R7202291 30519 421.03

# NATIONAL BUREAU OF STANDARDS REPORT

10 494

FIRE ENDURANCE THERMAL ANALYSIS OF CONSTRUCTION WALLS



U.S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

#### NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards ' was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in four broad program areas. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Measurement Services and the following technical divisions:

Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic and Molecular Physics—Radio Physics <sup>2</sup>—Radio Engineering <sup>2</sup>—Time and Frequency <sup>2</sup>—Astrophysics <sup>2</sup>—Cryogenics.<sup>2</sup>

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; develops, produces, and distributes standard reference materials; relates the physical and chemical properties of materials to their behavior and their interaction with their environments; and provides advisory and research services to other Government agencies. The Institute consists of an Office of Standard Reference Materials and the following divisions:

Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Physical Chemistry. **THE INSTITUTE FOR APPLIED TECHNOLGGY** provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations in the development of technological standards, and test methodologies; and provides advisory and research services for Federal, state, and local government agencies. The Institute consists of the following technical divisions and offices:

Engineering Standards—Weights and Measures — Invention and Innovation — Vehicle Systems Research—Product Evaluation—Building Research—Instrument Shops—Measurement Engineering—Electronic Technology—Technical Analysis.

THE CENTER FOR RADIATION RESEARCH engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center consists of the following divisions:

Reactor Radiation-Linac Radiation-Nuclear Radiation-Applied Radiation.

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in the selection, acquisition, and effective use of automatic data processing equipment; and serves as the principal focus for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

Information Processing Standards—Computer Information — Computer Services — Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System, and provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

Office of Standard Reference Data—Clearinghouse for Federal Scientific and Technical Information 4—Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

<sup>&</sup>lt;sup>1</sup> Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234. <sup>2</sup> Located at Boulder, Colorado 80302.

<sup>&</sup>lt;sup>3</sup> Located at 5285 Port Royal Road, Springfield, Virginia 22151.

# NATIONAL BUREAU OF STANDARDS REPORT

# **NBS PROJECT**

# **NBS REPORT**

4219112

September 29, 1971

10 494

# FIRE ENDURANCE THERMAL ANALYSIS OF CONSTRUCTION WALLS

by

Francis C. W. Fung Fire Research Section Building Research Division Institute for Applied Technology National Bureau of Standards Washington, D. C. 20234

#### IMPORTANT NOTICE

NATIONAL BUREAU OF STA for use within the Government. B and review. For this reason, the whole or in part, is not authoriz Bureau of Standards, Washington the Report has been specifically p

Approved for public release by the director of the National Institute of Standards and Technology (NIST) on October 9, 2015 accounting documents intended ubjected to additional evaluation isting of this Report, either in Office of the Director, National the Government agency for which pies for its own use.



U.S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

يە ئەھر ئەھر

2 2 7 1

12

2<sup>-0</sup>

# Table of Contents

\ · · · ·

.

Abstract	Page					
1.0 Introduction	2					
2.0 Governing Equation and Boundary Conditions	3-8					
Problem Formulation and Finite Difference Equations						
4.0 Discussion of Numerical Program	14-15					
5.0 Sample Cases Calculated	16-19					
5.1 Description of Panels						
5.2 Thermal Properties						
5.3 Input Data	20-23					
Comparison Plots	20-23					
Reference	24, 25					
Flow Chart	26					
Program Listing	27-33					
Acknowledgement	34					

.

## ABSTRACT

A general one dimensional transient heat transfer numerical program has been developed for composite building constructions with arbitrary air gap location S. The complete Fortran language program as used on the NBS Univac 1108 computer is given. A discussion of the program and instruction for its use are facilitated by the aid of examples. Numerical solutions using the present program compare favorably with experimental data in standard fire endurance tests.

#### 1.0 INTRODUCTION

The fire performance of building constructions is generally evaluated by a large scale laboratory fire endurance test (ASTM E 119) in which one surface is exposed to fire, controlled according to a prescribed increasing temperature history simulating the burnout of combustibles. The fire endurance rating of the construction is the time period during which it withstands the fire exposure without (a) structural failure, (b) the development of cracks through which flames can cross, or (c) the temperature rise on the unexposed surface exceeding a prescribed limit (250°F rise average, 325°F rise at a single point). Where the failure criterion is due to heat transmission without complications due to structural or physical effects, heat transfer analysis should provide a means for prediction and design.

A particular aspect of the fire endurance test which is not well defined but which probably plays a significant role in fire performance, is the effect of mass flow (air and combustion gases) due to pressure differences since typical building constructions consist of a series of composite layers and intermediate air layers, a transient heat and air infiltration model was formulated. The program is particularly suitable for evaluating the thermal fire endurance of building constructions where various combinations of solid-to-solid and solid-to-air contacts are encountered. For each solid layer, the present program has provisions for phase changes, heat generation and absorption, and thermal property variations commonly found in building materials. Through the air spaces the modes

of heat transfer include radiation and convection with temperature-dependent heat transfer coefficients and air properties.

A number of analog and numerical programs for fire endurance evaluations had been in existence for some time [1, 2, 3, 4]. A more flexible and general finite difference program was developed by Krokosky as recently as 1970 [5]. For a review of the existing thermal analysers for fire endurance evaluation one is thus referred to [4 and 5]. The present numerical program was developed to incorporate into fire endurance analyses the following features which are desirable and yet

not readily available in existing programs:

- 1. Options to handle heat exposure on one or both sides of structure.
- Heat balances in air spaces to allow for air infiltration, and heat generation and absorption in air spaces.
- 3. For ease of application to building structures an input card, say 101101, is sufficient to instruct the computer of the specified number of solid layers and air spaces in a given problem.
- 4. Temperature-dependent properties and known chemical heat exchanges of various building materials are stored in a subroutine and called by an input card, say 2331, where the numbers indicate coded materials stored in the subroutine.
- 5. Duration as well as amount of known chemical heat exchanges can be varied in any material.

### 2.0 GOVERNING EQUATION AND BOUNDARY CONDITIONS

The governing equation for one dimensional transient heat flow is the well known heat diffusion equation. Including a term for internal heat

generation, this can be expressed as,

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial k} \right) + g = \rho_c \frac{\partial T}{\partial \theta}$$
(1)

where,

T= absolute temperature in solid.

x = coordinate in direction of heat flow.

k = heat conduction coefficient.

g = time rate of heat generation per unit volume in solid.

 $\rho$  = density of solid.

c = specific heat capacity of solid.

A= time

Boundary Conditions [ 6, 7]:

The following types of boundary conditions need to be evaluated for the general problem;

- (a) solid to air
- (b) energy balance in air space
- (c) air to solid
- (d) solid to surrounding
- (e) solid to symmetry plane
- (f) solid to solid
- (g) furnace gases to first surface layer.

Figure 1

Solid 2 Solid 1 Space

4

(a) Solid to Air (See Figure 1)  

$$\frac{\rho_1 c_1 \Delta x_1}{2} \frac{\partial T_1}{\partial \theta} = -k_1 \frac{\partial T_1}{\partial x} - \sigma \epsilon_{12} (T_1^4 - TA^4) -h_1 (T_1 - TA) + g_1 \frac{\Delta x_1}{2} \quad (2)$$
(b) Energy Balance in Air Space (See Figure 1)  

$$\ell_a c_{pa} \rho_a \frac{\partial TA}{\partial \theta} = h_1 (T_1 - TA) -h_2 (TA - T_2) + m c_{pa} (T_1 - T_2) + \ell_a g_a \quad (3)$$
(c) Air to Solid (See Figure 1)  

$$\frac{\rho_2 c_2 \Delta x_2}{2} \frac{\partial T_2}{\partial \theta} = k_2 \frac{\partial T_2}{\partial x} + \sigma \epsilon_{12} (TA^4 - T_2^4) + h_2 (TA - T_2) + g_2 \frac{\Delta x_2}{2} \quad (4)$$

In the above equations the subscripts 1 and 2 indicate solid 1 and solid 2 respectively as shown in Figure 1, and where  $\epsilon_{12} = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$ 

and  $\varepsilon_1$ ,  $\varepsilon_2$  are emissivity of surface 1 and surface 2,

T2, T1: surface temperatures as shown in Figure 1

 $\Delta x_1, \Delta x_2$ : incremental length in x direction

σ: Stefan Boltzman constant

TA: temperature of air  $h_1 = K\left(\frac{T_1 - TA}{L}\right)^{\frac{1}{4}}$ : convection heat transfer coefficient from solid to air

L: characteristic dimension of panel

k1, k2: heat conduction coefficient in solid 1, and 2

g<sub>1</sub>, g<sub>2</sub>: time rate of heat generation or absorption per unit volume in solid 1 and 2

 $l_{a}: \text{ air gap spacing} \\ c_{pa}: \text{ specific heat capacity of air} \\ \rho_{a}: \text{ density of air} \\ h_{2} = K \left( \frac{TA - T_{2}}{L} \right)^{\frac{1}{4}}: \text{ convection heat transfer coefficient from air to solid} \\ \end{cases}$ 

- m: rate of mass transfer per unit area due to pressure difference
- g<sub>a</sub>: rate of heat generation per unit volume in air space due to combustibles.
- K: an empirical convection heat transfer constant, K=.27 for vertical surfaces, and K=.38 for horizontal surfaces.

(d) <u>Solid to Ambient (See Figure 2)</u>  $\frac{\rho_{c}\Delta x}{2} \frac{\partial T}{\partial \theta} = -k \frac{\partial T}{\partial \theta} - \sigma \varepsilon (T^{4} - T_{0}^{4}) - h_{0}(T - T_{0}) + g \frac{\Delta x}{2}$ (6)

where the additional variables are,

T<sub>o</sub>: ambient temperature  $h_o = K \left( \frac{T - T_o}{L} \right)^{\frac{1}{4}}$ : convection heat transfer coefficient 6: emissivity of surface T: surface temperature of solid Figure 3 -Solid  $T_s$ Solid Air Space Symmetry plane

### (e) Solid to Symmetry Plane (See Figure 3)

By symmetry, temperature on both solid surfaces that face each other are equal, however  $T \ge T_s$ . So there will be heat transfer from solid to air. At the interface we have,

$$\frac{\rho c \Delta x}{2} \frac{\partial T}{\partial \theta} = -k \frac{\partial T}{\partial x} - h_s (T - T_s) + g \frac{\Delta x}{2} - \sigma \varepsilon (T^4 - T_s^4)$$
(8a)

At the air space we have,

$$l_{s}c_{pa}\rho_{a}\frac{\partial T_{s}}{\partial \theta} = h_{s}(T - T_{s}) + \sigma \varepsilon (T^{4} - T_{s}^{4})$$
(8b)

where,

T: surface temperature of solids

T<sub>s</sub>: temperature of air in symmetry plane  

$$\ell_s$$
: distance from solid to symmetry plane  
 $h_s = K\left(\frac{T - T_s}{L}\right)^{\frac{1}{4}}$ : convection heat transfer coefficient from solid to  
symmetry plane.

Figure 4 -

# (f) Solid to Solid (See Figure 4)

Consider interface between Solid 1 and Solid 2 as shown in Figure 4. Let  $T_1$  and  $T_2$  be the interface temperature in each solid respectively. A heat balance for the interface node can be expressed as,  $T_2 = T_1$ ,

$$\rho_1 c_1 \frac{\Delta \mathbf{x}_1}{2} \frac{\partial \mathbf{T}_1}{\partial \theta} + \rho_2 c_2 \frac{\Delta \mathbf{x}_2}{2} \frac{\partial \mathbf{T}_2}{\partial \theta} = g_1 \frac{\Delta \mathbf{x}_1}{2} + g_2 \frac{\Delta \mathbf{x}_2}{2} - k_1 \frac{\partial \mathbf{T}_1}{\partial \mathbf{x}} + k_2 \frac{\partial \mathbf{T}_2}{\partial \mathbf{x}}$$
(5)

where subscript indicates conditions in solid layer 1 or 2.

# (g) Furnace Gases to First Solid Surface (See Figure 5)

Consider heat transfer from furnace gases to first solid surface. The main modes of heat transfer will be radiation and convection.

A good approximation of ASTM E 119 fire curve is given by the following three formulas, (where T = temperature in degrees C, and  $\Theta$  = time in minutes);

 $T = 940 \frac{\Theta}{\Theta + 4} \circ C + 20 \circ C \qquad 0 < \Theta < 50 \text{ min}$   $(error \pm 2\%)$   $T = 926^{\circ}C + 0.70^{\circ}C - 0.0131(120 - \Theta)^{2} \circ C$   $50 \text{ min} < \Theta < 115 \text{ min}$  (no appreciable error)  $T = 926^{\circ}C + 0.70^{\circ}C \qquad 115 \text{min} < \Theta < 480 \text{ min}$  (linear exact)

Heat balance from furnace to first solid surface,

$$\frac{\rho c \Delta x}{2} \frac{\partial T_{l}}{\partial \Theta} = k \frac{\partial T}{\partial x} + \sigma \varepsilon (T_{F}^{\mu} - T_{l}^{\mu}) + h_{F} (T_{F} - T_{l}) + g \frac{\Delta x}{2}$$
(9)

where  ${\rm T}_{\rm F}$  is absolute furnace temperature, and

$$h_{F} = K \left( \frac{T_{F} - T_{I}}{L} \right)^{\frac{1}{4}}$$

#### 3.0 PROBLEM FORMULATION AND FINITE DIFFERENCE EQUATIONS

Consider general one-dimensional heat transfer problem containing N solid layers and m air spaces in any order. To facilitate formulation and discussion let's introduce i as the running index for air spaces. In Figure 6, a general multi-layer configuration is shown, where numbers in circles indicate the applicable equation at the given node as discussed in the previous section.



Figure 6. A Composite Wall with N Layers Note: Number in circle indicates applicable equation as discussed in Section 2.0.

To solve our problem numerically with the nonlinear heat diffusion equation and associated complex system of boundary conditions we shall use forward time differencing and central space differencing scheme. Furthermore, we must use three subscripts.

Let:

T<sub>i,j</sub>: Temperature of jth node in ith solid i: 1...N (number of solid layers) j: 1...n (number of nodes on solid layer ) k: 1...m (number of air spaces) See Figure 7 for finite differencing network.

Figure 7. Sketch of Finite Differencing Network in a Solid Layer



Furthermore, let

 $TA_k$ : Temperature of kth air spacing

0: Time

 $\Delta O$ : Time increment

 $T'_{i,j}: \text{ Temperature at } (\Theta + \Delta \Theta) \text{ of jth node in ith solid}$  $\ell_{i}: \text{ Thickness of ith solid}$ 

lA<sub>1</sub>: Thickness of kth air spacing

 $\Delta x_{i} = \frac{l_{i}}{n-1}$ : Difference spacing for ith solid

g. : rate of heat generation per unit volume

k ... heat conduction coefficient

 $\alpha_i$ : heat diffusion coefficient

ga,: rate of heat generation per unit volume in air space

 $m_{\rm p}$ : rate of mass transfer per unit area

Applying our finite differencing scheme we have the following general finite difference expressions corresponding to the previously discussed governing equation and boundary conditions; [6, 7, and 8]

Governing equation

$$T_{ij} = \frac{1}{M_{i}} (T_{i(j-i)} + T_{i(j+i)}) + (1 - \frac{2}{M_{i}})T_{ij} + \frac{g_{ij}\Delta x_{i}}{k_{ij}M_{i}}$$
(1)

St. mil

where  $M_{i} = \frac{(\Delta x_{i})^{2}}{\alpha_{i} \Delta \Theta}$ 

From equation (1) we require  $M_i > 2$  for stability. Solid to Air,

$$T_{i,n}^{i} = T_{i,n} + \frac{2}{M_{i}} (T_{i,n-1} - T_{i,n}) - R_{i} [(T_{i,n})^{4} - (T_{i+1,1})^{4}] - H_{i} (T_{i,n} - TA_{k})^{\frac{5}{4}} + \frac{g_{i,n}\Delta x_{i}^{2}}{\frac{k_{i,n}M_{i}}{k_{i,n}M_{i}}}$$
(2)

where

$$R_{i} = \frac{2\Delta\theta\sigma\varepsilon_{12}}{\Delta x_{i}\rho_{i}c_{i}}$$

$$c_{i}: \text{ specific heat of ith layer.}$$

$$\varepsilon_{12} = \frac{1}{\frac{1}{\varepsilon_{1}} + \frac{1}{\varepsilon_{2}} - 1}: \text{ where } \varepsilon_{1} \text{ and } \varepsilon_{2} \text{ are emmisivity of two parallel}$$

$$\text{ solid layers.}$$

$$H_{i} = \frac{2\Delta\theta K}{\rho_{i}c_{i}\Delta x_{i}}(L)^{\frac{1}{4}}$$

L: characteristic dimension of panel.

Air Space Heat Balance

$$TA_{k}' = TA_{k} + P_{k}(T_{i,n} - TA_{k})^{\frac{15}{4}} - Q_{K}(TA_{k} - T_{i+1,1})^{\frac{5}{4}} + S_{k}(T_{i,n} - T_{i+1,1}) + GA_{k}$$
(3)

where

$$\begin{split} P_{k} &= \left(\frac{K}{L^{3}}\right) \frac{\Delta \theta}{\ell A_{k} c_{pa} \rho_{a}} \\ \rho_{a}: & \text{ air density function of temperature.} \\ c_{pa}: & \text{ specific heat of air.} \\ Q_{K} &= \left(\frac{K}{L^{3}}\right) \frac{\Delta \theta}{\ell A_{k} c_{pa} \rho_{a}} \\ S_{k} &= \frac{m \Delta \theta}{\ell A_{k} \rho_{a}} \\ S_{k} &= \frac{g a_{k} \Delta \theta}{\ell A_{k} \rho_{a}} \\ GA_{k} &= \frac{g a_{k} \Delta \theta}{c_{pa} \rho_{a}} \\ \frac{Air \text{ to Solid}}{T_{i+1,1}^{i} = T_{i+1,1}^{i} + R_{i} [(T_{in})^{4} - (T_{i+1,1})^{4}] - \frac{2}{N_{i+1}} (T_{i+1,1} - T_{i+1,2}) \\ &+ H_{i+1} (TA_{k} - T_{i+1,1})^{\frac{5}{4}} \end{split}$$

 $R_i, M_{i+1}, H_{i+1}$  as defined before.

Solid to Ambient

$$T_{N,n}^{*} = T_{N,n} + \frac{2}{M_{N}}(T_{N,n-1} - T_{N,n}) - R_{N}(T_{N,n}^{4} - T_{0}^{4}) - H_{N}(T_{N,n} - T_{0})^{\frac{5}{4}} + \frac{G_{N,n}(\Delta x_{N})^{2}}{k_{N,n}M_{N}}$$
(6)

where

$$R_{N} = \frac{2\Delta\theta\sigma\varepsilon_{N}}{\Delta x_{N}\rho_{N}c_{N}}$$

$$\varepsilon_{N}: \text{ emisivity of solid (last node to ambient).}$$

$$H_{N}, k_{N,n} \text{ and } M_{N} \text{ as defined before}$$

$$T_{o}: \text{ ambient temperature}$$

$$\frac{\text{Solid to Symmetry Plane}}{T_{N,n}^{\prime} = T_{N,n} + \frac{2}{M_{N}}(T_{N,n-1} - T_{N,n}) - H_{N}(T_{N,n} - T_{s})^{\frac{5}{4}} + \frac{G_{N,n}(\Delta x_{N})^{2}}{k_{N,n}M_{N}}$$

$$- R_{N}(T_{N,n}^{4} - T_{s}^{4}) \qquad (8a)$$

$$T_{s}^{\prime} = T_{s} + P_{s}(T_{N,n} - T_{s})^{\frac{5}{4}} + R_{N}(T_{N,n}^{4} - T_{s}^{4}) \qquad (8b)$$

where

 $T_s$ : temperature at symmetry plane

$$P_{s} = \left(\frac{K}{L^{\frac{1}{2}}}\right) \frac{\Delta\theta}{\ell_{s}c_{pa}\rho_{a}}$$

 $\ell_s$ : distance between solid surface and symmetry plane. Solid to Solid  $T'_{i+1,1} = T'_{i,n}$ 

$$T_{i,n}^{\prime} = [A_{i}T_{i,n} + A_{i+1}T_{i+1,1} + B_{i}g_{i,n} + B_{i+1}g_{i+1,1} + D_{i,n}(T_{i,n-1} - T_{i,n}) - D_{i+1,1}(T_{i+1,1} - T_{i+1,2})](A_{i} + A_{i+1})$$
(5)

where

$$A_{i} = \frac{\rho_{i}c_{i}\Delta x_{i}}{2}$$

$$B_{i} = \frac{\Delta x_{i}\Delta \theta}{2}$$

$$D_{i,n} = \frac{k_{i,n}\Delta \theta}{\Delta x_{i}}$$

$$D_{i+1,1} = \frac{k_{i+1,1}\Delta \theta}{\Delta x_{i+1}}$$

g<sub>i,j</sub>: rate of heat generation per unit volume in ith solid. Furnace Gases to First Solid Surface

$$T_{1,1} = T_{1,1} + R_1 (T_F^4 - T_{1,1}^4) + H_1 (T_F - T_{1,1}) + \frac{G_{1,1} \Delta x_1}{k_{1,1} M_1} - \frac{2}{M_1} (T_{1,1} - T_{1,2})$$
(9)

where

$$R_{1} = \frac{2\Delta\theta\sigma\varepsilon_{0}}{\Delta x_{1}\rho_{1}c_{1}}$$

emisivity of first surface (furnace gases to 1st solid).
 T<sub>F</sub>: furnace temperature

$$H_{1} = \frac{K}{L^{\frac{1}{4}}} \frac{2\Delta\theta}{\rho_{1}c_{1}\Delta x_{1}}$$

## 4.0 DISCUSSION OF NUMERICAL PROGRAM

A flow chart of the main program is presented in Figure 7. A listing of the complete numerical program is also presented at the end of this report. The logical sequence of the main program can be grasped readily by first considering the flow chart.

A list of input parameters is read in on data cards (examples of which are shown at Section 5.3) as follows:

NN= number of solid layers

N= number of nodes in each layer

M= number of air spaces

- ID= sequence of numbers 1 or 0, specifying the sequence of solid layers and air spaces, e.g., 101011101 means solid-air-solid-air-solidsolid-solid-air-solid.
- IDD= sequence of numbers specifying the material of each solid layer, e.g., 122321 means the six solid layers of the problem are of materials 1, 2, 2, 3, 2, 1 in that order. Various temperature dependent material properties are stored in Subroutine Prop.

AL(I): thickness of ith solid layer in feet

ALPHA(I): heat diffusion coefficient of ith solid layer, ft<sup>2</sup>/hr.

(ALPHA assumed constant other temperature dependent thermal properties

stored in Subroutine Prop.

RHO(I): density of ith solid layer in 1b/ft<sup>3</sup>

AI(I): thickness of air gap spacing in feet

GA(k): rate of heat generation per unit volume due to combustibles in kth air space, Btu/ft<sup>3</sup>-hr.

DTHETA: time increment in fraction of hour.

AMO: Mass flux through walls in lb/ft<sup>2</sup>-hr

GM1, GM2, GM3 etc: Heat absorption or release due to phase change in material 1, 2, or 3 etc., Btu/ft<sup>3</sup>hr.

Subroutine Prop: stores temperature dependent thermal properties and phase change reactions of some common building materials. This subroutine can be expanded as desire when new materials are encountered. When called from the main program this subroutine supplies the thermal properties for the ith layer of solid currently being calculated. The function subroutines are self explanatory. The comment statement at the beginning of each function subroutine properly identifies it with the corresponding equation and boundary conditions in section 3.0.

### 5.0 SAMPLE CASES CALCULATED

### 5.1 Description of Panels

Case 1: Four solid layers (gypsum, wood, wood, gypsum), three air gaps, heat from one side as shown:



Case 2: Four solid layers (gypsum, wood, wood, gypsum), three air gaps, heating from both sides as shown:



Case 3: One solid layer (plywood either 1/2" or 5/8" thick), heating from one side of panel.

Case 4: Two solid layers and one air gap (Brick - Air - Brick), heating from one side as shown:



#### 5.2 Thermal Properties

The following thermal properties taken from Ref. 1 and Ref. 2 are used in all calculations,  $\varepsilon = .9$  for all surfaces.

$$K = (.05 + T)$$
 Btu/hr ft°F 400°F

Heat of moisture desorption and calcination: 20,740 Btu/ft<sup>3</sup>

#### Plywood

 $\alpha = .006 \text{ ft}^2/\text{hr}$   $\rho = 31 \text{ lb/ft}^3$   $c = .67 \text{ Btu/lb}^{\circ}\text{F}$   $K = .065 \text{ Btu/hr} \text{ ft}^{\circ}\text{F}$ 

Heat of moisture desorption: 15 00 Btu/ft<sup>3</sup>

# <u>Brick</u>

α = .028 ft<sup>2</sup>/hr
ρ = 110 lb/ft<sup>3</sup>
c = .216 Btu/lb°F
K = 1.0 Btu/hr ft°F 0<T<200°F
K = .46 + 2T/10,000 Btu/hr ft°F 200°F<T<2000°F
Heat of moisture desorption = 5800 Btu/ft<sup>3</sup>

# 5.3 Input Data

The following are print outs of input data for the sample cases calculated:

Case 1: Four solid layers, 3 air gaps, furnace on one side of panel. (gypsum - air - wood - air - wood - air - gypsum)

	4		5	3	1	68.000	.000	5380.000	1500.000
1	0	1	0 1	0 1					
1	3	3	1						
			°520		٥00°		°220	.000	
			°520		.000				
			°02		800 。		60.000	<u>。</u> 260	
			.042		。006		31.000	.670	
			.042		。006		31.000	<u>。</u> 670	
			°02		800 ه		60.000	<b>.</b> 260	

Case 2:	Four solid	l layers, 3 air	gaps furnace of	n both sides	of panel.		
(Note:	Symmetry ha	s been invoked	gypsum - air	- wood - sym	metry plane)		
$\begin{array}{c} 2\\ 1 & 0 & 1\\ 1 & 3\end{array}$	5 1	2 68.000	.000	5380.000	2250,000		
	。500 。052 。042	。000 。008 。006	60.000 31.000	.260 .670			
Case 3:	One solid	layer (plywood)	) furnace on on	e side of par	nel.		
1	5 0	1 68.000	.00 5800.00	0 1500.000	0		
J	•042	.006 31	.000 .670				
Case 4:	Two solid	layers and one	air gap (brick	- air - bri	ck) furnace		
on one side of wall.							
$\begin{array}{c} 2\\ 1 & 0 & 1\\ 2 & 2 \end{array}$	2 5 <sup>·</sup> 1	1 68.000	) .00 5	800.000	1500.000		
	•5 •313 •313	.000 .023 .023	110.000 110.000	.216 .216			
Comparison plots of calculation and standard fire endurance tests are							
presented in fig. 8, 9, and 10. Tests were conducted at NBS, Washington,							
D.C. and National Gypsum Corporation, Buffalo, N.Y.							

Finally a word of caution in the use of a thermal analyzer program with air gap heat balances such as the present program. Due to the low heat capacity of air, one must exercise caution in selecting the incremental  $\triangle \Theta$  and  $\Delta \chi$  such that the air gap temperature will not rise above the temperature of the node preceeding it. From experience when this occurs instability will set in. The solution is then to decrease  $\Delta \Theta$  or  $\Delta \chi$ and at the same time maintaining the criteria M>2. The time increment  $\Delta \Theta$  is 5 seconds and the number of nodes is 5 in all calculated cases except case 4 where  $\Delta \Theta$  is decreased to 2.5 seconds and n is increased to 25 to avoid the instability problem discussed in above.











#### REFERENCE

- Harmathy, T. Z., "A Treatize on Theoretical Fire Endurance Rating," ASTM Special Technical Publication No. 301, American Society for Testing and Materials, Philadelphia, 1961, Page 10
- Lawson, D. I. and McGuire, J. H. "The Solution of Transient Heat Flow Problems by Analogous Electric Networks," Proceedings, Institution of Mechanical Engineers, Vol 167, 1953, Pages 275-287.
- Robertson, A. F. and Gross, D., "An Electrical Analog Method of Transient Heat Flow Analysis," Journal of Research of the National Bureau of Standards, Vol. 61, 1958, Pages 105-115.
- Krokosky, E. M., "An Analog Simulator for Evaluating Materials Subjected to the Standard ASTM Fire Curve," Journal of Materials American Society of Testing Materials, Vol. 2, No. 4, 1967, Pages 801-816.
- Krokosky, E. M., "Fire Intensity-Resistance Evaluation," Journal of the Structural Division Proceedings of the American Society of Civil Engineers, Nov. 1970, Pages 2501-2519.
- Ozisik, M. N., "Boundary Value Problems of Heat Conduction," 1968, International Textbook Company, Pennsylvania.

ş

- Kreith, F., "Principles of Heat Transfer", 1967, International Textbook Company, Pennsylvania
- Fox, L., "Numerical Solution of Ordinary and Partial Differential Equations," Addison-Wesley, Massachusetts, 1962.
- 9. Nottage, H.B., "The Thermal Properties of Building Materials Used in Heat Flow Calculations", Amer. Soc. of Heating and Vent. Engineers Research Bulletin, Vol. 53, No. 2, 9, 1947.



```
С
   I IPUTS
С
   MN= NUMBER OF SOLIDS
С
     NE NUMBER OF NODES IN SOLID
С
    M = NUMBER OF AIR SPACES
С
   ITEST = AN INTEGER THAT INDICATES WHETHER FORMULA 6 OR FORMULA 8
С
   WILL BE USED IN COMPUTATIONS: 1 INDICATES FORMULA 6 ANY OTHER
С
   NUMBER INDICATES FORMULA 8
С
    TO = INITIAL TEMPERATURE NOW 68
С
   GM1 = HEAT RELEASE PER UNIT VOLUME DUE TO MOISTURE VAPORIZATION FOR
     GYPSUM
С
С
   542 = HEAT RELEASE PER UNIT VOLUME DUE TO MOISTURE VAPORIZATION FOR
С
     BRICK
С
   GM3 = HEAT RELEASE PER UNIT VOLUME DUE TO MOISTURE VAPORIZATION FOR
С
     GCOW
Ċ
    ID AN ARRAY OF INTEGERS THAT INDICATES THE SOLID-AIR CONFIGURATION
С
  THATS BEING TESTED OF AN AIR GAP NON-ZERO = SOLID
    A DATA CARD WITH 1010101 WOULD INDICATE 4 SOLIDS AND THREE AIR GAPS
С
С
   IDD AN ARRAY OF INTEGERS THAT INDICATE THE TYPE OF SOLIDS 1= GYPSUM
С
   2= BRICK 3= WOOD SUPPOSE THERE WERE 4 SOLIDS GYPSUM, WOOD, BRICK
С
   AND GYPSUM THEN DATA CARD WOULD BE PUNCHED AS 1321
С
   AL = SOLID THICKNESS IN FEET
С
   ALPHA = HEAT DIFUSSION COEFFICIENT
С
            DENSITY OF SOLID IN CUBIT FEET
    RH0 =
С
    C=SPECIFIC HEAT CAPACITY OF SOLID
    AI = AIR GAP DISTANCE IN FEET
С
C
    GA = HEAT RELEASE PER UNIT VOLUME IN AIR GAP
С
   OUTPUTS
С
   T(I,J) PRIME = TEMPERATURE AT TIME(THETA+DTHETA) OF JTH NODE IN
С
   ITH SOLID LAYER
С
   TA(I) = TEMPERATURE OF MID-POINT OF AIR SPACING BETWEEN ITH AND
С
   I+1 LAYER OF SOLID
                       THETA = TIME
       IMPLICIT DOUBLE PRECISION(A-H, O-W)
       JOUBLE PRECISION T11, T22, T33, T44, T66, T88 , T55
       REAL TOP
                       AL + ALPHA + RHO + C + AI + GA + X + Y + GM1 + GM2 + GM3
       DIMENSION T(20,10) AL(20) AI(20) TA(20) DELTAX(20) AM(20) H(20)
     1 BH(20),AK(20,10),G(20,10),EPSLON(20),RHO(20),C(20),S(20),
     2 P(20), R1(20), Q(20), ID(80), GA(20), ALPHA(20)
       JIMENSION X(500,5),Y(500,5),NRMX(5)
                                                           / A(20),B(20),
     1 RHOA(10), D(20,10), IDD(20), THETA1(20,10), THETA2(20,10)
       NA=0
    THETA = TIME IN HOURS
С
       THETA=0.000
   EP AND EPN = EMISSIVITY
С
       EP=.83500
       EPN=.900
   HH=CHARACTERISTIC HEAT TRANSFER COEFFICIENT
C
       HH=.1500
```

```
C
    CPA= SPECIFIC HEAT CAPACITY FOR AIR
       CPA=0.25D0
Ĉ
   AMO= VOLUME AIR FLOW THROUGH THE LAYERS, CUBIC FEET PER HOUR
       AMO= 0.00
С
   ROA1= DENSITY OF AIR IN LB PER CURIC FOOT
       ROA1=.05D0
С
   SIGMA = BOLTZMAN STEFAN CONSTANT
       SIGMA=0.1714D-8
С
   AK = HEAT CONDUCTION COEFFICIENT
C
       READ IN DATA THAT DESCRIBE PANELS AND READ IN OTHER DATA
       READ 90, NN, N, M, ITEST, TO,
                                       GM1, GM2, GM3
       KK=NN+M
       READ 91+(ID(I)+I=1+KK)
       READ 91, (IDD(I), I=1, NN)
       READ 92, (AL(I), ALPHA(I) , RHO(I), C(I), I=1, NN)
       IF(M.EQ.0)GO TO 307
       READ 97, (AI(1), GA(1), I=1, M)
C DTHETA = TIME INCREMENT
       DTHETA=1.D0/ 720.D0
307
       DO 301 J=1,N
       DO 301 I=1.NN
301
       T(I_{i}J)=T0
       IF(M.EQ.0) GO TO 308
       DO 302 I=1+M
302
       TA(I) = TO
308
       DO 305 I=1,NN
       H(I) = HH
305
       EPSLON(I)=EP
       EPSLON(NN)=EPN
       EPSLON(1) = EPN
       DO 104 I=1,NN
104
       DELTAX(I)=AL(I)/FLOAT(N-1)
       Do 105 I=1, NN
       AM(I)=DELTAX(J)**2/(ALPHA(I)*DTHETA)
       BH(I)=(2.*H(I)*DTHETA)/(RHO(I)*C(I)*DELTAX(I))
       R1(I)=(2.*DTHFTA*SIGMA*EPSLON(I ))/(DELTAX(I)*RHO(I)*C(I))
105
       PRINT 100, NN, N, M, ITEST, TO,
                                          GM1, GM2, GM3
309
       PRINT 101, (ID(I), I=1, KK)
       PRINT 101, (IDD(I), I=1, NN)
       IF(M.EQ.0)GO TO 310
       PRINT 102, (AI(I), GA(I), I=1, M)
310
       PRINT 102, (AL(I), ALPHA(I), RHO(I), C(I), I=1, NN)
       PRINT 311, (DELTAX(I), AM(I), BH(I), R1(I), H(I), I=1, NN)
       PRINT 102, (EPSLON(I), I=1, NN)
       G1=GM1
       G2=GM2
       G3=GM3
       TS=T0
       TF=T0
C
   PLOT VALUES
       X(1,1)=THETA*60.D0
       X(1,2)=THETA*60.D0
       X(1,3)=THETA*60.D0
       X(1,4)=THETA*60.D0
       X(1,5)=THETA*60.D0
       Y(1,1) = (TF)
       Y(1,2) = (TA(1))
       Y(1,3) = (T(2,N))
```

```
Y(1,4) = (TA(2))
       Y(1,5) = \{T(4,N)\}
       II=2
       PRINT 87
       PRINT 88
       PRINT 89, TF, T(1,1), T_{\Delta}(1), T(2,N), T_{\Delta}(2), T(3,1), T_{\Delta}(3), T(4,N), THETA
       MM=N-1
1
       I=1
       IA=1
       DO 106 JJ=1+N
       00 106 LL=1, NN
       G(LL,JJ)=0.000
                                .
105
       K=0
     COMPUTE TF
                    FORMULA 7
С
       IF(THETA.GE.1.D0)GO TO 415
       TF=T0+101520.D0*THETA/(60.D0*THETA+4.D0)
       60 TO 417
       IF(THETA.GE.1.9D0)G0 TO 416
415
       TF=(925.D0+42.D0*THETA=0.0131D0* (120.D0=60.D0*THETA)**2)*1.8D0
     1 +32.00
       GO TO 417
       TF=(926.D0+42.D0*THETA)*1.8D0+32.D0
416
C COMPUTE T(1+1) AND TPRIME
417
       IJ=IDD(1)
    TEST PROPERTIES FOR CURRENT SOLID
C
       CALL PROP(T( 1, 1), A( 1, 1), THETA1(1, 1), THETA2(1, 1), THETA,
     1 DTHETA, G(1,1), G1, G2, G3, IJ)
       AKK = AK(1,1)
924
       TPRIME =T(1,1)+R1(1) *(TF-T(1,1))*(TF+T(1,1)+920.00)*((TF+460.00)
     1 **2+(T(1,1)+460,D0)**2)+BH(1)*DABS(TF-T(1,1))**,25*(TF-T(1,1))
     2 + (G(1,1)*DELTAX(1)**2)/(AKK*AM(1)) -2.D0/AM(1)*(T(1,1)-T(1,2))
       T(1,1) = TPRIME
С
    COMPUTE TPRIME(I, J) FORMULA 1
       IF(AM(I).LE.2.D0)G0 TO 77
5
       (I)COI=LI
       DO 10 J=2,MM
    TEST PROPERTIES FOR CURRENT SOLID
С
       CALL PROP(T( I, J), AK( I, J), THETA1(I, J), THETA2(I, J), THETAP
     1 DTHETA, G(I, J), G1, G2, G3, IJ)
522
       AKK = AK(I,J)
       T(I,J) = T11(AM(I), T(I,J-1), T(I,J+1), T(I,J), G(I,J), AKK
     1 DELTAX(I))
       CONTINUE
10
      IF(I.EQ.NN)GO TO 45
       IF(ID(IA+I).E0.0)G0 TO 12
С
    SOLID TO SOLID COMPUTATION
       IJ=IDD(I)
С
    TEST PROPERTIES FOR CURRENT SOLID
       CALL PROP(T( I,N),AK( I,N ),THETA1(I,N),THETA2(I,N),THETA,
     1 DTHETA, G(I, J), G1, G2, G3, IJ)
932
       AKK = AK(I,N)
       DO 875 JK=1,NN
       A(JK)=(RHO(JK)*C(JK)*DELTAX(JK))/2.D0
       B(JK)=(DELTAX(JK)*DTHETA)/2.DO
       D(JK,N) = (AK(JK,N) * DTHETA) / DELTAX(JK)
       D(JK+1)=(AK(JK+1)*DTHETA)/DELTAX(JK)
875
       T(I_PN) = T55(A(I), T(I_PN), A(I+1), T(I+1, 1), B(I), G(I_PN), B(I+1),
     1 G(I+1+1), D(I+N), T(I+N-1), D(I+1+1), T(I+1+2))
                                       29
```

F

```
T(I+1=1)=T(I=N)
       I = I + 1
       GO TO 5
    COMPUTE TPRIME FORMULA 2 AIR SPACE COMPUTATION
C
12
       IF(AM(I).LE.2.D0)G0 TO 75
       K=K+1
       LJ=IDD(I)
С
    TEST PROPERTIES FOR CURRENT SOLID
       CALL PROP(T( I , N), AK( I, N ), THETA1(I, N), THETA2(I, N), THETA,
     1 DTHETA, G(I,N), G1, G2, G3, IJ)
       AKK=AK(I,N)
611
       T(I_{P}N) = T22(AM(I)_{P}T(I_{P}N)_{P}T(I_{P}N-1)_{P}R1(I)_{P}T(I+1,1)_{P}BH(I)_{P}TA(K)_{P}
     1 G(I,N) , AKK, DELTAX(I))
   COMPUTE TAPRIME FORMULA 3
Ċ
       RHOA(K)=39.67400/(TA(K)+460.Dc)
       P(K) = (H(K) * DTHETA) / (AT(K) * CPA * RHOA(K))
       GA(K)=0.000
       S(K)=(AMO*DTHETA)/(AI(K))
       \Im(\kappa) = (H(\kappa+1)*DTHETA)/(AI(\kappa)*CPA*RHOA(\kappa)))
       GAA=GA(K)
       COMPUTE TPRIME(I+1,1) FORMULA 4
С
       IF (AM(I+1).LE.2.D0)G0 TO 80
       IJ=IDD(I+1)
      T(I+1,1)=T44(T(I+1,1),R1(I),T(I,N),AM(I+1),BH(I+1),TA(K),T(I+1,2),
     1 G(I+1+1) + AKK+ DELTAX(I+1))
       IF(K.EQ.M)K=0
       IF(I.EQ.NN)GO TO 45
39
       I = I + 1
       1A=IA+1
       GO TO 5
      DECIDE BETWEEN FORMULAS 6 AND 8
С
45
       IF(ITEST.NE.1)G0 T0 37
С
    COMPUTE T(NN,N) FORMULA 6
       IF(AM(NN).LE.2.D0)G0 T0 78
       T1=T0
          IJ=IDD(NN)
    TEST PROPERTIES FOR CURRENT SOLID
С
       CALL PROP(T( NN+N )+AK( NN+N), THETA1( NN+N)+THETA2( NN+N)+THETA+
     1 DTHETA,G( NN,N),G1,G2,G3,IJ)
431
       AKK=AK(NN+N)
       T(NN+N) = T66(T(NN+N) + AM(NN) + T(NN+N-1) + R1(NN) + T1 + BH(NN) +
     1 G(NN,N),AKK,DELTAX(NN))
       GO TO 209
    COMPUTE T(NN+N) FORMULA B
C
37
       IF (AM(NN).LE.2.D0)G0 TO 79
       IJ=IDD(NN)
    TEST PROPERTIES FOR CURRENT SOLID
С
       CALL PROP(T( NN+N )+A<( NN+N)+THETA1( NN+N)+THETA2( NN+N)+THETA+
     1 DTHETA, G( NN, N), G1, G2, G3, IJ)
432
       AKK=AK(NN,N)
       T(NN,N) = T88(T(NN,N), T(NN,N-1), TS, AM(NN), BH(NN),
     1 G(NN+N) + AKK+DFLTAX(NN) + R1(NN))
       PS=0.15D0*DTHETA/(0.500*CPA*ROA1)
       TS=TS+PS*DABS(T(NN+N)-TS)**.25*(T(NN+N)-TS)
       IF(MOD(NA,10).NE.0)GO TO 57
209
       PRINT 89, TF, T(1,1), TA(1), T(2,N), TA(2), T(3,1), TA(3), T(4,N), THETA
  PLOT VALUES
```

```
X(II)1)=THETA*60.D0
       X(II;2)=THETA*60.00
       X(II,3)=THETA*60.D0
       X(II,4) = THETA*60.00
       X(II,5)=THETA*60.00
      Y(II_{1}I) = (TF)
      Y(T_{1}, 2) = (T_{A}(1))
      Y(II,3) = (T(2,N))
      Y(II_{4})=(TA(2))
      Y(TT_{0}5) = (T(4_{0}N))
       II=II+1
57
       IF(THETA.GT..83300) GO TO 200
       NA=NA+1
Ĉ
    INCREMENT TIME
       THETA=THETA+DTHETA
       GO TO 1
       II=II-1
200
       PRINT 87
       NROW=500
       NRMX(1) = II
       NRMX(2)=I1
       NRMX(3) = II
       NRMX(4)=II
       NRMX(5) = II
       NARGS=5
       CALL PLOTS (NADGS, X, Y, NRMX, NROW)
       STOP
78
       PRINT 81, AM(NN)
       STOP
79
       PRINT
               82, AM(NN)
       STOP
77
        PRINT 83, AM(I)
       STOP
80
       PRINT 84, AM(I+1)
       STOP
75
       PRINT 85, AM(I)
       STOP
31
       FORMAT(1X, M NOT GREATER THAN 2 FORMULA 6 M=", E14.8)
82
       FORMAT(1X, M NOT GREATER THAN 2 FORMULA 8 M=1, E14.8)
93
       FORMAT(1X, M NOT GREATER THAN 2 FORMULA 1 M=1, E14.8)
       FORMAT(1X, M NOT GREATER THAN 2 FORMULA 4 M=",E14.8)
84
       FORMAT(1X, M NOT GREATER THAN 2 FORMULA 2 M=1, E14.8)
85
       FORMAT( .
                        TE
                                    T(1,1)
                                                    T_{\Lambda}(1)
                                                                    T(2+N)
88
     1 TA(2)
                                     TA(3)
                                                             THETA')
                     T(3,1)
                                                 T(4 \cdot N)
101
       FORMAT(2013)
100
       FORMAT(1X:416:5F11.3)
98
       FORMAT(10F6.0)
92
       FORMAT( 4F6.0)
97
       FORMAT(2F6.0)
91
       FORMAT(2011)
       FORMAT(1X,1X,213,3F14.2)
216
90
       FORMAT(412,5F6.0)
89
       FORMAT(1x,F12.3,1X,F12.3,1X,F12.3,1X,F12.3,1X,F12.3,1X,F12.3,
     1 F12.3,1X,F12.3,1X,F6.3)
       FORMAT(1H1)
57
       FORMAT(1x, 4F14.3)
102
       FORMAT(1X, 4D26.16)
312
       FORMAT(1X, F14.8, 4D26.16)
311
```

,

66 FORMAT(1X+F12.3+1X+F12.3+1X+F12.3+13X+F12.3)
317 FORMAT(1X+3F12.3+D26.16+3F12.3)
END

DOUBLE PRECISION FUNCTION T11(AM,T1,T2,T3,G,AK,DELTAX) IMPLICIT DOUBLE PRECISION(A-H,O-W) C FORMULA 1 T11=(T1+T2)/AM+ (1.D0-2.D0/AM)\*T3 +(G\*DELTAX\*\*2)/(AK\*AM) PORMAT(' FORMULA 1') RETURN END

C FORMULA 2 DOUBLE PRECISION FUNCTION T22(AM,T1,T2,R1,T3,H,TA,G,AK,DELTAX) IMPLICIT DOUBLE PRECISION(A=H,O=W) T22=T1+2.D0/AM\*(T2=T1)=R1\*(T1=T3)\*(T1+T3+920.D0)\*((T1+460.D0)\*\*2+ 1(T3+460.D0)\*\*2)=H\*DABS(T1=TA)\*\*.25\*(T1=TA)+(G\*DELTAX\*\*2)/(AK\*AM) FORMAT(1X,3F12.3,D26.16,3F12.3) 2 FORMAT(' FORMULA 2')

2 FORMATU FORMULA 201 RETURN END

C FORMULA 3 DOUBLE PRECISION FUNCTION T33(TA,P,T1,Q,T2,S,GA) IMPLICIT DOUBLE PRECISION(A-H,O-W) T33=TA +P\*DABS(T1-TA)\*\*.25\*(T1-TA)-Q\*DABS(TA-T2)\*\*.25\*(TA-T2)+ 1 S\*(T1-T2)+GA

2 FORMAT(\* FORMULA 3\*) RETURN END

C FORMULA 4

DOUBLE PRECISION FUNCTION T44(T1,R1,T2,AM,H,TA,T3,G,AK,DELTAX) IMPLICIT DOUBLE PRECISION(A-H,O-W) T44=T1 tR1\*(T2=T1)\*(T2)T1)

T44=T1 +R1\*(T2-T1)\*(T2+T1+920.D0)\*((T2+460.D0)\*\*2+(T1+460.D0)\*\*2)
1 -2.D0/AM\*(T1-T3)+H\*DABS(TA-T1)\*\*.25\*(TA-T1)+(G\*DELTAX\*\*2)/(AK\*AM)
FORMAT(' FORMULA 4')
RETURN
END

C FORMULA 6 DOUBLE PRECISION FUNCTIONT66(T1;AM;T2;R1;T0;H;G;AK;DELTAX) IMPLICIT DOUBLE PRECISION(A=H;0=W) T66=T1+2.D0/AM\*(T2=T1)=R1\*(T1=T0)\*(T1+T0+920.D0)\*((T1+460.D0)\*\*2) 1 +(T0+460.D0)\*\*2)=H\*DABS(T1=T0)\*\*.25\*(T1=T0)+(G\*DELTAX\*\*2)/(AK\*AM) 2 FORMAT(\* FORMULA 6\*)

RETURN END

```
С
   FORMULA 8
        DOUBLE PRECISION FUNCTION TES(T1, T2, TS, AM, H, G, AK, DELTAX, R1)
        IMPLICIT DOUBLE PRECISION(A-H, 0-W)
        T88=T1+2.D0/AM*(T2-T1)-H*DABS(T1-TS)**.25 *(T1-TS)+(G*DELTAX**2)/
      1 (AK*AM)
        FORMAT( * FORMULA 8*)
 2
        RETURN
        END
        FORMULA
 С
        DOUBLE PRECISION FUNCTION T55(A1+T1+A2+T2+B1+G1+B2+G2+D1+T3,D2+
      1 T4)
        IMPLICIT DOUBLE PRECISION (A-H, O-W)
        T55=(A1*T1+A2*T2+B1*G1+B2*G2+D1*(T3-T1)-D2*(T2-T4))/(A1+A2)
        RETURN
        END
       SUBROUTINE PROP(T1+AK, THETA1, THETA2, THETA; DDTHET+G; GM1+GM2; GM3+IJ
     1)
       IMPLICIT DOUBLE PRECISION(A-H, 0-W)
   TEST PROPERTIES FOR GYPSUM
С
       GO TO (501,502,503),IJ
       IF(
             T1.GE.0.000.AND.
501
                                   T1.LE.200.D0)AK=.5D0
       IF(
              T1.GE.200.D0.AND.
                                  T1.LE.400.D0)AK=.3D0
       IF(
              T1.GE.400.D0.AND.
                                   T1.LE.2000.D0)AK
                                                        =.2D0+T1/4000.D0
       AK=AK/4.0
      IF(
             T1.GE.212.D0.AND.T1.LE.220.D0
                                              )THETA1=THETA
      IF(
             T1.GE.212.D0)THETA2
                                     =THETA-THETA1
       IF (THETA2.LT.DDTHET) GO TO 522
       IF (THETA2
                     .GE.0.000.AND.THETA2
                                             .LE.200.DO*DDTHET)G
                                                                       \Xi =
     1 (GM1+14100.D0)/(200.D0*)DTHET)
       GO TO 522
C TEST PROPERTIES BRICK
502
       IF(
             T1.GE.0.0D0.ANO.
                                   T1.LE.200.D0)AK=1.D0
       IF(
              T1.GE.200.D0.AND.
                                   T1.LE.2000.D0)AK
                                                         =.46D0+2.D-4*T1
             T1.GE.212.D0.AND.T1.LE.220.D0
      IF(
                                              )THETA1=THETA
             T1.GE.212.DO)THETA2 =THETA-THETA1
      IF(
       IF (THETA2
                     .LT.DDTHET)GO TO 522
       IF(THETA2
                     .GE.0.000.AND.THETA2 .LE. 100.DO*DDTHET)G
                                                                      -
     1 GM2/(100.D0*DDTHET)
       GO TO 522
      TEST PROPERTIES FOR WOOD, DOUGLAS FIR
C
503
      AK=.065D0
             T1.GE.212.D0.AND.T1.LE.220.D0 )THETA1=THETA
      IF(
      IF(
             T1.GE.212.D0)THETA2
                                     =THETA-THETA1
      IF (THETA2
                     .LT.DDTHET)GO TO 522
       IF (THE TA2
                     .GE.0.000.AND.THETA2 .LE. 200.D0*DDTHET)G
                                                                      \Xi =
    1 GM3/(200.D0*DDTHET)
522
       RETURN
       END
```

### Acknowledgement

The author wishes to acknowledge the contributibution of Mr. Vernon Dantzler, Applications Section, Computer Services Division, for coding the Fortran program, and for his indispensible and cheerful help in modifying and updating the Fortran program.

The author also wishes to thank Mr. J. Newton Breese for his part in preparing the graphs and the flow chart for reproduction.



