-3 showing relevant values leading to the standard deviation calculation.

Table E-2. Summary of Effects for Single Factors and Interactions

Factors and Interactions	Effect
A	-8.00
B	24.00
C	-2.25
D	-5.50
AB	1.00
BD	4.50
ABC	-0.75
ABD	0.50
ACD	-0.25
ABCD	-0.25

The closer the effect of factors and interactions to zero (0), the less sensitive they are. That constitutes the basic criteria for sensitivity. It follows that factor B is more sensitive than factor A, etc. Note that the higher in order of interaction the lower the absolute value of the corresponding effect.

Table E-3. Higher Order Interactions to Estimate Standard Error

Interactions	Effect	$(\text{Effect})^2$
ABC	-0.75	0.5625
ABC	0.50	0.2500
ACD	-0.25	0.065
ABCD	-0.25	-.065
	TOTAL =	0.9425

Table E-4 summarizes the factors and interactions of interest as well as their respective effects and standard deviation.

Table E-4. Summary of Estimated Effects with Their Standard Deviations

Factors and Interactions	Effect	Standard Deviation
A	-8.00	± 0.20
B	24.00	± 0.20
C	-2.25	± 0.20
D	-5.50	± 0.20
AB	1.00	± 0.20
BD	4.50	± 0.20

Apriori, factors A, B, and D seem to be most sensitive, because of the relatively high effect values. Also, interaction BD appears to be sensitive, for the same reason.

VITA

Nadir Khoudja was born on July 23, 1953 in Algiers. He has been in the United States since 1975. He received a Bachelor of Science degree in Fire Protection and Safety Engineering from the Illinois Institute of Technology, Chicago, Illinois in June, 1980.

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The increasing number of users of fire models demands their validation by a third party team to investigate the reliability of the models with respect to concerns of potential users. Due to insufficient documentation of the subject fire model, verification of it was limited and informal. However, quantitative and detailed procedures for sensitivity study and performance validation were applied. A deterministic model, predicting fire behavior in structure, was selected to illustrate partial model assessment procedures. The development and application of two generic methodologies for sensitivity analysis and performance validation are described. The subject fire model is FAST from which 16 input parameters were selected for sensitivity analysis study. Comparative Graphical Results are illustrated over simulation time for the input parameters.

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