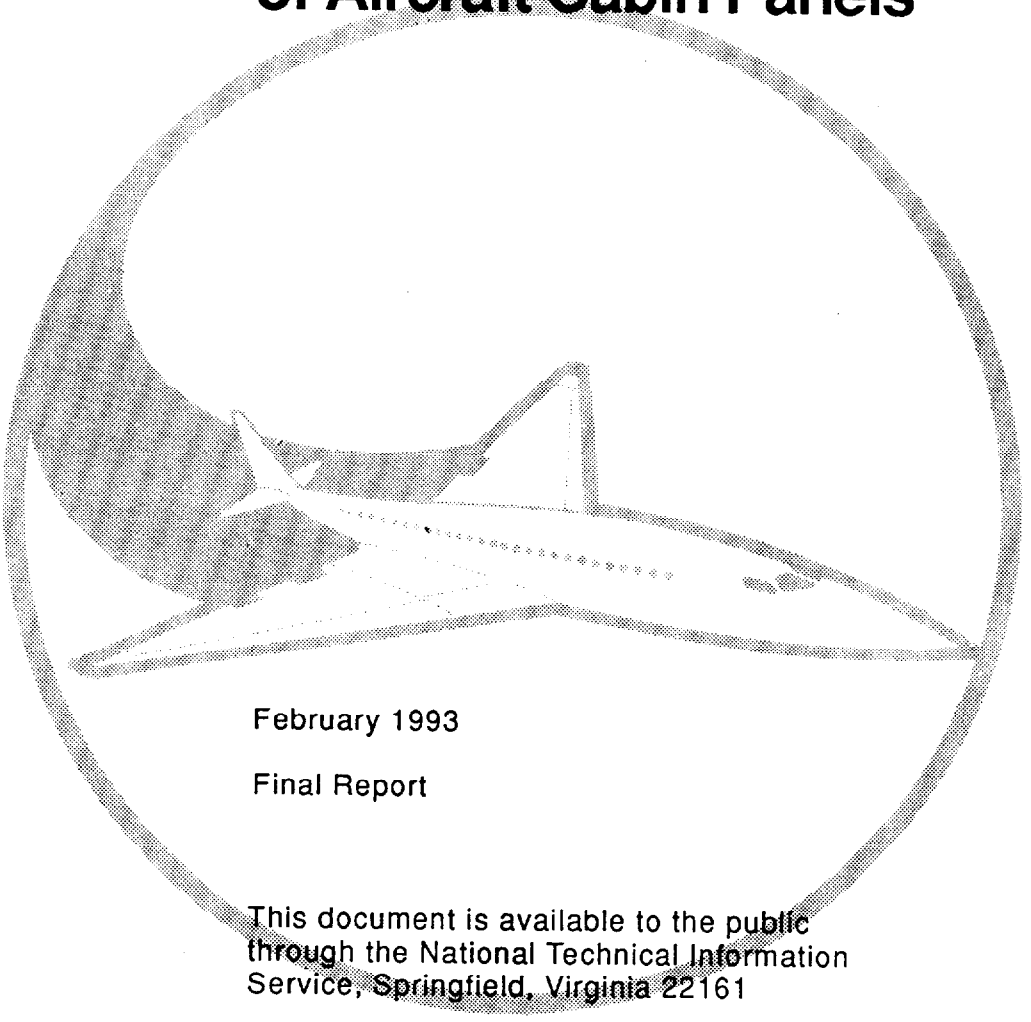
DOT/FAA/CT-92/3

FAA Technical Center
Atlantic City International Airport
N.J. 08405

Modeling the Heat Release Rate of Aircraft Cabin Panels



February 1993

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Pag

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-92/3		

4. Title and Subtitle	5. Report Date
MODELING THE HEAT RELEASE RATE OF AIRCRAFT CABIN PANELS	February 1993
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
W.J. Parker (NIST) and R. Filipczak (FAA)	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
National Institute of Standards and Technology U.S. Department of Commerce Gaithersburg, MD 20899	11. Contract or Grant No. DTFA 03-87-A-0005
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405	Final Report
	14. Sponsoring Agency Code ACD-240

15. Supplementary Notes

16. Abstract

A computer model was developed to calculate the heat release rate of aircraft cabin composite panels based on the panel's thermophysical, chemical, and geometric properties. The model calculates the temperature through the panel as a function of time and uses this along with measured kinetic constants to deduce mass loss rate which is multiplied by the heat of combustion of the volatiles. The calculated results are in general agreement with the measured heat release obtained from the Ohio State University (OSU) calorimeter.

17. Key Words	18. Distribution Statement
Heat Release Rate Calorimeter Fire	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	52	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

EXECUTIVE SUMMARY vii

1. INTRODUCTION 1

2. DESCRIPTION OF CABIN PANELS 2

3. HEAT RELEASE RATE MODEL 3
   3.1 Description 3
   3.2 Internal Radiative Heat Transfer 4
   3.3 Surface Heat Transfer 5
   3.4 Energy Equations 6
   3.5 Mass Loss Rate Calculations 7
   3.6 Heat release Rate Calculations for OSU Calorimeter 8
   3.7 Computer Implementation 8

4. THERMOPHYSICAL PROPERTIES 9
   4.1 Thermal Conductivity 9
   4.2 Specific Heat 10
   4.3 Emissivity 10

5. THERMOCHEMICAL PROPERTIES 10
   5.1 Kinetic Constants 10
   5.2 Heat of Combustion of the Volatiles 12
   5.3 Heat of Pyrolysis 12

6. HEAT RELEASE RATE MEASUREMENTS 12
   6.1 OSU Calorimeter 12
   6.2 Cone Calorimeter 13

7. COMPARISON OF CALCULATED AND MEASURED RESULTS 13
   7.1 Temperature 13
   7.2 Heat Release Rate 13

8. DISCUSSION AND CONCLUSIONS 15

9. REFERENCES 16

APPENDIX - COMPUTER PROGRAM

LIST OF TABLES

1. Property Values Used in Calculations. 18

2. Parameters Required by the Model 19

3. Peak Heat Release Rates and Two Minute Total Heat Releases for Panels A, B and C. 19

LIST OF FIGURES

1. Model of Single Honeycomb Cell. 20

2. Model for View Factor Calculation. 20

3. Model for Calculating Heat Release Rate in OSU. 21

4. TGA Plot for Panel A. 22

5. Arrhenius Plot for Panel A (High Temperature Reaction). 22

6. Arrhenius Plot for Panel A (Intermediate Temperature Reaction). 23

7. Arrhenius Plot for Panel A (Low temperature Reaction). 23

8. Surface and Interior Temperatures for Panel A in OSU at an Exposure of 35 kW/m^2. 24

9. Heat release Rate of Panel A in Cone at 35 kW/m^2. 24

10. Calculated Contributions of Panel A Components to the Heat Release Rate at an Exposure of 35 kW/m^2. 25

11. Heat release rate of Panel A in OSU at 35 kW/m^2. 25

12. Heat release rate of Panel B in Cone at 35 kW/m^2. 26

13. Heat release rate of Panel B in OSU at 35 kW/m^2. 26

14. Heat release rate of Panel C in Cone at 35 kW/m^2. 27

15. Heat release rate of Panel C in OSU at 35 kW/m^2. 27

16. Heat release rate of Panel A in Cone at 30 kW/m^2. 28

17. Heat release rate of Panel A in Cone at 40 kW/m^2. 28

18. Heat Release Rate of Panel 2 in Cone at 35 kW/m^2. 29

19. Heat Release Rate of Panel 1 in Cone at 35 kW/m^2. 29

LIST OF ABBREVIATIONS

A ------ Pre-exponential factor (s^{-1})
b ------ Parameter used in view factor calculation (-)
B ------ Blowing Factor (-)
c ------ Specific heat (kJ/kg-K)
E ------ Activation Energy (kJ/mole)
f(i,j) - Radiation view factor from element i to element j (-)
F ------ Radiation View factor Between Facing Squares
g ------ Acceleration due to gravity (9.8 m/s^2)
h ------ Convective heat transfer coefficient ($kW/m^2.K$)
h_{in} ---- Rate of flow of enthalpy in the incoming air (kW)

h_{out} --- Rate of flow of enthalpy in the exhaust duct (kW)

h_{vol} --- Enthalpy flux of volatiles through the surface (kW/m^2)

k_{air} --- Thermal conductivity of air (kW/m-K)

k_{sol} --- Thermal conductivity of solid (kW/m-K)

ℓ ------ Plate height (m)
L ------ Honeycomb core thickness (m)
$\dot{m}''$ ----- Mass loss rate per unit area (kg/m^2-s)
$\dot{m}°''$----- Value of $\dot{m}''$ with no blowing (kg/m^2-s)
N ------ Number of Honeycomb elements (-)
p ------ Width of plate (m)
$\dot{q}''_{OSU}$ -- Measured heat release rate in OSU calorimeter (kW/m^2)

$\dot{q}''_{hrr}$ -- Heat release rate (kW/m^2)

$\dot{q}''_{cond}$ - Conduction heat flux (kW/m^2)

Q ------ Total convective heat transfer to vertical plate (kW/m^2)
R ------ Gas constant (8.134 J/mole-K)
S ------ Surface area (m^2)
T ------ Temperature (K)
T_f------ Flame temperature after ignition (K)

T_o ----- Ambient temperature prior to ignition (K)

v ------ Kinematic Viscosity (m^2/s)
w ------ Thickness of facing (m)
x ------ Thickness of cell wall (m)
y ------ Cell width (m)
z ------ Depth of each honeycomb element (m)
Z ------ Ratio of the mass of each element to its original mass (-)
Z_f ----- Residual value of Z at end of pyrolysis (-)

$\dot{Z}$ ------ Fractional mass loss rate (-)
ε ------ Emissivity of front face (-)
ε_r ----- Emissivity of rear face (-)

σ ------ Stefan Boltzmann constant ($kW/m^2.K^4$)
ρ ------ Density (kg/m^2)
τ ------ Time step (s)
X_R ----- Radiative fraction (-)

SUBSCRIPTS

cond --- heat conduction
eff ---- effective value
e ------ external
f ------ final value
fr ----- flame radiation
o ------ ambient value
sol ---- solid
vol ---- volatiles

EXECUTIVE SUMMARY

A computer model was developed to calculate the heat release rate of aircraft cabin composite panels in the Ohio State University (OSU) calorimeter. The model is based on the panel's thermophysical, thermochemical and geometrical properties. The model calculates the temperature profile through the panel as a function of time and uses this along with the measured kinetic constants of the individual materials to deduce the mass loss rate history. This mass loss rate is multiplied by the heat of combustion of the volatiles to obtain the heat release rate which would be measured in the Cone calorimeter. This heat release rate is used in an energy balance at the surface of the specimen to calculate the rise in enthalpy of the flue gases in the OSU calorimeter and thus its heat release rate. The model can be used on a desk top computer and is user friendly. The heat release rates calculated for various types of panels under different exposure conditions were compared with the heat release rates measured in the Cone calorimeter at the National Institute of Standards and Technology and the OSU calorimeter at the Federal Aviation Administration Technical Center. In spite of the gross assumptions made to simplify this complex problem, the calculated results are in general agreement with the measurements. The model can be used to look at the effects of external heat flux, panel thickness, cell size, and relative amounts of the different materials present along with their thermochemical and thermophysical properties.

1. INTRODUCTION

The purpose of this project was to provide a computer model which will (1) predict the heat release rate of aircraft cabin panels in the Ohio State University (OSU) calorimeter as modified by the Federal Aviation Administration, (2) identify the contributions of the individual layers to the heat release rate of the panel assembly, and (3) determine the sensitivity of the heat release rate to the incident heat flux, panel thickness, core size, and to the properties of the facing materials and the decorative coatings. The motivation is to be able to predict the fire performance of a particular panel design without actually constructing and testing it.

At least 15 percent of all fatalities in transport aircraft accidents are a result of fire [1]. The flammability of the cabin lining materials can be a contributing factor in the deaths that occur during low impact, survivable accidents. The FAA established a committee in June of 1978 to examine the factors affecting the ability of the aircraft occupants to survive in the post crash environment and the range of solutions available. This committee, known as the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee was composed of fire safety experts from the National Aeronautics and Space Administration, FAA, the aerospace industry and the general public. They recommended the development of safer cabin materials and the implementation of a method using radiant heat to evaluate their flammability. The OSU calorimeter was chosen for this purpose based on a preliminary examination of existing flammability test methods with 1/4 scale cabin modeling results [2], and confirmation of these findings by full scale cabin fire tests [3]. An exposure flux of 35 kW/m^2 in the calorimeter was selected based on achieving a good correlation with full scale aircraft cabin fire tests conducted at the FAA Technical Center in Atlantic City.

The sidewall, ceiling, stowage and partition panels which line the interior of the aircraft cabins are now required to have a peak heat release rate measured in the OSU calorimeter of no greater than 65 kW/m^2 and the heat released during the first two minutes after ignition can be no greater than 65 kW min $/m^2$ [4]. The external radiant flux to be used in these measurements is 35 kW/m^2. As a result of a series of round robin studies, FAA made several modifications to the OSU calorimeter to improve its reproducibility between different laboratories [4]. For example the rear surface of the specimen is exposed to air rather than to an insulated backing as specified in the ASTM E906 standard. The specimen is wrapped in aluminum foil except for the exposed surface and is oriented vertically during the test. A wire screen may be used to help maintain thermoplastic materials in place along with a drip pan to insure the continued burning of any melted material at the required flux level. Both the upper pilot and the lower pilot specified in

ASTM E906 are used simultaneously in these tests. FAA specified modified upper pilots to assure the pilot flames are not extinguished by the combustion products.

In this project a computer model was developed to calculate the chemical heat release rate as measured by oxygen consumption in the Cone calorimeter [5]. The thermochemical and thermophysical properties were determined for use as input data to the model. The accuracy of the model was checked by measurements in the Cone calorimeter. This chemical heat release rate was then used in an energy balance to calculate the increase in the enthalpy flow through the OSU calorimeter and thus its reported heat release rate. This prediction was checked with the OSU calorimeter at the FAA Technical Center in Atlantic City. The agreement for some of the panels was within the scatter of the experimental data for the Cone and quite close to the OSU without any normalization. In other cases the need for better property data is indicated. The project has demonstrated that it is in fact possible to model the heat release rate for aircraft cabin panels in the calorimeters.

2. DESCRIPTION OF CABIN PANELS

A typical panel construction is a Nomex (TM)[1] honeycomb with facing sheets which consist of glass, Kevlar (TM) or graphite fibers which are impregnated with either epoxy or phenolic resin. In addition the exposed face will have a decorative finish. This may simply be a thin, light- colored coating of Tedlar (TM) (polyvinyl fluoride) or it may include an embossing layer on top of the facing sheet and a layer of opaque Tedlar on which the inked patterns are printed. This might be protected by a thin layer of transparent Tedlar.

Heat release rate calculations were made on five types of panels during the course of this research. Two were from the stockpile of materials used in the extensive fire research program conducted at the FAA Technical Center and at NIST. They are labeled 1 and 2, and are generally referred to as epoxy fiberglass and phenolic fiberglass, respectively. They are described in an FAA report by Quintiere et al.[6]

1. Epoxy fiberglass: Epoxy glass facings, face and back 1 ply 7781 style woven fiberglass impregnated with epoxy resin, fire retardant, and co-cured to a 1/8 in. (3.2 mm) cell, 1.8 lb (29 kg/m^3) Nomex honeycomb with a thickness of 1/4 in. (6.35 mm). The exposed surface is covered with 2 mil white Tedlar. The total panel mass was 1.8 kg/m^2.

---

[1]The use of trade names are for descriptive purposes only, and should not be construed as an endorsement by the National Institute of Standards and Technology (NIST) or the Federal Aviation Administration (FAA).

2. Phenolic fiberglass: Phenolic glass facings, face and back 1 ply 7781 style woven fiberglass impregnated with a modified phenolic resin, and co-cured to 1/8 in. (3.2 mm) cell, 1.8 lb (29 kg/m^3) Nomex honeycomb with a thickness of 1/4 in. (6.35 mm). The exposed surface is covered with 2 mil white Tedlar. The total panel mass was 2.1 kg/m^2.

The other three decorative panels were obtained from Heath Tecna specifically for this project. They were all phenolic fiberglass with a modified formulation which led to the measurement of different kinetic constants than Panel 2. These three panels were identical except for the thickness. Panels A, B and C had thicknesses of 1/4 in. (6.35 mm), 1/2 in. (12.7 mm) and 1/8 in. (3.2 mm) respectively.

3. HEAT RELEASE RATE MODEL

3.1. Description

The heat release rate model considers the aircraft cabin panel to consist of two facing sheets separated by a Nomex honeycomb as seen in figure 1. The front surface is exposed to a constant external radiant flux and the rear face is in contact with aluminum foil as it is in the OSU calorimeter. The front surface continually loses heat by thermal radiation. The emissivity of the surface is assumed to be unity. Prior to ignition of the panel surface, the surface also loses heat by convection to the surroundings. When the temperature of the surface becomes high enough to sustain flame spread from the contacting pilot, flame will quickly spread to cover the entire surface. This critical temperature will be around 200°C which is considerably lower than the ignition temperature required by a non-impinging pilot because of the additional radiation to the surface from the flame itself. The model is not very sensitive to the actual value of this critical temperature since the rate of temperature rise of the surface is very large. The surface is now heated by radiation and convection from the flame. The convective heat transfer coefficient is reduced due to blowing caused by the flow of volatile pyrolysis products from the surface during periods of significantly large mass loss rate. The rear surface loses heat to the surroundings by natural convection and by radiation from the aluminum foil which is assumed to have the emissivity of polished aluminum. The heat transfer inside the panel is by solid and gas phase heat conduction and by internal radiation. The cell walls are assumed to have an emissivity of unity. Convective heat transfer and radiation blockage by pyrolysis products inside the cells have not been taken into account. The heat of pyrolysis is also neglected. Room temperature values were found for the thermal conductivity and specific heat of the solid materials. They are both then assumed to be proportional to the absolute temperature.

The model treats this assembly as N+2 slices or elements parallel to the front surface each having a uniform temperature. The honeycomb itself is divided into N elements of equal thickness. Each of the facing sheets is taken as an individual element which contains the fiber, the resin and the decorative coating. The density and specific heat of the individual components are combined appropriately to get these properties of the slice. The number of slices, N, into which the honeycomb is divided is selected by the operator at the keyboard based on a compromise between the calculation time and the accuracy required. Only very small differences are observed if the number is greater than 10000 per meter of panel thickness. This is 60 for a 1/4 inch (6.35 mm) thick panel. The temperatures obtained from the numerical solution of the energy equation are taken to be the temperatures at the center of each element.

The Tedlar coating comes off very early in the exposure before ignition occurs and thus is not expected to contribute significantly to the heat release rate. This was borne out by the fact that phenolic fiberglass specimens produced similar results whether exposed on the rear surface or the front surface. Based on this finding the Tedlar coating was neglected in the model. Many in-use panels will often have a more complicated decorative consisting of several layers, including inks and embossing resins, which may significantly add to heat release. If the model is required to be used for more durable coatings, then the coating will be treated as part of the facing and will add another reaction whose kinetic constants will need to be determined.

3.2. Internal Radiative Heat Transfer

The energy equations are developed for a single honeycomb cell divided into N elements as seen in Figure 1. In order to determine the radiation exchange between the exposed honeycomb surfaces and the exposed portions of the facing material at each end, a set of radiation shape factors had to be calculated.

For simplicity, the hexagonal cross section of the cell was represented by a square cross section for the purpose of calculating the radiation exchange between the interior surfaces of the elements within each cell. The radiation shape factor for two parallel square surfaces of equal size facing each other and having no offset is given by

$$F = F(b) = 4[(b^2+1)^{1/2}\tan^{-1}(b/(b^2+1)^{1/2}) - \tan^{-1}(b) - \ln((2b^2+1)/(b^2+1)^2)/4b]/\pi b \qquad (1)$$

where b is the ratio of the length of one side of the square divided by the separation distance between the surfaces [9]. The radiation view factors controlling the radiation exchange among the surfaces of all of the elements were derived from this formula using the laws of reciprocity and conservation of energy(i.e. the radiation passing

in through one square face of the element minus that passing out through the other face must be that which is incident on the solid bounding area of the element as seen in Figure 2). The cross section of the cell is a square of side y. The depth of each element of the cell is z where z is equal to the thickness, L, of the core divided by the number of elements, N, into which the cell is divided. The numbers denote the surface areas of the elements and the letters indicate the cross sectional areas which form the boundaries between them. Consider the radiation exchange between elements 1 and 5. The fraction of the radiation leaving element 1 that falls on the surface of element 5 is the radiation shape factor f_{15} and the fraction of the energy leaving element 5 and falling on element one is f_{51}.

$$f_{15} = f_{1c} - f_{1d} \quad \text{(Conservation of Energy)} \tag{2}$$

$$S_5 f_{51} = S_1 f_{15} \quad \text{(Reciprocity)} \tag{3}$$

where f_{1c} and f_{1d} are the shape factors calculated from Equation 1 and S_1 and S_5 are the areas of the elements: $S_1 = y^2$, $S_5 = 4yz = 4yL/N$, $f_{1c} = F(y/3z) = F(Ny/3L)$ and $f_{1d} = F(y/4z)$.

3.3. Surface Heat Transfer

The model assumes a constant external radiant flux impinging on the surface since the objective is to calculate the heat release rate in the OSU calorimeter. The emissivity is assumed to be 1.0 throughout the exposure. The total heat transfer by laminar free convection from a smooth vertical plate of height ℓ and width p is given by Schlichting [8] as

$$Q = 0.677 p \ell^{3/4} k (T-T_o) [g(T-T_o)/(4v^2 T_o)]^{1/4} \quad kW \tag{4}$$

where k and v are the thermal conductivity and kinematic viscosity of air and g is the acceleration due to gravity. Using property data on air from Eckert and Drake [9], the ratio $k/v^{1/2}$ can be expressed as 6.51×10^{-3} $kWs^{1/2}/K$ over the range from 300 to 700 K to within ± 3 percent. The height of the specimen is 100 mm. Thus the convective heat transfer coefficient at the rear surface and also at the front surface prior to ignition is given by

$$h = 9.8 \times 10^{-3} (T/T_o - 1)^{\frac{1}{4}} \quad kW/m^2\text{-}K \tag{5}$$

The convective heat transfer coefficient to the surface from the flame is taken to be 0.025 $kW/m^2.K$. This follows from the observation that the heat transfer to water cooled heat flux gauges from weakly radiating flames to the surface is typically 30 kW/m^2 and that the flame temperature measured by a small thermocouple probe is around 1200°C. However, the convective heat transfer coefficient must be reduced by a blowing factor [10] when the rate of mass loss is high. This factor is given by

$$B = (\dot{m}''' c_{vol}/h)/(\exp(\dot{m}''' c_{vol}/h)-1) \quad kJ/kg \tag{6}$$

The specific heat of the volatiles is taken to be 1.2 kJ/kg-K and h is 0.025 kW/m^2-K. The effective heat transfer coefficient is then given by

$$h_{eff} = Bh \tag{7}$$

where B goes to 1 for low mass loss rates and 0 for high ones.

3.4 Energy Equations

Recalling that the convective heat transfer through the air in the honeycomb is neglected, the energy equations are given by:

$$\begin{aligned}\rho_1 c_1 y^2 w_1 \frac{\partial T_1}{\partial t} &= \epsilon \dot{q}_e''' y^2 - \epsilon\sigma (T^4_1 - T^4_o) y^2 \\ &-2 [k_{sol} y^2 + (k_{air} - k_{sol}) (y-x)^2] (T_1 - T_2)/z \\ &+\epsilon\sigma (y-x)^2 \sum_{j=1}^{N+2} f(1,j) (T^4_j - T^4_1) + h(T_f - T_1) y^2\end{aligned} \tag{8}$$

$$\begin{aligned}&\rho_2 c_2 [y^2 - (y-x)^2] z \frac{\partial T_2}{\partial t} = \\ &[k_{sol} y^2 + (k_{air} - k_{sol}) (y-x)^2] (2T_1 - 3T_2 + T_3)/z \\ &+4\epsilon\sigma (y-x) z \sum_{j=1}^{N+2} f(2,j) (T^4_j - T^4_2)\end{aligned} \tag{9}$$

$$\begin{aligned}&\rho_2 c_2 [y^2 - (y-x)^2] z \frac{\partial T_i}{\partial t} = \\ &[k_{sol} y^2 + (k_{air} - k_{sol}) (y-x)^2] (T_{i-1} - 2T_i + T_{i+1})/z \\ &+4\epsilon\sigma (y-x) z \sum_{j=1}^{N+2} f(i,j) (T^4_j - T^4_i)\end{aligned} \tag{10}$$

$$\begin{aligned}&\rho_2 c_2 [y^2 - (y-x)^2] z \frac{\partial T_{N+1}}{\partial t} = \\ &[k_{sol} y^2 + (k_{air} - k_{sol}) (y-x)^2] (T_N - 3T_{N+1} + 2T_{N+2})/z \\ &+4\epsilon\sigma (y-x) z \sum_{j=1}^{N+2} f(N+1,j) (T^4_j - T^4_{N+1})\end{aligned} \tag{11}$$

$$\rho_{N+2} c_{N+2} y^2 w_{N+2} \frac{\partial T_{N+2}}{\partial t} = -\epsilon_r \sigma (T^4_{N+2} - T^4_o) y^2$$
$$+2 [k_{sol} y^2 + (k_{air} - k_{sol}) (y-x)^2] (T_{N+1} - T_{N+2}) / z \qquad (12)$$
$$+\epsilon \sigma (y-x)^2 \sum_{j=1}^{N+2} f(N+2, j) (T^4_j - T^4_{N+2}) - h(T_{N+2} - T_o) y^2$$

where the first element is the exposed facing sheet and the N+2 element is the rear facing sheet. The cell width is y, w is the thickness of the facing sheet, x is the thickness of the Nomex sheet from which the honeycomb is made, z is the thickness of the slice (thickness of panel divided by the number of slices), ε is the emissivity (which is assumed to be the same as the absorptivity of all of the surfaces except for the rear face), h is the surface heat transfer coefficient, ρ is the density, c is the specific heat, k is the thermal conductivity, σ is the Stefan-Boltzmann constant, T is the absolute temperature and t is the time.

3.5 Mass Loss Rate Calculations

The fractional mass loss rate, $\dot{Z}$, at any depth (i.e. for any slice) is assumed to be governed by a first order Arrhenius equation:

$$\dot{Z} = A(Z-Z_f)\exp(E/RT) \qquad (13)$$

using the calculated temperature, T, and the mass retention fraction, Z, for that slice. The mass retention fraction is defined as the mass of the slice at any given time divided by its original mass. Z_f is the residual mass fraction at the end of the pyrolysis. A is the pre-exponential factor, E is the effective activation energy, and R is the gas constant. The local rate, $\dot{Z}$, is multiplied by the heat of combustion of the volatiles and integrated over the depth of the specimen in order to obtain the heat release rate determined from oxygen depletion as would be measured in the Cone calorimeter. Separate equations are required for each of the components. There are also additional equations needed for the competing reactions. The kinetic constants for each of these equations were determined by analysis of the TGA data as described below.

3.6 Heat Release Rate Calculations for OSU Calorimeter

The calculated heat release rate, $\dot{q}''_{OSU}$, for the OSU calorimeter is equal to the increase in the enthalpy flow of the exhaust gases, $\dot{h}_{out} - \dot{h}_{in}$, divided by the area, A, of the specimen. This calculation takes into account the external heat flux, $\dot{q}''_e$, chemical heat release rate (as calculated for the Cone calorimeter), $\dot{q}''_{hrr}$, flame radiation, re-radiation from the surface, heat conduction, $\dot{q}''_{cond}$, into the solid, and the enthalpy, $\dot{h}_{vol}$, of the volatiles leaving the surface. This is illustrated by the diagram in figure 3. The calculated heat release rate measured by the OSU is given by

$$\dot{q}''_{OSU} = \frac{(h_{out}-h_o)}{A} = \dot{q}''_e + h_{vol} + (1-\chi_R)\dot{q}''_{rhr} - \sigma(T^4-T_o^4) - \dot{q}''_{cond} \qquad (14)$$

where χ_R is the radiative fraction, σ is the Stefan-Boltzmann constant, and T is the surface temperature of the specimen.

3.7. Computer Implementation

A user friendly program was written which asks for such things as the external radiant flux, ambient temperature, time step, cell size, honeycomb thickness, thermophysical properties, thermochemical properties, and type of material comprising the facings. The program is listed in the appendix. As it is currently configured the program takes about 2 hours running time on a 486/33 Mhz computer with a math co-processor to predict the heat release rate for two minutes of real time for a 1/4 inch (6.35 mm) panel. During the run the time, temperatures at the front and rear surfaces and at the midpoint between them, mass remaining in the front and the rear facing sheets, the total mass loss rate, the chemical heat release rate as would be measured in the Cone calorimeter, the enthalpy rise of the flue gases as would be measured in the OSU calorimeter, and the total heat released up to the currently calculated time in the OSU calorimeter in kW*min are all recorded. In addition, the calculated heat release rate contribution from each of the components (front facing, core and rear facing) is also recorded.

The external radiant flux, $\dot{q}''_e$, the ambient temperature, T_o, the honeycomb core thickness, L, the cell width, y, and the description of the facing sheets are specified by the operator for each computer run along with the number of honeycomb elements, N, and the time step, τ. The required thermophysical and thermochemical properties are built into the model for each material. It was found in numerical "experiments", that in order to obtain a stable numerical solution with the typical property values, the following condition must be met:.

$$\tau N/L < 20 \quad \text{sec} \qquad (15)$$

It is necessary that N be at least 10000 per meter of thickness in order to avoid getting a solution which varies significantly with the grid size. For this grid spacing a time step of no greater than 0.002 seconds is required for a stable solution.

4. THERMOPHYSICAL PROPERTIES

4.1. Thermal Conductivity

The thermal conductivity of the solid material (k_{sol}), Nomex in this case, needs to be known separately, as is seen in equations (8) - (12).
It is assumed that the temperature is uniform throughout the facing materials so that it is only the thermal conductivity of the honeycomb panel that needs to be taken into account. The thermal conductivity of the honeycomb was determined by the guarded hot plate method [11]. In order to be able to subtract out the effect of the facings on each side of the honeycomb panel, the effective thermal conductivity was measured for two complete panels of different thickness. Panel B was 12.7 mm thick with an effective thermal conductivity of 5.4×10^{-5} kW/m.K. Panel C was 6.4 mm thick with an effective thermal conductivity of 3.0×10^{-5} kW/m.K. The temperature drops across each panel were given by $\Delta T_B = q_B L_B / k_B$ and $\Delta T_C = q_C L_C / k_C$. If the heat flux is the same through both panels ($q=q_B=q_C$) then the temperature drop across the length $L_B - L_C$ in the center of Panel B is given by $\Delta T = \Delta T_B - \Delta T_C$. The thermal conductivity of the honeycomb itself ($k = q\Delta L/\Delta T$) is then given by

$$k = (L_B - L_C) / (L_B/k_C - L_C/k_C) \qquad (16)$$

This yielded a value of 7.4×10^{-5} kW/m.K. This has a thermal radiation component and an air conduction component in addition to the solid phase heat conduction component. The formula for the thermal conductivity of air was determined by regression analysis of the data given in the table on the properties of gases from reference [9]:

$$k_{air} = 4.2 \times 10^{-6} + 7.9 \times 10^{-8}\ T - 1.5 \times 10^{-11}\ T^2 \qquad (17)$$

Taking the value at 300 K (room temperature) and multiplying by the fraction of the cross section that was open yields an effective value of 2.37×10^{-5} kW/m.K for the air conduction component. The thermal radiation component assuming a mean free path of 3 mm (the width of the cell) was 1.81E-5 kW/m.K. When these were subtracted out and the remainder was divided by the solid portion of the cross sectional area, a value of 3.7×10^{-4} kW/m.K was obtained for the thermal conductivity of Nomex. The thickness of the Nomex wall used for this calculation was 0.127 mm. The thermal conductivity was assumed to increase in proportion to the absolute temperature. Thus

$$k_{sol} = (3.7 \times 10^{-4})T/300 \quad kW/m.K \tag{18}$$

4.2 Specific Heat

The specific heat of Nomex given by Gaur [12]

$$c = 0.0436 + 0.00375T \quad kJ/kg.K \tag{19}$$

The specific heat of the facings were determined from the published values for each component and the mass fractions present. The values for the phenolic/fiberglass, epoxy/fiberglass and the phenolic/graphite facings at 300 K were 1.13, 1.07 and 1.08 respectively and all were assumed to increase in proportion to the absolute temperature.

The specific heat at ambient temperature was also determined from the early rate of temperature rise of a blackened specimen of epoxy fiber glass to be 1.0 kJ/kg.K. at 25°C.

4.3. Emissivity

The emissivity of the phenolic fiberglass panel was determined to be 0.8 from the differences in slope of the temperature curves at early times for blackened and un-blackened panels exposed at the same radiation level. However, the emissivity of the surface goes up as the temperature rises and reactions begin to occur at the surface well below the ignition temperature. After ignition it can be assumed that the panels are black due to charring. For simplicity it is assumed in the model that the emissivity is unity starting at the beginning of the exposure. This could result in a small decrease in the calculated ignition time. The emissivity of the walls of the honeycomb cavities are also assumed to be black at all times. Since the rear surface is in contact with aluminum foil, its emissivity was taken to be that of aluminum which is about 0.1 at 3 microns. This is where the peak occurs for black body radiation at 1000 K. Eckert and Drake [13] give values of 0.08 at 3.6 microns and 0.17 at 2.1 microns. The absorptivity is assumed to be equal to the emissivity for all of the surfaces.

5. THERMOCHEMICAL PROPERTIES

5.1. Kinetic Constants

The thermogravimetric analysis data (TGA) used to determine the kinetic constants was originally obtained at NIST with a heating rate of 5°C per minute both in nitrogen and in air. This was done because it was not clear which would be the most appropriate. The facing sheet, which is very thin, contributes most of the heat during the peak burning period and it is surrounded by air at the beginning of the exposure. The out-gassing of this sheet tends to exclude oxygen from the surface during the major portion of the

burning period. It is not clear how effective this blocking really is. The preliminary results indicated that a better agreement could be obtained between the prediction of the model and the measured heat release rate if the kinetic data taken in air were used for input to the model. However, the material was nearly depleted by the time the temperature range of active pyrolysis in a fire environment was reached in the TGA apparatus. Consequently, the measurements were repeated at a heating rate of 20°C per minute in air by the staff at the FAA Technical Center. This led to better agreement as will be shown below. Nevertheless the conditions under which the kinetic data are taken and the manner in which they are reduced could be a topic for further research. There is a method of separating the kinetic constants for the different reactions using multiple heating rates. This was not done here.

Measurements were taken individually on the Nomex honeycomb and on the coated and un-coated facing sheets. Figure 4 shows the TGA curve for Panel A (full panel). Data were taken from this curve and entered into an electronic spread sheet in order to construct the Arrhenius plot in Figure 5. $Ln[\dot{Z}/(Z-Z_f)]$ is plotted against the reciprocal of the absolute temperature. This parameter comes from taking the natural logarithm of Equation 13. Z_f was adjusted to obtain the relatively straight region at the left side of the graph. The value of Z_f that provides the best fit to a straight line defines its effective value for this particular reaction. The departure from a single straight line fit to the data over the complete set of points indicates the presence of multiple reactions which must be resolved. Starting from the high temperature side on the left of the graph a least squares fit is used to represent a limited number of points with reasonable accuracy. The negative slope of that line is equal to an effective activation energy (E) divided by the gas constant (R). The intersection of that line with the y axis (1/T=0) yields the logarithm of the pre-exponential factor (A). The kinetic constants, E, A and Z_f define the highest temperature reaction.

Now, the fractional mass loss rate represented by these constants is given by Equation (13). The rates determined by this equation are now subtracted from the original rates plotted in Figure 5. These rate differences are used to define a new Arrhenius plot as seen in Figure 6 where the rates used to obtain the above straight line are omitted. The final mass fraction is adjusted on the spread sheet until a reasonably straight line fit can be obtained for a new set of points starting at the left side of the plot. This adjusted value defines the final mass fraction for the second reaction. The slope of the new line and its y intercept yields the effective activation energy and pre-exponential factor (A) for the second reaction. These constants are then again substituted into equation 13 to produce a new set of rates which are subtracted from the second set of rates used in Figure 6. These new rate differences are used to plot a third Arrhenius plot as shown in Figure 7 in order to determine the constants for the third reaction. This was

sufficient for the reactions involved for the phenolic fiber glass. However, this process could be repeated for as many additional reactions as necessary to represent all of the points by straight line segments, each representing successively lower temperature reactions. The computer program as written allows for as many as four reactions for each material. The kinetic constants are tabulated in Table 1. Since Panels A, B and C are composed of the same materials it is only necessary to list the constants for the honeycomb core and the facings for panels 1, 2 and A.

5.2 Heat of Combustion of the Volatiles

The heat of combustion of the volatiles was determined in the Cone calorimeter. The total heat released during the first minute after ignition was divided by the total mass loss during the same period. This calculated heat of combustion was averaged over all of the runs for Panels A, B and C for which there were suitable mass loss data. The same procedure was followed for Panel 1. Since both Panel 2 and Panel A had phenolic fiberglass facings and there was a scarcity of reliable mass loss data on Panel 2, the heat of combustion obtained for panels A, B and C was also used for Panel 2. The values obtained are tabulated in Table 1. There is some error in these values due to a small unknown contribution from the volatiles released by the honeycomb during the measurement period.

The heat of combustion of the honeycomb was measured by exposing it in the Cone calorimeter without the facings attached.

It is important to stress that it is the heat of combustion of the volatiles and not the heat of combustion of the material, that is required by the model. These can be very different for charring materials. Thus, the heat of combustion measured in an oxygen bomb calorimeter is not suitable for this purpose.

5.3 Heat of Pyrolysis

The heat of pyrolysis can be determined with a differential scanning calorimeter (DSC). However, it was assumed to be small enough to be neglected in the model and therefore was not measured. This assumption was made for simplification of the model and no further justification is provided. It should be considered in future refinements of the model.

6. HEAT RELEASE RATE MEASUREMENTS

6.1. OSU Calorimeter

The heat release rates of all of the panels were measured in the OSU calorimeter by personnel at the FAA Technical Center at 35 kW/m^2. Temperature measurements were also made at the front and rear

surfaces and midway in between using 0.51 mm diameter (20 mil, 24 gauge) thermocouples. To measure the surface temperature, a hole was drilled through the panel, a pair of thermocouple wires threaded through, separated, spot welded, and bent back to touch the surface. The specimens were oriented vertically and were wrapped in aluminum foil except for the exposed surface. The rear surface was allowed to lose heat through an air space to the sheet metal back of the specimen holder. Both the upper and lower pilots specified in ASTM E906 were used in each of these tests. Except for the thermocouples, the tests were run in accordance with the new FAA regulations.

6.2. Cone Calorimeter

Heat release rate measurements were also made in the Cone calorimeter at NIST at 30, 35, and 40 kW/m^2 on Panel A and at 35 kW/m^2 only on the others. The data were taken in the vertical orientation with two modifications of the standard method. The rear surface was not placed against a low density backing board. The aluminum foil covering the surface was exposed to the laboratory air. Also, the gas piloting arrangement specified by the FAA for the OSU calorimeter was used in these tests instead of the spark ignition.

7. COMPARISON OF CALCULATED AND MEASURED RESULTS

7.1 Temperature

Figure 8 shows the calculated and measured temperature histories for the front and rear surfaces of Panel A and for the midpoint between them. The measurements were taken on 3 separate runs. However, the front surface thermocouple was defective on one of the runs so its results are not shown. The rear surface thermocouple gave very low readings on one of the runs. Otherwise there is good agreement between the calculated and experimental results.

7.2 Heat Release Rate

In Figure 9 the calculated heat release rate history for Panel A is compared with the measured heat release rates for the same panel during three runs in the Cone calorimeter at 35 kW/m^2. The scatter shown in Figure 9 is typical of multi component materials when using oxygen depletion techniques. The calculated curve is bracketed by the three measured ones.

Figure 10 shows how total calculated heat release rate is divided among the contributions of the front face, honeycomb core and the rear face. The upper curve is the sum of the three components. At the time of the peak heat release rate the contribution of the core is about 11 percent while the contribution from the rear face is negligible. Two minutes after ignition the core accounts for 64 percent and the rear face accounts for 10 percent.

In Figure 11 the calculated OSU heat release rate of Panel A is compared with that measured in the calorimeter for three runs. The experimental data is duplicated quite well. The magnitude of the calculated peak is in agreement with the measured one. However, it is shifted nearly 10 seconds in time. Outside of this time shift and the pronounced dip around 50 seconds the calculated curve follows the measured curve reasonably well.

Panel B differs from Panel A only in its core thickness which is twice as large. In Figure 12 the calculated heat release rate curve is compared with three measured curves in the Cone. Again the agreement is good near the peak but after 45 seconds the calculated curve rises above the measured ones. There is also a considerable spread between the measured heat release rates in this region. In Figure 13 the calculated OSU heat release rate for Panel B is compared with the measurements in the OSU calorimeter. The agreement is good except for the dip around 50 seconds. In Figure 14 the calculated heat release rate of Panel C is compared with the measured heat release rates in the Cone calorimeter. There is good agreement with the peaks. In contrast to Panel B the measured values at later times tend to fall above the calculated curve rather than below it. Here the dip is stronger for the measured curves than for the calculated one. Figure 15 shows the calculated and measured curves for Panel C in the OSU calorimeter. Except for the delay in the peak and the dip at 50 seconds the agreement is adequate over the first two minutes.

It is the value of the peak heat release rate and the total heat released over the first 2 minutes after ignition that are the specific criteria in the FAA regulations. The calculated and measured values of these are tabulated in Table 3 for Panels A, B and C in order to show the effect of core thickness. The calculated peaks show a 14 percent increase in going from Panel C to Panel B while the average of the measured values shows no trend. This is in spite of the fact that the calculated values are essentially within the scatter of the experimental data. In fact the highest measured peak for each panel increases by 13 percent in going from Panel C to Panel B. Both the calculated and the average of the measured 2 minute total heat release increases by 30 percent in going from Panel A to Panel C. The measured averages of the 2 minute total heat release are 11 percent higher than the calculated values. On the other hand the calculated peaks were 6 percent greater than the measured ones on the average for the 3 panels.

In general, as the thickness of the panel is increased the total heat released during the first two minutes increases, whereas no significant difference is seen in the peak heat release.

At an external radiation level of 30 kW/m^2 the calculated curve for Panel A in the Cone falls well above the measured one except at the peak where they are relatively close, as seen in Figure 16. On the other hand the calculated and measured curves fall quite close

together at 40 kW/m^2 except at the peak, as seen in Figure 17. No reason for this difference has yet been found.

Figures 18 and 19 show marginal agreement for panels 2 and 1 respectively in the Cone calorimeter. Better property data may be required to achieve greater agreement for these panels.

8. DISCUSSION AND CONCLUSIONS

1. A computer model has been developed which can predict the approximate magnitude and shape of the heat release rate curves for aircraft cabin panels over the first two minute interval after ignition in the OSU and Cone calorimeters for the boundary conditions specified by the FAA. Thus the model accounts quantitatively for differences in the heat release rates measured in the two calorimeters operating under the specified boundary conditions. This model can predict the contributions of the individual components. It is based on physical principles and utilizes input data on the geometrical properties of the panels and on the thermochemical and thermophysical properties of their materials of construction. It has not been necessary to use any adjustable parameters to get acceptable agreement with the experimental results. A number of assumptions have been made in the development of the model. However, radiation absorption by the volatile pyrolysis products in the interior of the honeycomb have not been taken into account.

2. The kinetic constants of the materials comprising the panels can be obtained from TGA measurements in air at a heating rate of 20°C per minute. Multiple reactions can be sorted out in the analysis of the data. However, material combinations must be separated into their chemical components which are then analyzed separately. There are other techniques, involving runs at different heating rates, for analyzing TGA data to obtain the kinetic constants for multiple reactions. These were not tried here.

3. The heat of combustion of the volatiles, as required by the model, can be obtained from runs on the material in the Cone calorimeter. The total heat release over the one minute interval following ignition divided by the total mass loss over this interval provides a suitable value for the required heat of combustion of the volatiles. However, this value should be averaged over several runs. It is not valid to use heats of combustion of the material measured in an oxygen bomb calorimeter. The latter procedure can yield very different values for charring materials. It is not necessary that a material be part of a finished panel to obtain its heat of combustion in the Cone calorimeter, only that it be present in sufficient quantities for accurate heat and mass release rate measurements. Measurements in either the vertical or horizontal orientations would be satisfactory.

4. The model can be used for a parametric study of the effects of core thickness, cell size, external radiation level and the material property values. The thickness of the cell wall could also be a parameter but as the program is currently written it has a fixed value of 0.127 mm.

5. The agreement between the calculated and measured values of peak and two minute average heat release rates in the OSU calorimeter was quite good for Panels A, B and C. Additional work is needed to demonstrate the adequacy of the model over a wider range of panel materials and constructions. Also, it would be useful to evaluate panels finished with thick decoratives since the decorative finish may be a major contributor to the heat release.

6. The computer program used to obtain the calculated temperatures and heat release rates for this report is contained in the Appendix. Improvements could probably be made which would improve its efficiency and reduce its computation time.

9. REFERENCES

1. Final Report of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, Federal Aviation Administration, Vol. 1, Report FAA-ASF-80-4, June 26, 1980.

2. Sarkos, C. P., Filipczak, R. A., and Abramhowitz, A., "Preliminary Evaluation of an Improved Flammability Test Method for Aircraft Materials," Federal Aviation Administration, Report DOT/FAA/CT-84/22, December 1984.

3. Hill, R. G., Eklund, T. I., and Sarkos, C. P., "Aircraft Interior Panel Test Criteria Derived from Full-Scale Fire Tests," Federal Aviation Administration, Report DOT/FAA/CT-85/23, September 1985.

4. Federal Register/ Vol. 51, No. 139/ Monday, July 21, 1988 / Rules and Regulations, pp 26206-26221.

5. American Society for Testing and Materials, E906-83: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter. ASTM, Philadelphia, PA, 1990.

6. Quintiere, J.G., Babrauskas, V., Cooper, L., Harkleroad, M., Steckler, K., and Tewarson, A., "The Role of Aircraft Panel Materials in Cabin fires and their Properties," DOT/FAA/CT-84/30, June 1985.

7. Zijl, H. "Large-Size Perfect Diffusors," Philips Technical Library, Eindhoven, Netherlands 2nd edition, 1960

8. Schlichting, H., "Boundary Layer Theory," 4th Edition, McGraw Hill, pp 332-334, 1960

9. Eckert, E.R.G. and Drake, R.M., "Analysis of Heat and Mass Transfer," McGraw-Hill, Inc., p 780, 1972

10. Marksman, G. A. "Combustion in the Turbulent Boundary Layer on a Vaporizing Surface," Tenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, P. 1337. (1965)

11. ASTM-C177, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of a Guarded Hot Plate Apparatus," ASTM Book of Standards, Volume 04.06, American Society for Testing and Materials, Philadelphia, PA (1990)

12. Gaur, U., "Heat Capacity and Other Thermodynamic Properties of Linear Molecules," VIII: Polyesters and Polyamides, J. Physical Chemistry Reference Data 12 (1), 65-89 (1983)

13. Eckert, E.R.G. and Drake, R.M., "Analysis of Heat and Mass Transfer," McGraw-Hill, Inc., p 789, 1972

TABLE 1 PROPERTY VALUES USED IN THE CALCULATIONS

PANEL FACING OR CORE		1	2	A, B, C FRONT	A, B, C BACK	CORE
ACTIVATION ENERGY kJ/MOLE	(1)	80.2	14.5	43.2	40.81	38.98
	(2)	156.1	62.36	62.36	74.61	
	(3)			110.9	153.15	
PRE-EXPONENTIAL FACTOR s^{-1}	(1)	$1.43x10^4$	0.01	614	161	2.77
	(2)	$1.35x10^8$	2000	833	1927	
	(3)			46630	2.17E7	
FINAL MASS FRACTION	(1)	0.73	0.84	0.991	0.975	0
	(2)	0.57	0.64	0.72	0.89	
	(3)			0.47	0.677	
HEAT OF COMBUSTION kJ/kg		12800	8900	8900	8900	27800
MASS kg/m^2		0.455	0.43	0.72	0.42	*
SPECIFIC HEAT kJ/kg.K		1.07	1.13	1.13	1.13	0.0436 + 0.00375T **
THERMAL CONDUCTIVITY kW/m.K		-	-	-	-	3.7E-4
DENSITY kg/m^3		-	-	-	-	323
THICKNESS m		-	-	-	-	1.27E-4
EMISSIVITY		1	1	1	1	1

* Not used in calculations
** Temperature in degrees Kelvin

(1) First Reaction
(2) Second Reaction
(3) Third Reaction

TABLE 2. PARAMETERS REQUIRED BY THE MODEL

Adiabatic flame temperature	2000°C
Radiative fraction	0.3
Minimum temperature for flame spread	200°C
Thermal conductivity of air at ambient temperature	3.7E-4 kW/m.K
Specific heat of volatiles	1.2 kJ/kg-K
Convective heat transfer coefficient from flame	0.025 $kW/m^2.K$
Emissivity of Aluminum	0.1

TABLE 3. PEAK HEAT RELEASE RATES AND TWO MINUTE TOTAL HEAT RELEASES FOR PANELS A, B AND C IN THE OSU CALORIMETER

PANEL	CORE THICK. (mm)	PEAK CALC.	PEAK MEAS.	PEAK MEAS. AVE.	2 MIN. TOTAL CALC.	2 MIN. TOTAL MEAS.	2MIN. TOTAL MEAS. AVE.
C	3.18	48.2	50.0 47.2 42.6	46.6	38.0	47.1 42.2 37.6	42.3
A	6.35	51.4	53.5 50.1 49.6	51.1	45.0	49.9 49.5 49.5	49.6
B	12.7	54.9	53.3 47.3 38.3	46.3	49.4	60.1 57.7 47.1	55.0
PERCENT INCREASE, C TO B		14		0	30		30

* Peak heat release rates are in kW/m^2 and 2 minute total heat releases are in $kW.min./m^2$.

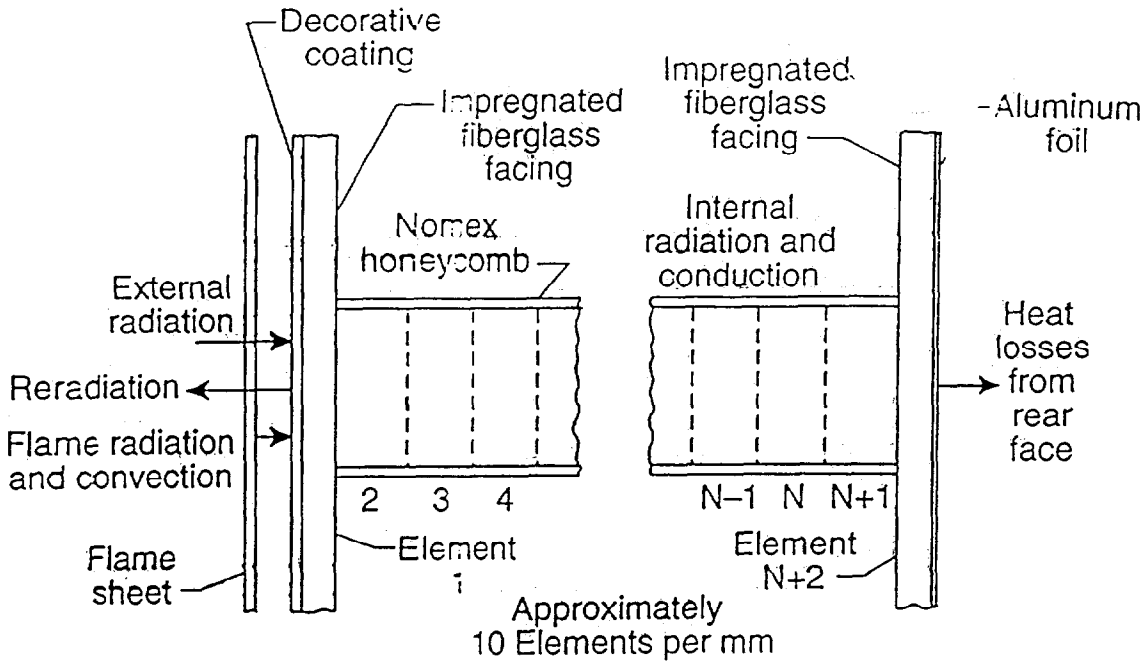


Figure 1. Model of Single Honeycomb Cell.

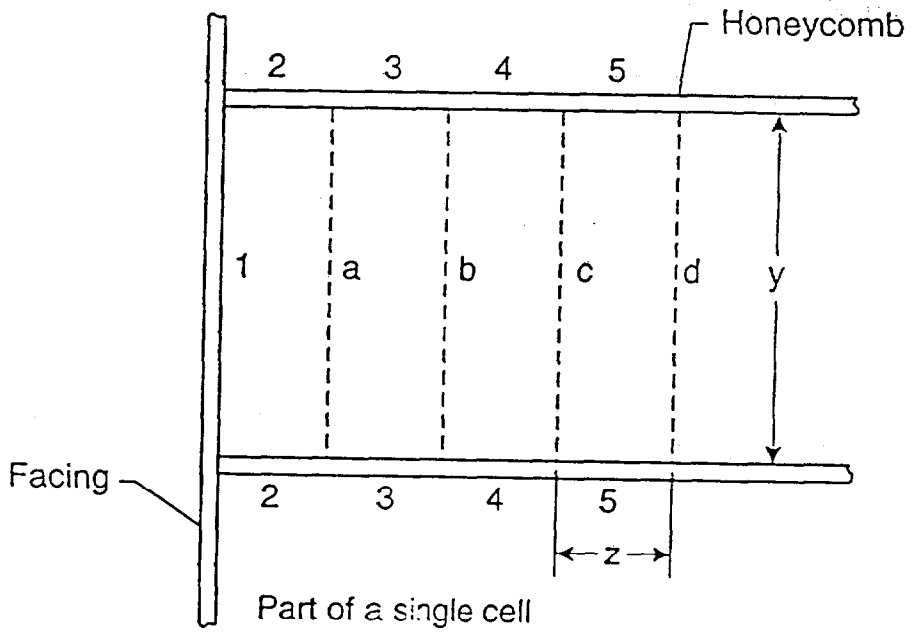


Figure 2. Model for View Factor Calculation

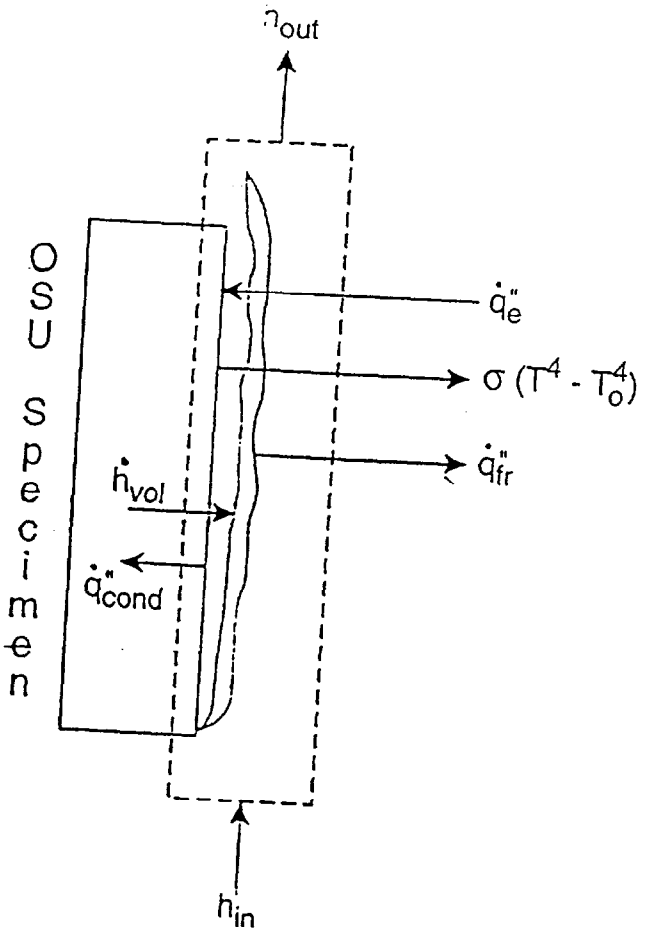


Figure 3. Model for Calculating Heat Release Rate in OSU

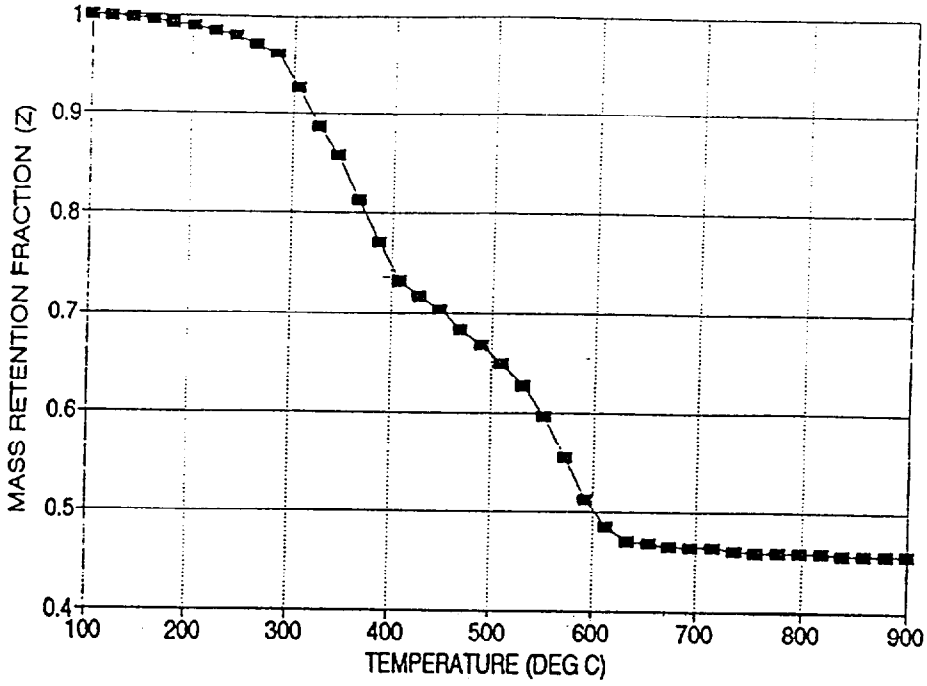


Figure 4. TGA Plot for Panel A.

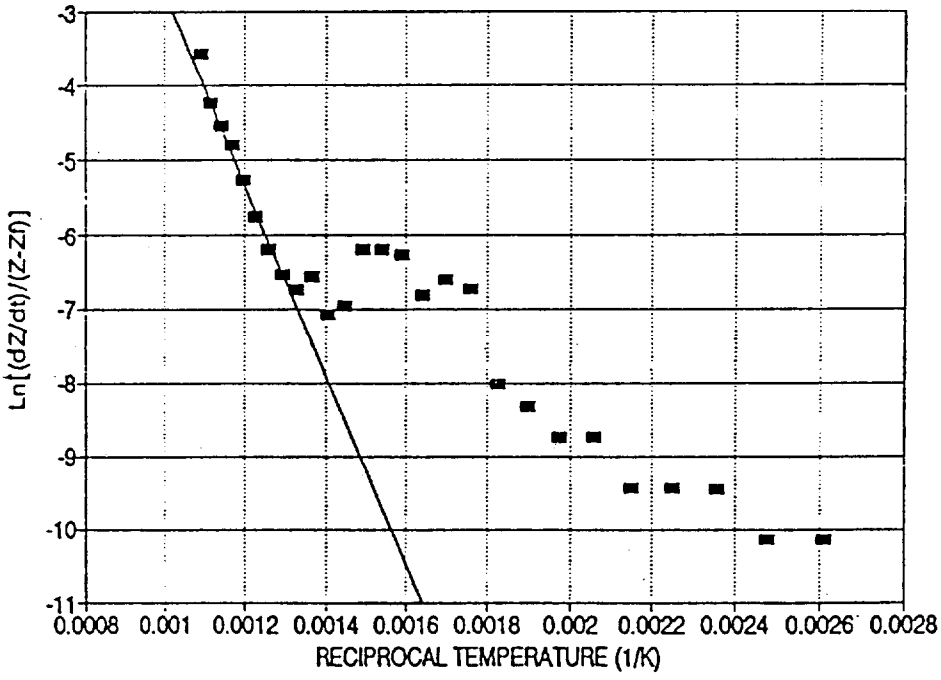


Figure 5. Arrhenius Plot for Panel A (High Temperature Reaction).

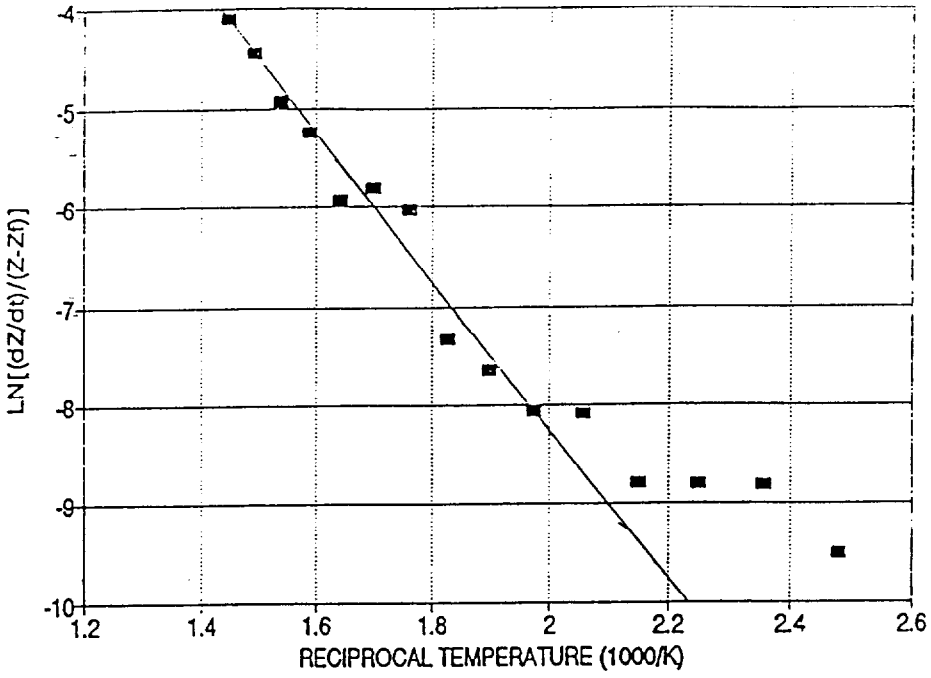


Figure 6. Arrhenius Plot for Panel A (Intermediate Temperature Reaction).

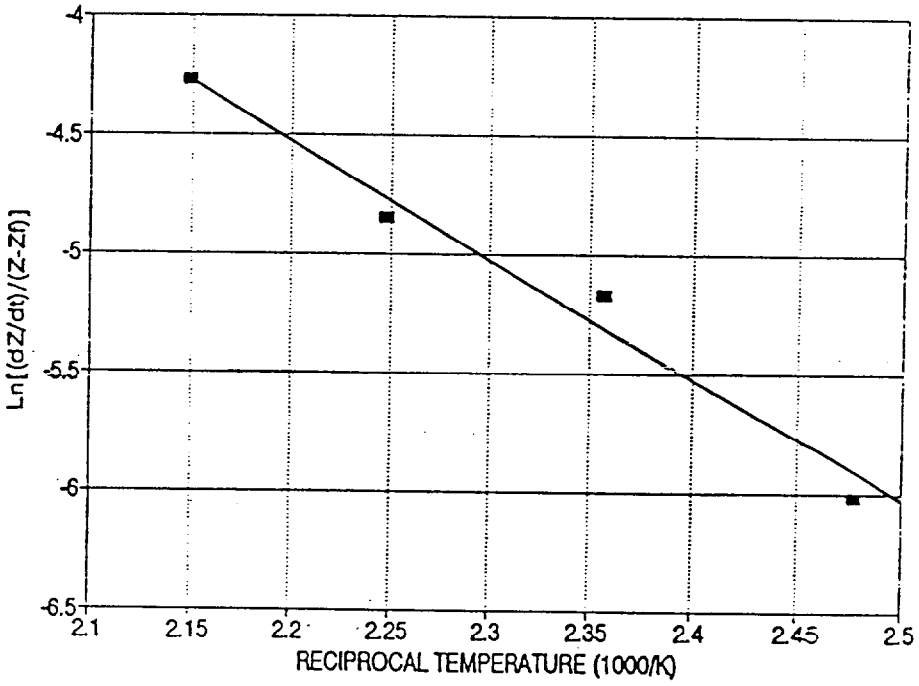


Figure 7. Arrhenius Plot for Panel A (Low temperature Reaction).

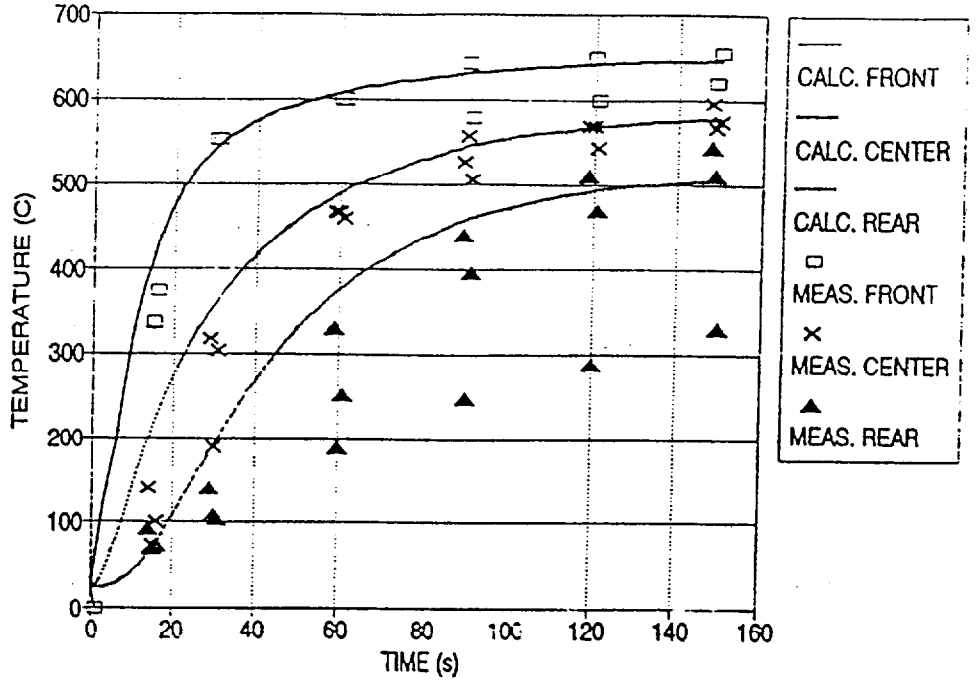


Figure 8. Surface and Interior Temperatures for Panel A in OSU at an Exposure of 35 kW/m^2.

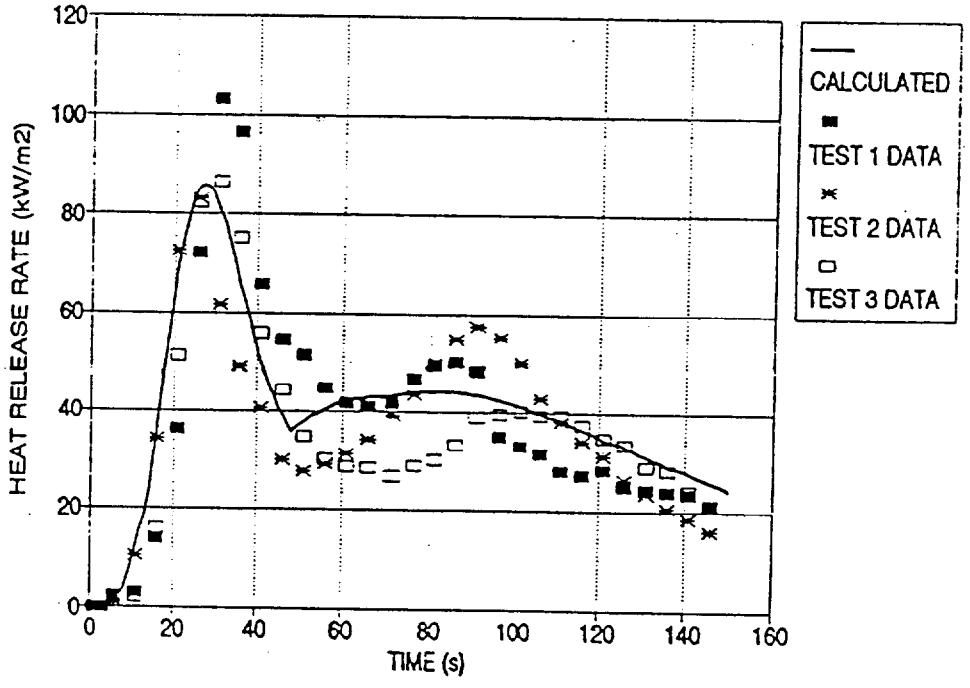


Figure 9. Heat release Rate of Panel A in Cone at 35 kW/m^2.

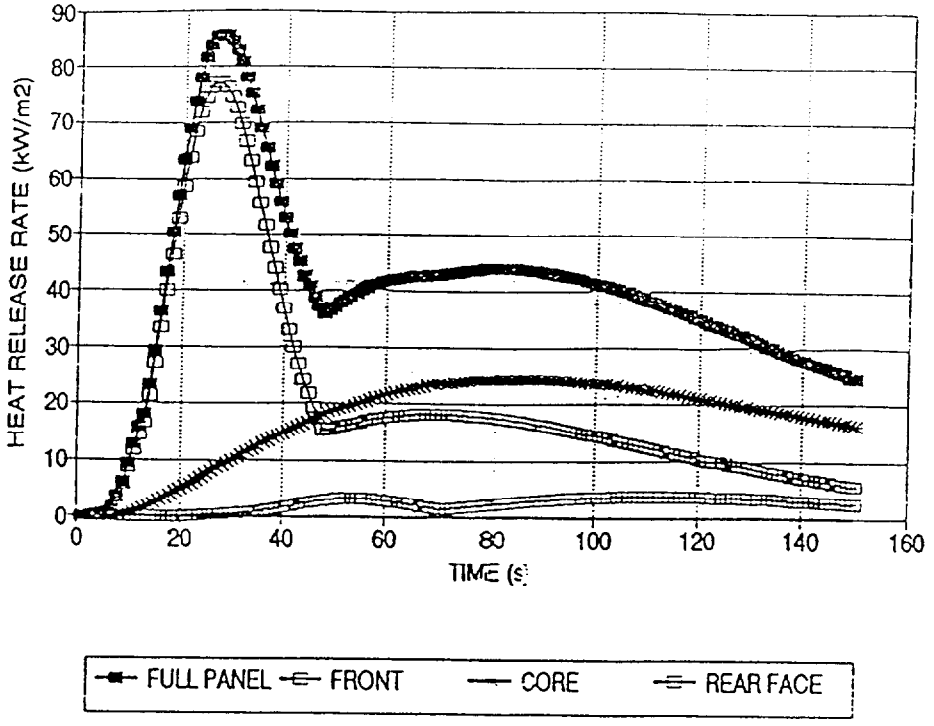


Figure 10. Calculated Contributions of Panel A Components to the Heat Release Rate at an Exposure of 35 kW/m^2.

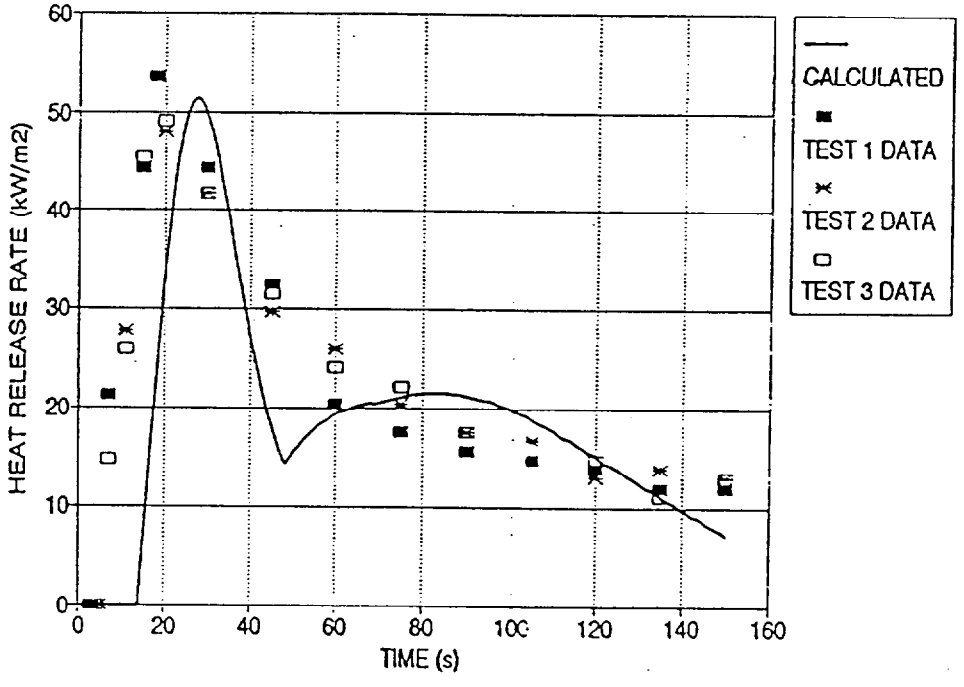


Figure 11. Heat release rate of Panel A in OSU at 35 kW/m^2.

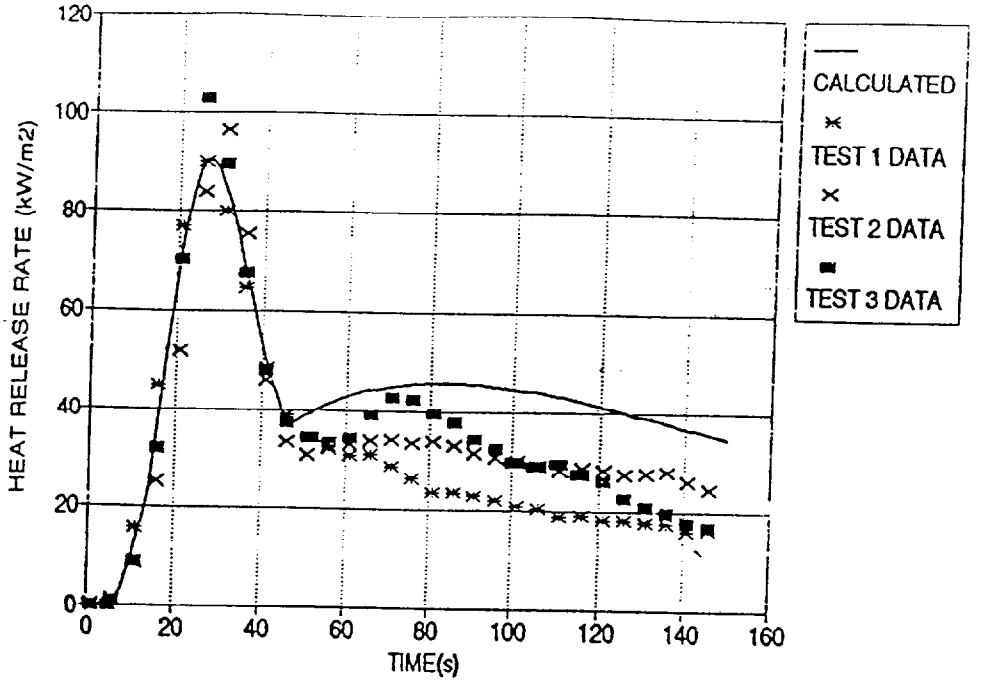


Figure 12. Heat release rate of Panel B in Cone at 35 kW/m^2.

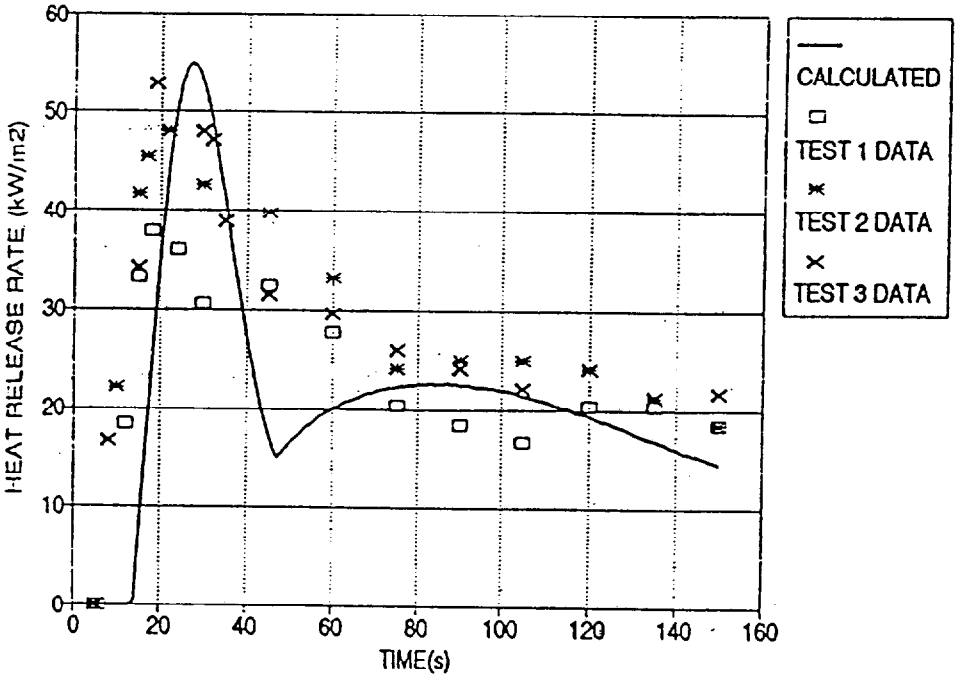


Figure 13. Heat release rate of Panel B in OSU at 35 kW/m^2.

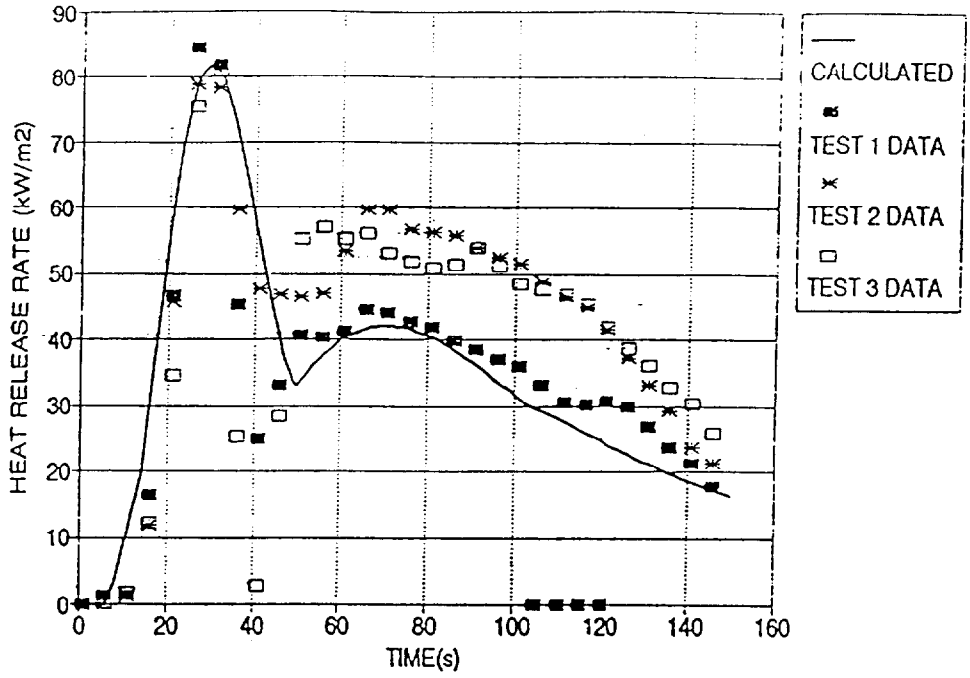


Figure 14. Heat release rate of Panel C in Cone at 35 kW/m^2.

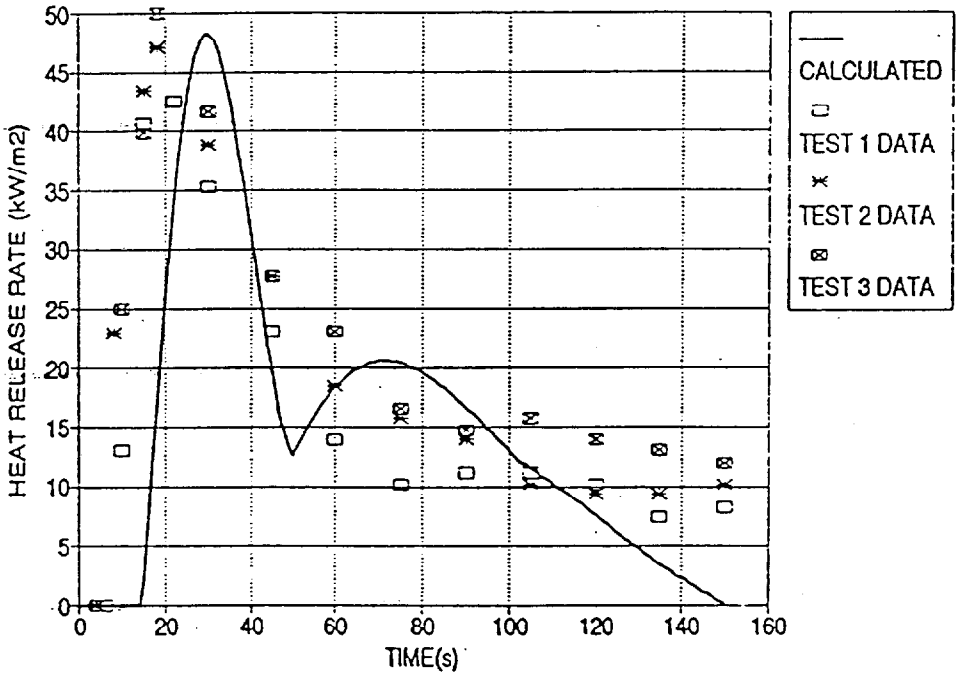


Figure 15. Heat release rate of Panel C in OSU at 35 kW/m^2.

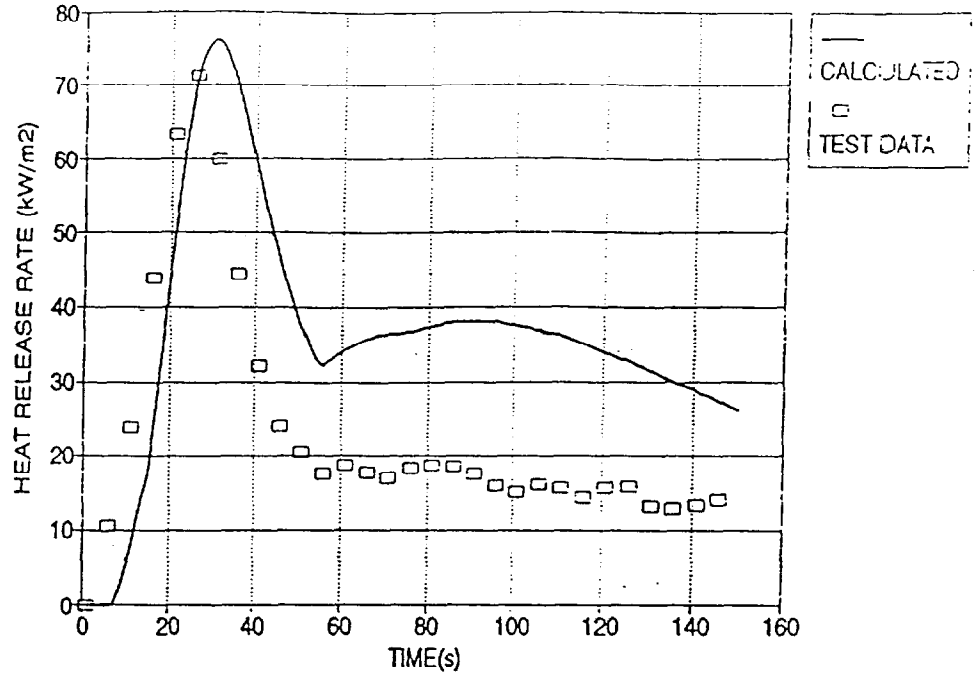


Figure 16. Heat release rate of Panel A in Cone at 30 kW/m^2.

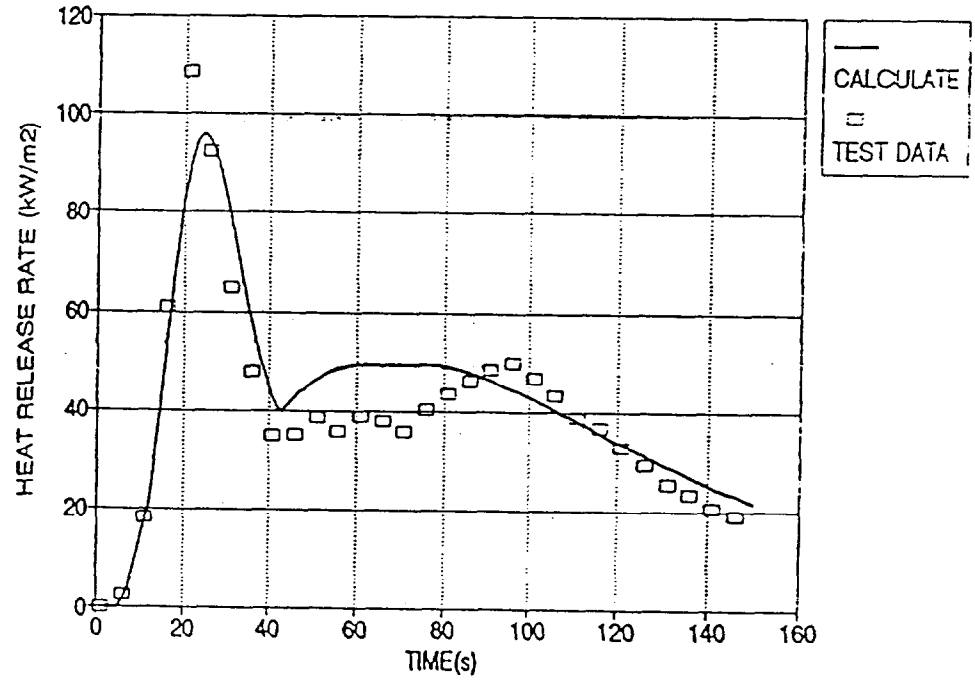


Figure 17. Heat release rate of Panel A in Cone at 40 kW/m^2.

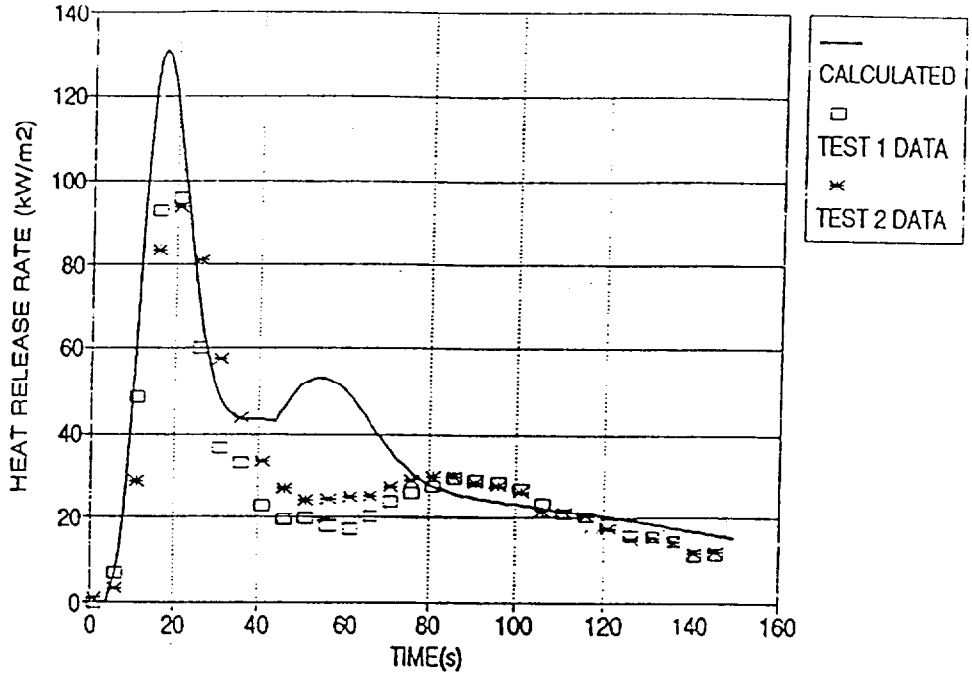


Figure 18. Heat Release Rate of Panel 2 in Cone at 35 kW/m^2.

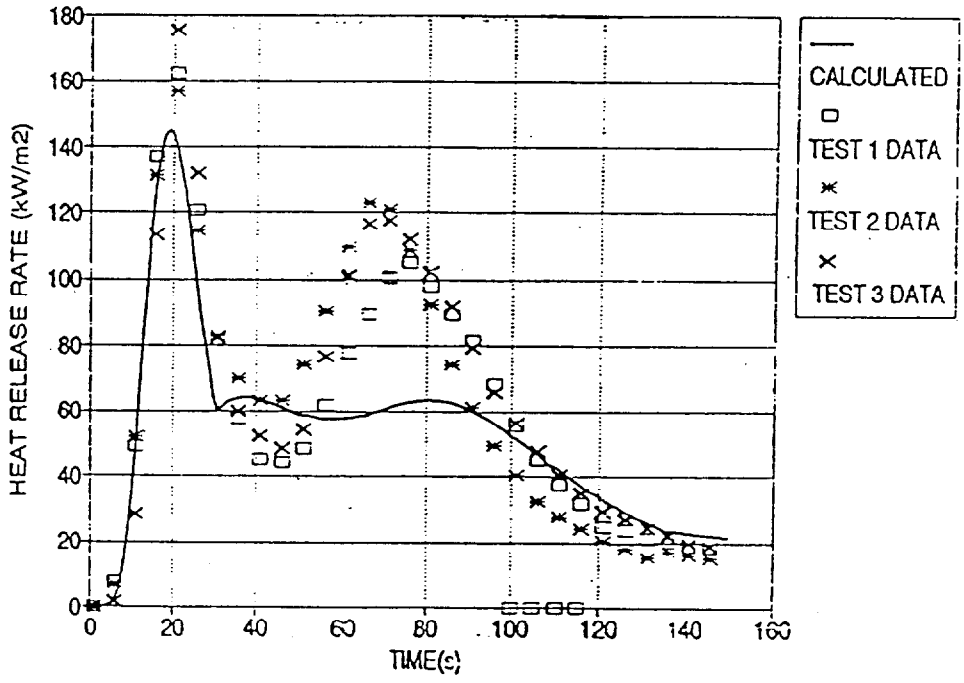


Figure 19. Heat Release Rate of Panel 1 in Cone at 35 kW/m^2.

APPENDIX: COMPUTER PROGRAM

```
C     P30
C     PANEL
C
C     PANEL BURNING RATE IN AIR
C     1/10/92
C
C     Nomenclature:
C         AE1: Front surface activation energy.
C         AE2: Internal activation energy.
C        AE10: Rear surface activation energy.
C        BETA: Radiating area ratios.
C      BRATIO: On the shape factors calculation, it is the ratio
C              of the length of one side and the distance between
C              the squares.
C              BRATIO = (CELL - 2 halves of THICK2) / HSEP
C                   B = b / h
C        CELL: Each temperature element is treated as a square.
C             Front view.  CELL is its length: 0.0032 m (1/8 inch).
C       CELL2: Area of the square of length CELL; (CELL**2).
C     CELLTHK: Actual length of a temperature element (CELL-THICK2).
C      CELTK2: Actual area of a temperature element (CELLTHK**2).
C       CMASS: Determines if the mass loss will be calculated.
C      C1ZERO: Ambient specific heat of front surface (kJ/kg K)
C       DEPTH: Specimen thickness.  Entered in meters.
C        DIST: Array containing the distance of each point where the
C              temperature will be calculated with respect to the
C              first point.
C       EMISS: Front surface emissivity.
C      EMISSR: Rear surface emissivity.
C      EMISSI: Interior emissivity.
C       EXRAD: External radiant flux (kW/m2).
C        HAMB: Ambient heat transfer coefficient.
C      HFLAME: Flame heat transfer coefficient.
C        HCV1: Front surface heat of combustion.
C        HCV2: Internal heat of combustion.
C       HCV10: Rear surface heat of combustion.
C        HSEP: The distance between the front surface and a C
C              subdivision in depth.  Used on the shape factors C
           calculation.
C      KOLUMN: Number of temperature columns to be printed.
C      KSZERO: Ambient Ksolid (kW/m K).
C      MASMIN: Minimum mass (kg/m2).
C          NJ: Number of honeycomb elements (temperature elements).
C      NDIVP2: NDVSNS + 2.  Add two for the first and last side.
C      NDVSNS: Number of divisions for the temperature calculation.
C              It must be ≥ 3, and ≤ NDIV-2.
C       PREX1: Front surface pre-exponential factor.
C       PREX2: Internal pre-exponential factor.
C      PREX10: Rear surface pre-exponential factor.
C      PREX1S:
```

```
C           R: Universal gas constant (kJ/kg mol K).
C        REAR: If the losses from the rear surface will be
C              calculated,
C              REAR is set to 1, otherwise it is set to 0.
C     RHO2(1): Front surface density (kg/m3).
C     RHO2(2): Internal density (kg/m3).
C    RHO2(10): Rear surface density (kg/m3).
C       SIGMA: Stefan-Boltzmann constant (kW/m2 K4).
C        TAMB: Ambient temperature.  Entered in degrees Celsius;
C              converted to Kelvins by the program.
C      THICK2: Thickness of the sides of a temperature element.
C        TMAX: Test length (s).
C       TSTEP: Time step (s).
C         YIG: Determines if ignition will be included.
C
      PARAMETER(NDIV=202,NUM=200,PI=3.1416)
      REAL AEJ(NUM),AJ(NUM),CPSOL2(NDIV),
     &     F(NDIV,NDIV),F1(NDIV),
     &     HCVOLJ(NUM),KAIR(NDIV),KSOLID(NDIV),KSZERO,LAMBDA,
     &     MASSJ(NUM),MASS1,MASS2,MASS10,MDOT,RADEX(NDIV),
     &     RHO2(NDIV),TEMP(NDIV),TEMPC(NDIV),
     &     TEMPJ(NUM),TEMP1(NDIV),TEMP4(NDIV),Z(NUM),ZDOT(NUM),
     &     ZDOT1(NUM),ZFJ(NUM),ZFIN1(4),ZFIN10(4),PREX1(4),
     &     PREX10(4),AE1(4),AE10(4)
      CHARACTER*1CHANGE,CMASS,DATE*18,FILENM*30,PRIN,REAR,SPEC*30,
     &           STORE,YIG,PROGRAM*12
C
C CHANGES:
C    Input the nuMber of divisions for the temperature calculation.
C     NDVSNS must be smaller than or equal to NDIV-2 (48), but no
C     smaller than three (3):
10    WRITE(*,698)
      READ(*,*) NDVSNS
      IF (NDVSNS.LT.3.OR.NDVSNS.GT.NDIV-2) THEN
      WRITE(*,700) NDIV-2
      GO TO 10
      END IF
      NDIVP2=NDVSNS+2
C     Initialization:
C
C     Activation energy.
            AE22 = 38982
C
C     Length of the (square) temperature element.
           CELL = 3.2E-3
C
C     Ambient specific heat of the front surface.
          C1ZERO = 1.13
C
C     Specimen thickness.
           DEPTH = 6.35E-3
C
```

```
C     Emissivity.
           EMISS = 1.
          EMISSR = 0.1
          EMISSI = 1.
C
C     Heat transfer coefficient.
            HAMB = 0.012
          HFLAME = 0.025
C
C     Heat of combustion.
            HCV2 = 25550.
C
C     Ambient KSOLID.
          KSZERO = 3.7E-4
C
C     Pre-exponential factor.
        PREX22 = 2.77
C
C     Universal gas constant.
                R = 8.314
C
C      Density.
           RHO2(1) = 1079.
           RHO2(2) = 323.
      RHO2(NDIVP2) = 1052.
              RHO1 = RHO2(1)
             RHO10 = RHO2(NDIVP2)
C
C     Stefan-Boltzmann constant.
           SIGMA = 5.67E-11
C
C     Flame temperature.
          TFLAME = 2000
          CHIR = .3
C
C     Thickness.
          THICK1 = 3.27E-4
          THICK2 = 1.27E-4
         THICK10 = 3.65E-4
C
           ZFIN2 = 0.
C
C     Input section:
        PRINT *,' What is the name of the program?    '
        READ(*,'(A)') PROGRAM
        PRINT *,' Input a brief description of the specimen: '
        READ(*,'(A)') SPEC
        PRINT *,' What is the date? '
        READ(*,'(A)') DATE
        PRINT *,' Input the time step in seconds: '
        READ *, TSTEP
        PRINT *, ' What is the external radiant flux (kW/m2)?  '
```

```
      READ *, EXRAD
      PRINT *,' What is the ambient temperature (in deg C)?  '
      READ *, TAMBC
C     Convert to Kelvins:
      TAMB = TAMBC + 273.
      TAMB4 = TAMB**4
      K = 0
C
20        WRITE(*,25)
          READ(*,*) MENU
          IF (MENU.EQ.1) THEN
C             Get Epoxy Fiberglass Data.
              CALL EPOFI(ZFIN1,PREX1,AE1,ZFIN10,
     &             PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
            ELSE IF (MENU.EQ.2) THEN
C                    Get Phenolic Fiberglass Data.
                     CALL PHEFI(ZFIN1,PREX1,AE1,ZFIN10,
     &                PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
            ELSE IF (MENU.EQ.3) THEN
C                    Get Phenolic Fiberglass A data.
                     CALL PHEFIA(ZFIN1,PREX1,AE1,ZFIN10,
     &                PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
                ELSE IF (MENU.EQ.4) THEN
C                    Get Phenolic Graphite Data.
                     CALL PHEGRA(ZFIN1,PREX1,AE1,ZFIN10,
     &                PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
                                ELSE
                                    WRITE(*,30)
                                    GO TO 20
          END IF
C
      PRINT *,' Do you wish to change the properties? (Y/N) '
      READ(*,'(A)') CHANGE
      IF (CHANGE.EQ.'Y'.OR.CHANGE.EQ.'y') THEN
          PRINT *,' What is the ambient KSOLID (kW/m K)?  '
          READ *, KSZERO
          PRINT *,' Enter the ambient specific heat of the',
     &            ' front surface (kJ/kg K): '
          READ *, C1ZERO
          PRINT *,' What is the front surface emissivity?  '
          READ *, EMISS
          PRINT *,' Input the rear surface emissivity: '
          READ *, EMISSR
          PRINT *,' What is the interior emissivity?  '
          READ *, EMISSI
          PRINT *,' Enter the front surface thickness (m): '
          READ *, THICK1
          PRINT *,' Input the rear surface thickness (m): '
          READ *, THICK10
          PRINT *,' What is the front surface density (kg/m3)? '
          READ *, RHO2(1)
          PRINT *,' Input the internal density (kg/m3): '
```

```
            READ *, RHO2(2)
            PRINT *,' Enter the rear surface density (kg/m3): '
C CHANGES: 10 to NDIVP2
            READ *, RHO2(NDIVP2)
C
C CHANGES: 10 to NDIVP2
        END IF
            PRINT *,' Enter the cell size (inches): '
            READ *, CELLI
            CELL = CELLI/39.37
            PRINT *,' What is the panel thickness (inches)? '
            READ *, DEPTHI
            DEPTH = DEPTHI/39.37
C
        PRINT *,' Do you wish to calculate the mass loss? (Y/N) '
        READ (*,'(A)') CMASS
        NJ = NDVSNS
        PRINT *,' Do you want to include ignition? (Y/N) '
        READ (*,'(A)') YIG
        RLOSS = 1.
        PRINT *,' Do you want losses from the rear surface? (Y/N) '
        READ (*,'(A)') REAR
        IF (REAR.EQ.'N'.OR.REAR.EQ.'n') RLOSS=0.
        PRINT *,' What is the maximum test time (sec)? '
        READ *, TMAX
C
        CELL2 = CELL**2
        CELTHK = CELL - THICK2
        CELTK2 = CELTHK**2
C
        RHO2(1)=MASS1/THICK1
        RHO2(NDIVP2) = MASS10/THICK10
       RHO1 = RHO2(1)
       RHO10 = RHO2(NDIVP2)
C     Mass calculation:
          MASS1 = MASS1* CELL2
          MASS2 = RHO2(2) * (CELL2 - CELTK2) * DEPTH
C CHANGES: 10 to NDIVP2
        MASS10 = MASS10*CELL2
C
C     Initialize arrays:
C CHANGES: 10 to NDIVP2.
      DO 50 N = 1,NDIVP2
          TEMP(N) = TAMB
          TEMP1(N) = TAMB
          TEMP4(N) = TAMB4
50    CONTINUE
      DO 55 J = 1,NJ+2
          Z(J) = 1.
          ZDOT(J) = 0.
          ZDOT1(J) = 0.
55    CONTINUE
```

```
C
      PRINT *,' Do you wish to store the data on disk? (Y/N) '
      READ (*,'(A)') STORE
      IF (STORE.EQ.'Y'.OR.STORE.EQ.'y') THEN
          PRINT *,' Enter the output file name: '
          READ(*,'(A)') FILENM
          OPEN(3,FILE=FILENM)
          WRITE(3,70)  PROGRAM,SPEC,DATE,TSTEP,EXRAD,TAMBC,MENU,
     &                 CELLI,DEPTHI,NDVSNS,NJ,REAR,TMAX
          WRITE(3,80)
      END IF
      PRINT *,' Do you wish to print the data? (Y/N) '
      READ (*,'(A)') PRIN
      IF (PRIN.EQ.'Y'.OR.PRIN.EQ.'y') THEN
          OPEN (6,FILE='PRN')
          WRITE (6,68)
          WRITE(6,70) PROGRAM,SPEC,DATE,TSTEP,EXRAD,TAMBC,MENU,
     &                 CELLI,DEPTHI,NDVSNS,NJ,REAR,TMAX
      WRITE(6,80)
      TIME = 0
      MDOT = 0
      QDOT = 0
      QTOT = 0
        QOSU=0
        TOTQ=0
      DO 64 I = 1,NDIVP2
      TEMPC(I) = TAMBC
64    CONTINUE
      WRITE(6,500) TIME,TEMPC(1),TEMPC(MID),TEMPC(NDIVP2),
     & Z(1),Z(NDIVP2),MDOT,QDOT,QTOT,QOSU,TOTQ
      END IF
C
C CHANGES:
C
C     Calculation of the radiation shape factors:
C     BETA is the radiating area ratios.
C
      BETA = 2. * CELTK2 / (CELL * DEPTH)
      STOREF = 0.
C CHANGES: 8 to NDVSNS
      DO 90 N = 1,NDVSNS
         HSEP = N * DEPTH / NDVSNS
         BRATIO = CELTHK / HSEP
         LAMBDA = SQRT(BRATIO**2+1.)
         F1(N) = (LAMBDA * ATAN(BRATIO/LAMBDA) - ATAN(BRATIO) -
     &           LOG((2.*LAMBDA**2-1.)/LAMBDA**4) / (4.*BRATIO)) *
     &            4. / (PI*BRATIO)
90    CONTINUE
C
C CHANGES: 10 to NDIVP2
      DO 91 N = 1,NDVSNS+1
         F(1,N) = 0.
```

```
91    CONTINUE
C
      F(1,NDIVP2) = F1(NDVSNS)
C
      DO 93 INT = 2,NDVSNS+1
         DO 92 L = 2,INT
            STOREF = STOREF + F(1,L)
92       CONTINUE
         F(1,INT) = 1. - F1(INT-1) - STOREF
         F(INT,1) = BETA * F(1,INT)
         F(INT,INT) = 1. - 2. * F(2,1)
         STOREF = 0.
C
93    CONTINUE
      DO 94 INT1 = NDVSNS,2,-1
         DO 94 INT2 = 2,INT1
            F(INT2,INT2+(NDVSNS+1-INT1)) = F(NDVSNS+1-(INT1-1),1) -
     &                                     F(NDVSNS+1-(INT1-2),1)
            F(INT2+(NDVSNS+1-INT1),INT2) = F(INT2,INT2+(NDVSNS+1-IN
     &        T1))
94    CONTINUE
      DO 96 INT = 1,NDVSNS+1
         F(NDIVP2,INT) = F(1,NDVSNS+3-INT)
         F(INT,NDIVP2) = F(NDVSNS+3-INT,1)
96    CONTINUE
C
      F(NDIVP2,NDIVP2) = 0.
C
C     Calculation of parameters:
C
      DELTAL = DEPTH/NDVSNS
      PSI= THICK2/CELL
      A1 = EMISS * EXRAD * TSTEP / THICK1
      A2 = EMISS * SIGMA * TSTEP / THICK1
      A3 = 2 * (1-PSI) * (1-PSI) * TSTEP / (DELTAL * THICK1)
      A4 = 2 * (2-PSI) * PSI * TSTEP / (DELTAL * THICK1)
      A5 = A2 * (1-PSI) * (1-PSI)
      D2 = EMISSR * SIGMA * TSTEP / THICK10
      D3 = A3 * THICK1/THICK10
      D4 = A4 * THICK1/THICK10
      D5 = A5 * THICK1/THICK10
      B1 = (1-PSI)*(1-PSI)*TSTEP/((2-PSI)* PSI* DELTAL * DELTAL)
      B2 = TSTEP / DELTAL / DELTAL
      B3 = 4 * EMISSI * SIGMA * (1-PSI) * TSTEP/CELL/(2-PSI)/PSI
      QTOT = 0
      TOTQ = 0
C
       CENTER = NDIVP2/2
      MID = IFIX(CENTER)
      cvol = 1.2
C     Start calculation for the next time step:
100   CONTINUE
```

```
C
C     Properties determination:
C
C 3/27/90   Changed upper limit 10 to NDIVP2.
      DO 120 I = 1,NDIVP2
         CPSOL2(I) = 0.0436 + 0.00375 * TEMP1(I)
         RHO2(I) = 323.
         KSOLID(I) = KSZERO * TEMP1(I) / 298.
         KAIR(I) = 4.2E-6 + 7.9E-8* TEMP1(I) - 1.5E-11 * TEMP1(I)**2
120   CONTINUE
      CPSOL1 = C1ZERO * TEMP1(1) / 298.
      CPSOL10 = C1ZERO * TEMP1(NDIVP2) / 298.
C
C     Temperature calculation:
C
      HAMB = 9.8E-3 * (ABS(TEMP(1)/TAMB-1.))**0.25
      HAMB10 = 9.8E-3 *(ABS(TEMP(NDIVP2)/TAMB-1.))**0.25
      HF = HFLAME*BLOW
      IF ((YIG.EQ.'N'.OR.YIG.EQ.'n').OR.(TEMP(1).LT.473.)) HF=HAMB
      A6 = HF * TSTEP / THICK1
      D6 = HAMB10 * TSTEP / THICK10
C
C CHANGES: 10 to NDIVP2.
      DO 300 I = 1,NDIVP2
         RADEX(I) = 0.
         DO 300 J = 1,NDIVP2
            RADEX(I) = RADEX(I) + F(I,J) * (TEMP4(J)-TEMP4(I))
300   CONTINUE
C
      TF = (TFLAME-TAMB)*(1-CHIR)+TAMB
      IF ((YIG.EQ.'N'.OR.YIG.EQ.'n').OR.(TEMP(1).LT.473.)) TF = TAMB
C
            TEMP(1) = TEMP1(1) + (A1 - A2*(TEMP4(1)-TAMB4) -
     &               (A3*KAIR(1)+A4*KSOLID(1))*(TEMP1(1)-TEMP1(2))
     &              + A5*RADEX(1)+ A6*(TF-TEMP1(1)))/(RHO1*CPSOL1)
C
            TEMP(2) = TEMP1(2) + ((B1*KAIR(2) + B2*KSOLID(2)) *
     &                (2.*TEMP1(1) - 3.*TEMP1(2) + TEMP1(3)) +
     &                B3*RADEX(2)) / (RHO2(2)*CPSOL2(2))
C
       DO 320 I = 3,NDVSNS
            TEMP(I) = TEMP1(I) + ( (B1*KAIR(I) + B2*KSOLID(I)) *
     &                (TEMP1(I-1) - 2.*TEMP1(I) + TEMP1(I+1)) +
     &                B3*RADEX(I)) / (RHO2(I)*CPSOL2(I))
320    CONTINUE
C
        TEMP(NDIVP2-1)=TEMP1(NDIVP2-1)+((B1*KAIR(NDIVP2-1)+
     &                B2*KSOLID(NDIVP2-1)) * (TEMP1(NDIVP2-2) -

     &                3*TEMP1(NDIVP2-1) + 2.*TEMP1(NDIVP2)) +
     &                B3*RADEX(NDIVP2-1)) / (RHO2(NDIVP2-1) *
     &                CPSOL2(NDIVP2-1))
```

```
C
      TEMP(NDIVP2) = TEMP1(NDIVP2) +
     &               (-D2*(TEMP4(NDIVP2)-TAMB4)*RLOSS +
     &               (D3*KAIR(NDIVP2) + D4*KSOLID(NDIVP2)) *
     &               (TEMP1(NDIVP2-1) - TEMP1(NDIVP2)) +
     &               D5*RADEX(NDIVP2) - D6*(TEMP1(NDIVP2)-TAMB)*
     &               RLOSS) / (RHO10*CPSOL10)
C
      TDIFF1=TDIFF
       TDIFF = TEMP(1)-TEMP1(1)
      DO 330 I = 1,NDIVP2
         TEMP1(I) = TEMP(I)
         TEMP4(I) = TEMP(I)**4
         TEMPC(I) = TEMP(I) - 273.
330   CONTINUE
      IF (CMASS.EQ.'N'.OR.CMASS.EQ.'n') GO TO 470
C
C     Mass loss and heat release calculation:
C     The honeycomb is further divided into NJ elements
C     for the mass loss calculations.
C
         ZFIN2=0
      DO 400 J = 2,NJ+1
         TEMPJ(J) = TEMP(J)
       PREX2 = PREX22
       AE2 = AE22
         AJ(J) = PREX2
         AEJ(J) = AE2
         ZFJ(J) = ZFIN2
         HCVOLJ(J) = HCV2
         MASSJ(J) = MASS2/NJ
400   CONTINUE
C
          TEMPJ(1) = TEMP(1)
       TEMPJ(NJ+2) = TEMP(NDVSNS)
C
      HCVOLJ(NJ+2) = HCV10
         HCVOLJ(1) = HCV1
       MASSJ(NJ+2) = MASS10
          MASSJ(1) = MASS1
C
               MDOT = 0.
               QDOT = 0.
C
      DO 460 J = 2,NJ+1
         ZDOT1(J) = ZDOT(J)
         ZDOT(J) = 0.
C
         IF (Z(J).GT.ZFJ(J)) ZDOT(J) = AJ(J) * (Z(J)-ZFJ(J)) *
     &                               EXP(-AEJ(J)/(R*TEMPJ(J)))
C
         Z(J) = Z(J) - (ZDOT1(J)+ZDOT(J)) * TSTEP / 2.
```

```
          MDOT = MDOT + ZDOT(J)*MASSJ(J)
          QDOT = QDOT + ZDOT(J)*MASSJ(J)*HCVOLJ(J)
460     CONTINUE
C
        QDOT7 =QDOT/CELL2
        DO 465 L = 1,4
        ZDOT1(1)=ZDOT(1)
        ZDOT(1)=0
        IF(Z(1).GT.ZFIN1(L))
       &ZDOT(1)=(Z(1)-ZFIN1(L))
       &*PREX1(L)*EXP(-AE1(L)/(R*TEMPJ(1)))
        Z(1)=Z(1)-(ZDOT(1))*TSTEP
        MDOT=MDOT+ZDOT(1)*MASSJ(1)
        QDOT=QDOT+ZDOT(1)*MASSJ(1)*HCVOLJ(1)
465     CONTINUE
468     CONTINUE
C
        QDOT6=QDOT/CELL2-QDOT7
        DO 467 L = 1,4
        ZDOT1(NJ+2)=ZDOT(NJ+2)
        ZDOT(NJ+2)=0
        IF(Z(NJ+2).GT.ZFIN10(L))
       &ZDOT(NJ+2)=(Z(NJ+2)-ZFIN10(L))
       &*PREX10(L)*EXP(-AE10(L)/(R*TEMPJ(NJ+2)))
        Z(NJ+2)=Z(NJ+2)-(ZDOT(NJ+2))*TSTEP
        MDOT=MDOT+ZDOT(NJ+2)*MASSJ(NJ+2)
        QDOT=QDOT+ZDOT(NJ+2)*MASSJ(NJ+2)*HCVOLJ(NJ+2)
467     CONTINUE
469     CONTINUE
C
        QDOT8=QDOT/CELL2-QDOT6-QDOT7
          BL = 1.2*MDOT/HFLAME
          IF(BL.GT.0.5) GO TO 485
          IF(BL.LT.0.1) GO TO 487
          BLOW = BL/(EXP(BL)-1)
          GO TO 489
 485      BLOW = 0.0
          GO TO 489
 487      BLOW = 1.0
489     CONTINUE
        QDOT=QDOT/CELL2
        MDOT = MDOT * 1000. / CELL2
         IF(TEMP(1).LT.473)QDOT=0
470     QSTAR = (1-CHIR/2)*QDOT
        IF (QDOT.GT.25) QSTAR = (1-CHIR)*(QDOT-25)+25*(1-CHIR/2)
        QOSU=EXRAD+QSTAR+MDOT*CVOL*(TEMP(1)-TAMB)/1000+
       & SIGMA*RADEX(1)-(2*(1-PSI)*(1-PSI)*KAIR(1)+
       & 2*(2-PSI)*PSI*KSOLID(1))*(TEMP(1)-TEMP(2))/DELTAL-
       & SIGMA*(TEMP4(1)-TAMB4)-CPSOL1*MASS1*
       & (1.5*TDIFF-0.5*TDIFF1)/TSTEP/CELL2
         IF(QOSU.LT.0.0)QOSU=0
        K = K + 1
```

```
      TIME = K * TSTEP
      IF (ABS(TIME-IFIX(TIME)).GT.0.0001) GO TO 600
      QTOT = QTOT + QDOT
       IF(TEMP(1).LT.473) TIMEIG=TIME
       IF(TEMP(1).LT.473) QOSU=0
        TOTQ=TOTQ+QOSU
        IF(TEMP(1).GT.473)QOSUAV=TOTQ/(TIME-TIMEIG)
C
      WRITE(*,500) TIME,TEMPC(1),TEMPC(MID),TEMPC(NDIVP2),
     & Z(1),Z(NDIVP2),MDOT,QDOT,QOSU,QOSUAV
C
      IF (STORE.EQ.'Y'.OR.STORE.EQ.'y') THEN
      WRITE(3,507) TIME,TEMPC(1),TEMPC(MID),TEMPC(NDIVP2),Z(1),
     & Z(NDIVP2),MDOT,QDOT,QTOT,QOSU,TOTQ,QDOT6,QDOT7,QDOT8,
     & QOSUAV
      END IF
C
      IF (PRIN.EQ.'Y'.OR.PRIN.EQ.'y') THEN
      WRITE(6,500) TIME,TEMPC(1),TEMPC(MID),TEMPC(NDIVP2),Z(1),
     & Z(NDIVP2),MDOT,QDOT,QDOT6,QOSU,QOSUAV
      END IF
C
600   IF (TIME.LE.TMAX) GO TO 100
      IF (PRIN.EQ.'Y'.OR.PRIN.EQ.'y') WRITE(6,650)
C
C     ======================== Format Statements ===========
25    FORMAT(////1X,'Options for the panel material:',//5X,
     &       '1. Epoxy Fiberglass.',/5X,
     &       '2. Phenolic Fiberglass.',/5X,
     &       '3. Phenolic Fiberglass A',/5X,
     &       '4. Phenolic Graphite.',//5X,
     &       'Please select option number: ')
30    FORMAT(1X,'You must select one of the options; try again:')
35    FORMAT(/1X,'The number of temperature columns in the output ',
     &'must be',/1X,'smaller than or equal to ',I3,
     &'.  Enter your option: ')
68    FORMAT ('  '//)
70    FORMAT(1X,' The program is ',A,/,1X,A,/' The date is ',A18/
     &       ' The time step is ',F7.5, ' sec'/
     &       ' The external radiation is ',F4.0, ' kW/m2'/
     &       ' The ambient temperature is ',I4,' oC'/
     &       ' The material type is ',I2,/
     &       ' The cell size is ',F6.3,' inches.'/
     &       ' The panel thickness is ',F6.3,' inches.'/
     &      ' There are ',I4,' honeycomb elements for temp. calc.'/
     &       ' There are ',I4,' honeycomb elements for mass
     &          losscalc.'/
     &       ' Losses from the rear face? ',A3/
     &       ' The maximum test time is ',F6.0, ' sec')
C
C CHANGES:
C          Instead of 10 columns for temperature, we must allow for
```

```
C          NDIVP2 columns.  To be looked on later.
80     FORMAT(1X,/,2X,'TIME',3X,'T1',3X,'TM',3X,'TR',4X,'Z1',6X,
     &  'ZR',5X,'MDOT',5X,'QDOT ',3X,'QTOT',4X,'QOSU',3X,'TOTQ'/)
C
150    FORMAT(2X,'The number of honeycomb elements (temperature ',
     &'elements)',/2X,'must be greater than zero, and less than or
     &    ',
     &'equal to ',I4,'.',/2X,'If you want a larger number of ',
     &'elements, change the value',/2X,'of the parameter NUM.  ',
     &'Otherwise, try again:')
500    FORMAT(F6.0,3I5,3F8.3,4F8.1)
501    FORMAT(F6.0,2I5,3F8.3,3F8.1)
507    FORMAT(F6.0,3I5,3F8.3,8F8.1)
650    FORMAT('  '//)
698    FORMAT(2X,'Enter the number of honeycomb divisions for the',
     &' temperature calculation: ')
700    FORMAT(2X,'The number of divisions for the temperature',/2X,
     &'calculation must be greater than or equal to 3,',/2X,
     &'and smaller than or equal to ',I2,'; please try again:')
       STOP
       END
C
```

```
C     ================================================
      SUBROUTINE EPOFI(ZFIN1,PREX1,AE1,ZFIN10,
     & PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
C     Initialize with values corresponding to Epoxy Fiberglass
C     panel.

      DIMENSION ZFIN1(6),ZFIN10(6),PREX1(6),PREX10(6),AE1(6),AE10(6)

      REAL MASS1,MASS10
      ZFIN1(1)=.985
      ZFIN1(2)=0.761
      ZFIN1(3)=0.57
      ZFIN1(4)=0
      PREX1(1)=4.84E9
      PREX1(2)=4.79E13
      PREX1(3)=1202604
      PREX1(4)=0
      AE1(1)=83140
      AE1(2)=187065
      AE1(3)=124710
      AE1(4)=0
      ZFIN10(1)=0.985
      ZFIN10(2)=0.773
      ZFIN10(3)=0.572
      ZFIN10(4)=0
      PREX10(1)=166043
      PREX10(2)=4.82E10
      PREX10(3)=2.81E8
      PREX10(4)=0
      AE10(1)=76489
      AE10(2)=152515
      AE10(3)=161010
      AE10(4)=0
      HCV1 = 16600
      HCV10 = 16600
      MASS1 = 0.455
      MASS10 = 0.455
       C1ZERO = 1.07
      END
C
```

```
      SUBROUTINE PHEFI(ZFIN1,PREX1,AE1,ZFIN10,
     & PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
C     Initialize with values corresponding to Phenolic Fiberglass

      DIMENSION ZFIN1(6),ZFIN10(6),PREX1(6),PREX10(6),AE1(6),AE10(6)

      REAL MASS1,MASS10
      ZFIN1(1)=0.84
      ZFIN1(2)=0.64
      ZFIN1(3)=0
      ZFIN1(4)=0
      PREX1(1)=0.01
      PREX1(2)=2000
      PREX1(3)=0
      PREX1(4)=0
      AE1(1)=14500
      AE1(2)=62355
      AE1(3)=0
      AE1(4)=0
      ZFIN10(1)=0.84
      ZFIN10(2)=0.64
      ZFIN10(3)=0
      ZFIN10(4)=0
      PREX10(1)=1.5
      PREX10(2)=500
      PREX10(3)=0
      PREX10(4)=0
      AE10(1)=14500
      AE10(2)=48100
      AE10(3)=0
      AE10(4)=0
      HCV1 = 8900
      HCV10 = 8900
      MASS1 = 0.43
      MASS10 = 0.43
      C1ZERO = 1.13
      END
C
```

```
      SUBROUTINE PHEGRA(ZFIN1,PREX1,AE1,ZFIN10,
     & PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
C     Initialize with values corresponding to Phenolic Graphite  C
C     panel.

      DIMENSION ZFIN1(6),ZFIN10(6),PREX1(6),PREX10(6),AE1(6),AE10(6)

      REAL MASS1,MASS10
      ZFIN1(1)=0.973
      ZFIN1(2)=0.6
      ZFIN1(3)=0
      ZFIN1(4)=0.0
      PREX1(1)=590
      PREX1(2)=4.43
      PREX1(3)=0
      PREX1(4)=0.0
      AE1(1)=46334
      AE1(2)=51880
      AE1(3)=289800
      AE1(4)=0.0
      ZFIN10(1)=0.973
      ZFIN10(2)=0.6
      ZFIN10(3)=0
      ZFIN10(4)=0
      PREX10(1)=590
      PREX10(2)=4.43
      PREX10(3)=0
      PREX10(4)=0
      AE10(1)=46334
      AE10(2)=51880
      AE10(3)=289800
      AE10(4)=0
      HCV1 = 14900
      HCV10 = 14900
      MASS1 = 0.619
      MASS10 = 0.619
      C1ZERO = 1.13
      END

C
```

```
      SUBROUTINE PHEFIA(ZFIN1,PREX1,AE1,ZFIN10,
     & PREX10,AE10,HCV1,HCV10,MASS1,MASS10,C1ZERO)
C     Initialize with values corresponding to Phenolic Fiberglass A

      DIMENSION ZFIN1(6),ZFIN10(6),PREX1(6),PREX10(6),AE1(6),AE10(6)

      REAL MASS1,MASS10
      ZFIN1(1)=0.991
      ZFIN1(2)=0.72
      ZFIN1(3)=0.47
      ZFIN1(4)=0
      PREX1(1)=614
      PREX1(2)=833
      PREX1(3)=46630
      PREX1(4)=0
      AE1(1)=43200
      AE1(2)=62400
      AE1(3)=110900
      AE1(4)=0
      ZFIN10(1)=.9753
      ZFIN10(2)=0.89
      ZFIN10(3)=0.677
      ZFIN10(4)=0
      PREX10(1)=161
      PREX10(2)=1927
      PREX10(3)=2.17E7
      PREX10(4)=0
      AE10(1)=40809
      AE10(2)=74610
      AE10(3)=153153
      AE10(4)=0
      HCV1 = 8900
      HCV10 = 8900
      MASS1 = 0.72
      MASS10 = 0.42
      C1ZERO = 1.13
      END
```


☆U.S. GOVERNMENT PRINTING OFFICE: 1993 - 704-078/60272