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TRANSIENT HEAT AND MOISTURE TRANSFER TO SKIN  
THROUGH THERMALLY IRRADIATED CLOTH

Technical Report No. 8

from

Fuels Research Laboratory  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

H. C. Hottel  
G. C. Williams  
G. H. Miedel  
N. Y. Chen  
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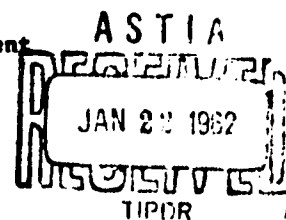
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| <p>AD<br/>Paul Research Lab., Massachusetts Institute of Technology, Cambridge, Massachusetts<br/>RAMBERT DRY AND HUMIDITY TRANSFER TO SKIN<br/>RAMBERT THERMALLY INSULATED CLOTH -<br/>G.C. Beretol, G.C. Williams, G.M. Menden, R.T. Chen,<br/>R.P. Jones</p> <p>Technical Report No. 9, 26 Dec 61, 12pp - 111m-cloth<br/>Contract No. DA19-120-Q-1500 Proj. 7-12-61-0007,<br/>Proj. 7-12-61-001, Unclassified Report</p> <p>Methods are presented to model the temperature response of skin covered by dry or moist cloth and exposed to high-intensity thermal irradiation 1) experimentally by using a copper-air skin simulant; 2) theoretically by finite-difference solution of the partial differential equations for heat and moisture transfer. Moisture transport is assumed to be due to water vapor diffusion only, neglecting bulk flow. The dry (open or diathermanous) cloth case is solved generally; the moist cloth system involves hygroscopic equilibrium of cloth and requires computer calculation of each specific case. The theoretical solution permits estimation of skin temperature response and inspection of influence of system parameters and time-variant irradiation of intensity as encountered in a nuclear explosion.</p> | <p>Accession No.<br/>Paul Research Lab., Massachusetts Institute of Technology, Cambridge, Massachusetts<br/>RAMBERT DRY AND HUMIDITY TRANSFER TO SKIN<br/>RAMBERT THERMALLY INSULATED CLOTH -<br/>G.C. Beretol, G.C. Williams, G.M. Menden, R.T. Chen,<br/>R.P. Jones</p> <p>Technical Report No. 9, 26 Dec 61, 12pp - 111m-cloth<br/>Contract No. DA19-120-Q-1500 Proj. 7-12-61-0007,<br/>Proj. 7-12-61-001, Unclassified Report</p> <p>Methods are presented to model the temperature response of skin covered by dry or moist cloth and exposed to high-intensity thermal irradiation 1) experimentally by using a copper-air skin simulant; 2) theoretically by finite-difference solution of the partial differential equations for heat and moisture transfer. Moisture transport is assumed to be due to water vapor diffusion only, neglecting bulk flow. The dry (open or diathermanous) cloth case is solved generally; the moist cloth system involves hygroscopic equilibrium of cloth and requires computer calculation of each specific case. The theoretical solution permits estimation of skin temperature response and inspection of influence of system parameters and time-variant irradiation of intensity as encountered in a nuclear explosion.</p> | <p>UNCLASSIFIED</p> <ol style="list-style-type: none"> <li>1. Skin Simulants</li> <li>2. Heat Protection</li> <li>3. Heat and Moisture Transfer</li> <li>4. Thermal Radiation</li> <li>5. Finite Difference Methods</li> <li>6. Contract DA19-120-Q-1500</li> </ol> | <p>AD<br/>Paul Research Lab., Massachusetts Institute of Technology, Cambridge, Massachusetts<br/>RAMBERT DRY AND HUMIDITY TRANSFER TO SKIN<br/>RAMBERT THERMALLY INSULATED CLOTH -<br/>G.C. Beretol, G.C. Williams, G.M. Menden, R.T. Chen,<br/>R.P. Jones</p> <p>Technical Report No. 9, 26 Dec 61, 12pp - 111m-cloth<br/>Contract No. DA19-120-Q-1500 Proj. 7-12-61-0007,<br/>Proj. 7-12-61-001, Unclassified Report</p> <p>Methods are presented to model the temperature response of skin covered by dry or moist cloth and exposed to high-intensity thermal irradiation 1) experimentally by using a copper-air skin simulant; 2) theoretically by finite-difference solution of the partial differential equations for heat and moisture transfer. Moisture transport is assumed to be due to water vapor diffusion only, neglecting bulk flow. The dry (open or diathermanous) cloth case is solved generally; the moist cloth system involves hygroscopic equilibrium of cloth and requires computer calculation of each specific case. The theoretical solution permits estimation of skin temperature response and inspection of influence of system parameters and time-variant irradiation of intensity as encountered in a nuclear explosion.</p> |
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FOREWORD

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T E A S K A D O K

## ABSTRACT

A study has been made of the action of cloth in protecting skin from thermal injury resulting from exposure to high-intensity thermal radiation. Methods have been developed to obtain temperature-time-depth data for a system simulating skin covered by a layer of dry or moist cloth. Experimentally this has been accomplished by the use of a copper-air simulant which accepts heat at the same rate as human skin but develops a proportionally stretched temperature profile.

The analysis of the moist cloth-skin simulant system involves some simplifying assumptions regarding the mode of moisture transport. It is applicable to low- and medium-intensity exposures constant or variable in time. The solution is not general but requires new computer calculations for every specific case. The model yields reasonable estimates of the skin temperature response; due to the uncertainty of a number of physical parameters there is a margin of tolerance which could be narrowed by further experiments combined with further calculations. The description of the intermediate role of moisture flow as contributing to the heat transport may still require refinement; however, there is as yet no simple way to evaluate the b.l. of water vapor through the pores of a fabric.

The current method facilitates the inspection of the influences on temperature distribution in the skin of various system properties and the surrounding conditions.

The skin enthalpy rise above a critical temperature level, a feasible basis for correlating burn data, has been found to be very sensitive to slight variations in the temperature response and deserves further testing.

Besides an account of recent research, this project incorporates a review of the experimental work done earlier and of the mathematical models with the methods for their solution.

## I. INTRODUCTION

Although thermal injury to skin has been an important medical problem for many years, quantitative studies on the relation between the temperature history and the production of cutaneous damage did not begin until the forties by Mantz and Henriques (5, 15, 16, 17). The importance of knowing the temperature history of skin during its exposure to thermal energy was pointed out by these authors. However, the problem of measuring the temperature rise in skin remains unsolved. The difficulty lies in the fact that the epidermis of the skin where the temperature history is essential to the analysis is only  $80\mu$  thick, and measurement of the temperature profile in such a thin layer is still beyond presently known techniques. In previous studies, (3) we have developed skin simulants made of copper and air with a stretch factor (depth magnification) 28.4 times that of skin. Thus the temperature profile in a skin layer  $100\mu$  thick can be measured accurately by means of the simulant over a distance of 2.84 mm.

The simulant has been used in evaluating the energy transport processes in a cloth-air gap-skin system by exposing the test assembly to high intensity solar radiation. Experimental temperature-time-depth data were thus obtained on the simulant. This paper presents the results of these experiments and the mathematical models proposed to describe the energy transport process in such systems. The presentation is divided into two parts. The first part deals with the dry cloth-skin system in which the heat transfer by conduction and radiation through the cloth layer is considered; the second part deals with the moist cloth-skin system in which in addition to conduction and radiation, diffusion of the moisture in the cloth layer also contributes importantly to the heat transfer from the cloth to the skin.

## II. EXPERIMENTAL

### A. SKIN SIMULANT

The principal interest in the present experiments was the temperature-time-depth variation in the skin simulant. No attempt was made to measure the temperature in any part of the cloth. In previous studies (5, 12) it was concluded that the complexity of the cloth structure made it impossible to

identify the cloth "surfaces" unambiguously. Consequently, little significance could be ascribed to experimentally measured cloth temperatures.

A soldered fin-type skin simulant (skin simulant #10) (3, 5) was used in all "in-contact" runs. It consisted of sixteen fins, with twelve mutually parallel and four perpendicular to the twelve to block the exposed air space and help to maintain more nearly isotherms in the individual fins of the main simulant. The fins were copper sheets, each 3.175 cm. and 7.95 cm. x 0.0102 cm. thick, bent into shallow channels as shown in Figure 1.5. The four guard fins were bent to a 3-inch radius arc in a specially machined die. In order to make simulants of this type symmetrical, six channels face one way and six the opposite way, i.e., all the flange toes faced toward the center of the simulant. The fins were soldered to a top sheet of copper having dimensions of 4.37 x 3.61 cm. x 0.0102 cm. thick. Five 0.0025 cm. diameter constantan wires were soldered onto the central copper fin, forming the hot junctions of the thermocouples. The five wires were led out from the bottom and soldered to heavier constantan leads (#24 B. and S. gage). A common copper lead wire was soldered to the copper sheet. The cold junction for the thermocouples consisted of several massive copper blocks, one for each constantan lead and another for the copper lead wire. The junctions were located inside the constant temperature box, where connections to the temperature recorder were made. A cylindrical simulant as shown in Figure 1.6 was also used in several experiments in which the cloth sample was set 0.038 cm. from the top surface of the simulant.

#### B. CLOTH SAMPLES

A series of six "standard" 9-ounce cotton sateen and 9-ounce Olive Green uniform cloths supplied by the Quartermaster Research and Development Command at Natick, Massachusetts, were used in the present investigation.

The optical properties of the cloths (5, 6) have been determined by the Naval Material Laboratory covering the wave-length range from 0.40 to 2.7 microns. These data have been integrated over the solar spectrum; the results are listed in Table 1.1.

Wooden embroidery rings 5-inches in diameter were used to hold the cloth samples. All cloth samples were oven dried at 105°C for 24 hours and then

cooled and conditioned in desiccators containing one of three items: (1) indicating silica gel, (2) saturated sodium nitrate solution (65-66% relative humidity at 15-30°C), and (3) saturated ammonium chloride solution (79.5% relative humidity at 20-30°C).

Table 1.1

OPTICAL PROPERTIES OF CLOTHS (INTEGRATED VALUE OVER SOLAR SPECTRUM)

| <u>Code No.</u> | <u>Designated Color</u> | <u>Reflectance</u> | <u>Absorptance</u> | <u>Transmittance*</u> |
|-----------------|-------------------------|--------------------|--------------------|-----------------------|
| QM-4            | White with CMC          | 0.67               | 0.19               | 0.14                  |
| QM-5-65         | Light gray with CMC     | 0.56               | 0.37               | 0.07                  |
| QM-6-40         | Medium gray with CMC    | 0.50               | 0.47               | 0.03                  |
| QM-7-22         | Dark gray with CMC      | 0.22               | 0.78               | 0                     |
| QM-8-12         | Black with CMC          | 0.11               | 0.89               | 0                     |
| QM-9-7          | Deep black with CMC     | 0.09               | 0.91               | 0                     |
| QM-3            | Olive green 107         | 0.18               | 0.79               | 0.03                  |

C. SOLAR FURNACE

The MIT Solar Furnace (5, 9, 10, 11) was used as the source of high intensity radiation. Intensity up to 6 cal/cm<sup>2</sup>-sec. over a 5 cm<sup>2</sup> target area was obtainable with a clear sky.

D. TEMPERATURE MEASUREMENT

A four channel 150-1500 series Sanborn recorder equipped with "low-level" preamplifiers was used to record the outputs of thermocouples. The recorder has a maximum sensitivity of 100µv per cm (or approximately 2.5°C for copper-constantan thermocouples). The time constant is 0.03 sec.

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\* Since the cloths were made from the same white 9 oz. cotton sateen stock, and it is unlikely that a simple dyeing process would change the geometry of the fibers, it is reasonable to assume that the cloth construction provides complete geometrical blockage of the incident light, and that the transmittance depends on the degree of opacity of the individual cloth fibers. These transmittance values should therefore be regarded not as due to direct transmittance through holes but to diathermancy of the cloths.

### III. PROCEDURE

Cloth samples were prepared several days in advance and kept in their respective desiccators until testing time. Then the sample was quickly transferred from the desiccator to a constant humidity box attached on the solar furnace. The constant humidity box was kept under the same condition as the desiccator. Constant temperature was maintained in the box with an air blower and a thermoregulator. After the skin simulant was placed behind the sample, the box was closed and the air blower was allowed to continue blowing for 10-15 minutes to insure constant temperature and relative humidity in the box. The air blower was stopped during the exposure of the sample to the radiation. The sample was exposed for one to 30 seconds to the high intensity radiation ranging from 0.3 to 6.0 cal/cm<sup>2</sup>-sec. The length of the exposure was controlled by a timing device which opened and closed the diaphragm shutter. The intensity of radiation was regulated by partially blocking off the primary mirrors of the solar furnace.

### IV. EXPERIMENTAL RESULTS

Experimental data obtained on six kinds of dry cloth are presented in the following figures in which the normalized temperature rise is plotted against the exposure time in seconds on logarithmic papers with the three or four skin depths as the parameters: Figure 1.7 combines the result on three opaque cloths (deco black, black, and dark gray); Figure 1.8 shows the result on the medium gray cloth; Figure 1.9 shows the result on the light gray cloth; and Figure 1.10 shows the result on the white cloth.

The experiments on moist cloth over skin were designed to study the effect of the radiation intensity on the coupling effect of moisture transfer on heat transfer. Two types of cloths, one black and one white were used.

The effect of moisture transfer on heat transfer can be illustrated by the following figures, in which the normalized temperature rise of the first thermocouple in the skin simulant is plotted against the exposure time, with intensity as the parameter. Figure 1.11 shows the result on the opaque cloth and Fig. 1.12 shows the result on the white cloth. The complete data may be found in reference (5).

## V. THEORETICAL - DRY CLOTH OVER SKIN SIMULANT SYSTEM

### A. THE MATHEMATICAL MODEL

The general assumptions made in the analysis are as follows. The system under consideration is sketched below:

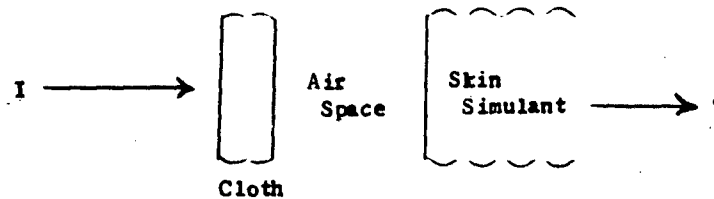


Figure 1.1

#### DRY CLOTH-AIR GAP-SKIN SIMULANT SYSTEM

1. Heat flow is unidirectional, occurring in the x-direction, from the cloth through the air space into the skin simulant. The surface of the cloth is irradiated by square wave radiation. It will be shown later that the general solution can be applied to radiation of any pulse form.

2. The cloth layer is considered to be a homogeneous solid. For cloths which show no measurable transmittance (e.g., deep black, black, and dark gray of the 9 oz. "standard" cotton sateen), radiant energy is absorbed at the surface of the cloth. For diathermanous cloths, the radiant energy is assumed to penetrate into the interior of the cloth layer in accordance with the Beer-Lambert law:

$$I_x = I_0 \exp(-\gamma x_c)$$

where  $I_x$  = intensity of radiation at a plane distant  $x_c$  cm from the irradiated surface.  
 $I_0$  = intensity of radiation entering the cloth layer, or  
 $I_0 = I(1 - r)$ , cal/cm<sup>2</sup>-sec.  
 $I$  = incident intensity of radiation.  
 $\gamma$  = extinction coefficient, cm<sup>-1</sup>, a characteristic constant of the cloth for the particular source of radiation in question.

If the measured "transmittance" of a diathermanous cloth of thickness  $L$  cm is  $\tau$ , then  $\exp(-\gamma L) = \tau/(1-r)$ , where  $r$  is the reflectance of the cloth.

The solution is applied specifically to the 9 oz. "standard" cotton sateen; it could be equally well be applied to either diathermanous or direct-transmitting cloths.

3. The physical properties of the cloth layer remain constant throughout the exposure.

4. Any effects due to moisture and/or chemical reaction are negligible.

5. Heat losses from the front surface of the cloth layer by convection and re-radiation are characterized by a single overall heat transfer coefficient  $U_0$ .

6. Heat transfer from the cloth layer through the air gap to the simulant is similarly characterized by an overall heat transfer coefficient  $U_1$ .

7. The skin simulant is considered to be a homogeneous opaque solid of infinite extent in its  $x$ -direction.

The validity of these assumptions must first be checked against experimental data obtained on an equivalent inanimate system. Furthermore it should be born in mind that such an analysis will be of value only if the temperature history data can in combination with some postulated mechanism of burning correlate the in vivo results.

The basic equations for the cloth layer are:

1. Opaque cloth

$$\frac{\partial T}{\partial \theta} = \left(\frac{k}{C_p}\right)_c \frac{\partial^2 T}{\partial x_c^2} \quad (1.1)$$

2. Diathermanous cloth

$$\frac{\partial T}{\partial \theta} = \left(\frac{k}{C_p}\right)_c \frac{\partial^2 T}{\partial x_c^2} - \frac{I_0}{C_p} \frac{\partial \exp(-\gamma x_c)}{\partial x_c} \quad (1.2)$$

The equation for the skin is

$$\frac{\partial T}{\partial \theta} = \left(\frac{k}{C_p}\right)_s \frac{\partial^2 T}{\partial x_s^2} \quad (1.3)$$

The surface boundary equations are:

1. For opaque cloth

(a) Front surface

$$I_o - U_o(T_{x_c=0} - T_{surr}) = -k_c \left. \frac{\partial T}{\partial x_c} \right|_{x_c=0} \quad (1.4)$$

(b) Back surface and skin surface

$$-k_c \left. \frac{\partial T}{\partial x_c} \right|_{x_c=L_c} = U_i(T_{x_c=L_c} - T_{x_s=0}) = -k_s \left. \frac{\partial T}{\partial x_s} \right|_{x_s=0} \quad (1.5)$$

2. For diathermanous cloth

(a) Front surface

$$k_c \left. \frac{\partial T}{\partial x_c} \right|_{x_c=0} = U_o(T_{x_c=0} - T_{surr}) \quad (1.6)$$

(b) Back surface and skin surface

$$\begin{aligned} -k_c \left. \frac{\partial T}{\partial x_c} \right|_{x_c=L_c} + I_o \exp(-\gamma L_c) &= U_i(T_{x_c=L_c} - T_{x_s=0}) \\ + I_o \exp(-\gamma L_c) &= -k_s \left. \frac{\partial T}{\partial x_s} \right|_{x_s=0} \end{aligned} \quad (1.7)$$

These equations are solved by a finite-difference approximation method which gives temperature as a function of the following five independent variables; time, depth,  $U_i$ ,  $U_o$ , and  $R$ , a property group. The solution is expressed as a relation among the following dimensionless groups.

|                              |                                                                  |         |
|------------------------------|------------------------------------------------------------------|---------|
| 1. Temperature group         | $T^o = \frac{k_c T}{I_o L_c}$                                    | } (1.8) |
| 2. Time group                | $\theta_c^o = \left(\frac{k}{C_p}\right)_c \frac{\theta}{L_c^2}$ |         |
| 3. Depth group               | $x_c^o = \frac{x_c}{L_c}$                                        |         |
| 4. Surface heat losses group | $U_o^o = \frac{U_o L_c}{k_c}$                                    |         |

5. Air gap group

$$U_1^0 = \frac{U_0 L_c}{k_c}$$

6.  $\bar{R}$  group

$$\sqrt{\frac{(kCp)_s}{(kCp)_c}} = \frac{\Delta x_c^0}{\Delta x_s^0}$$

Stated another way, the temperature-time-depth relation is a function of the three other groups.

The details of the solution are given in Appendix B.

#### B. GENERAL SOLUTION

The general solution consists of the temperature-time-depth relation as a function of the following parameters:

1.  $U_0^0$  the dimensionless surface heat loss group
2.  $U_1^0$  the dimensionless air gap group
3.  $\bar{R}$  the physical property ratio group

For opaque cloth, only one set of solutions is needed; for diathermanous cloth, a technique which uses the weighted mean of three sets of solutions, each representing radiation absorption at a different plane in the system, gives results within 1 to 1.4% of those obtained by a more rigorous method.

These three sets of solutions are as follows:

1. The case of incident radiant energy absorbed at the exposed cloth surface,
2. The case of incident radiant energy absorbed at  $X_c^0 = 0.75$ , and
3. The case of incident radiant energy absorbed at the surface of the skin simulant.

By taking advantage of the additive nature of the solutions, the temperature rise at any plane in any diathermanous-cloth problem can be obtained as the sum of the temperature rises due to assuming that the total energy absorption is lumped at three planes. The Beer-Lambert law is used to calculate absorption in the first half of the cloth, the second half, and the skin surface. These quantities are then treated as though lumped at the front surface of the cloth where  $X_c^0 = 0$ , at the plane  $X_c^0 = 0.75$ ,

and at the skin surface, where  $X_s^0 = 0$ .

1. Application to Other Types of Cloth Including those having Direct Transmittance

As a corollary to the above additive principle, these three curves can be weighted in any fashion according to known distribution rule of the incident radiation inside the cloth. For cloth having direct transmittance, an additional proportion of the Curve III solution is added. However, it must be noted that the solution is based on an opaque skin simulant, hence it is not applicable to diathermanous skin covered by a single open-weave cloth layer.

For cloths of different thicknesses and thermal conductivities, the general solutions are applicable. The only change is in the relationship between the actual temperature ( $^{\circ}\text{C}$ ) - time (sec) - depth(cm) and their dimensionless groups. Thus doubling the thermal conductivity of the cloth doubles the  $T^0$ ,  $\theta_c^0$ , and  $X_s^0$  scales. Halving the thickness doubles the  $T^0$  and  $X_s^0$  scales, and quadruples the  $\theta_c^0$  scale.

The general solutions also allow the prediction of the  $T^0$ ,  $\theta_c^0$ ,  $X_s^0$  data at the skin surface, and other depths where experimental data are not available.

The following examples illustrate the effects of diathermancy, thickness, thermal conductivity of the cloth, and the size of air gap and surface heat losses on the  $T^0 - \theta_c^0 - X_s^0$  relationship in the skin. The solutions are shown in the following figures.

Figures 1.13, 1.14 show  $\Delta T^0$  versus  $\Delta \theta_c^0$  at  $X_s^0 = 0$ , and  $X_s^0 = 0.05, 0.45$  respectively. The solutions are plotted on Cartesian scale to demonstrate the effect of diathermancy on the time lag between the initiation of the exposure and the rise in temperature in the skin. These figures are self-explanatory.

Figure 1.15 illustrates the effect of doubling the value of  $k_c$  on the  $T^0 - \theta_c^0 - X_s^0$  relationship. Curves to the right are calculated for white (W4) cloth, which is highly diathermanous, the curves to the left for opaque cloth. The different part  $k_c$  plays in these two types of cloth is interesting.

Figure 1.16 illustrates the effect of doubling the thickness for the same two types of cloth. It is seen that the variation in thickness has a much greater effect than thermal conductivity variation on the  $T^0 - \theta_c^0 - X_s^0$  relationship.

Figure 1.17 illustrates the relative importance of  $U_1^0$  and  $U_0^0$  on the  $T^0 - \theta_c^0 - X_s^0$ ; it is seen that, as expected,  $U_1^0$  is important at relatively small  $\theta_c^0$  and  $U_0^0$  becomes important at long  $\theta_c^0$  values.

## 2. Application to Relaxation Period.

Taking advantage again of the additive nature of the solution, the  $T^0 - \theta_c^0 - X_s^0$  relationship during the relaxation time, i.e., after the termination of the radiant source, can be obtained from the general solution by adding at the termination time to the general solution a negative radiation of the same intensity.

Figures 1.18, 1.19 show the temperature-time curves at two depth planes with radiation terminated at various dimensionless times, in the case of diathermanous white cloth and black opaque cloth, respectively. These figures are self-explanatory, and it is interesting to note the time when various depths of skin reach their maximum temperatures.

## 3. Application to Non-Square Wave Radiant Source.

Even though the general solutions are based on a radiant source of uniform intensity, solutions to radiant sources of any shape or duration can be obtained from these general solutions. An example is shown in Figure 1.20. The pulse shape and duration is that of a 1.46 Megaton nuclear explosion (2, 3, 5). The procedure is illustrated by the sketch at the lower right corner of Figure 1.26. Radiation of uniform intensity is added to the solution in a step-wise fashion until it reaches the maximum intensity, then negative radiation is added to the solution in the same way, (shown as double cross-hatched area) and net radiation received by the system is shown as the cross-hatched area. The dimensionless temperature rise group expressed in terms of the maximum intensity,  $I_{max}$ , is plotted against dimensionless time,  $\Delta\theta_c^0$ , for various depths in skin as shown in Figure 1.26.

In Figure 1.27, the temperature history at a dimensionless skin depth of 0.05 for the nuclear explosion is compared with that of square wave

radiation of the same energy, delivered in 4.5 and 1 dimensionless time units.

It is to be noted that the theoretical solution is solved by dividing the cloth into 6 increments and the modulus,  $\Delta x_c^{0a}/\Delta \theta_c^0$ , is chosen as 2; thus each time increment represents 0.0139 dimensionless time units which in turn is equal to about 0.034 sec. for the 9 oz cotton sateen. If the non-uniform pulse is to be delivered in a very short time, say 0.1 sec, the present general solution would only give a very crude approximation of the pulse shape (i.e., in three time increments). But the situation can be easily improved by increasing the modulus or by decreasing the size of each increment.

### C. DISCUSSION OF RESULTS

#### 1. Properties of the Cloth and Skin Simulant

For the optical properties of the cotton sateen cloth the values listed in Table 1.1 have been used in the evaluation of experiments as well as in the calculations.

Literature values for the specific heat of cotton fabrics vary between 0.32 (7) and 0.35 cal/gm°C, (2). A value of 0.34 cal/gm°C was used in the calculations.

In determining the heat conductivity of cloth by the conventional steady-state method, it is difficult to assign a proper effective thickness to the cloth in a situation involving both radiation and conductive heat transfer. A similar problem is posed by the measurement of density. These difficulties are avoided by combining the thickness term with both the density and thermal conductivity. For the former, a value of  $(\rho L)_c = 0.0273 \pm 2\% \text{ gm/cm}^2$  was measured by a method described in (4). The group  $(k/L)_c$  has to be estimated and improved by a trial-and-error method also explained in (4), which uses an adjustment of theoretical to experimental temperature responses. This method should give a better approximation of  $k_c$  for our purposes than the steady-state method. However, it presupposes correct values of the heat transfer coefficients  $U_0$  and  $U_1$ , which are not known precisely. Therefore the influence of a possible error in  $k_c$  will have to be tested (see V, C, 2).

The value of  $(k/L)_c$  for the 9 oz standard cotton sateen was determined to be around  $3.76 \times 10^{-5} \text{ cal/cm sec}^\circ\text{C}$ . If  $L_c$  is taken as 0.043 cm (measured

with a micrometer), then the above value corresponds to  $k_c = 1.62 \times 10^{-4}$  cal/cm sec<sup>°C</sup>, which is close to the value  $k_c = 1.5 \times 10^{-4}$  cal/cm sec<sup>°C</sup> indicated by other literature.

For the skin simulant (no. 10) used in the experiments the values  $k_s = 1.035 \times 10^{-3}$  cal/cm sec<sup>°C</sup> and  $(kCp)_s = 8.65 \times 10^{-4}$  cal<sup>2</sup>/cm<sup>4</sup>sec<sup>°C</sup><sup>2</sup> were measured. These differ slightly from the properties of average white skin agreed upon at an AFSWP conference (1), which are  $k_s = 1.065 \times 10^{-3}$  cal/cm sec<sup>°C</sup> and  $(kCp)_s = 8.5 \times 10^{-4}$  cal<sup>2</sup>/cm<sup>4</sup>sec<sup>°C</sup><sup>2</sup>.

## 2. Comparison of the Theoretical Analysis with the Experimental Data on the Dry Cloth - Air Gap - Skin Simulant System

Using the physical properties mentioned above, the experimental data (Figures 1.7 - 1.10) are transformed into their dimensionless form and replotted in Figures 1.20 - 1.23, for comparison with two sets of theoretical results. The dotted lines are based on  $U_0^0 = 0.1$  and  $U_1^0 = 2.0$  (corresponding to a surface heat transfer coefficient  $U_0 = 3.76 \times 10^{-4}$  cal/cm<sup>2</sup>sec<sup>°C</sup> and an air gap of width 0.008 cm with an air conductivity of  $0.6 \times 10^{-4}$  cal/cm sec<sup>°C</sup>). The solid lines represent  $U_0^0 = 0.2$  and  $U_1^0 = 5.0$ .

The theoretical solution can be expected to be influenced by the heat transfer coefficients, the thermal conductivity of cloth, the transmittance and residual moisture of cloth.

Figures 1.20 - 1.23 show that the effect of the temperature rise in the skin simulant of changing the assumed values of  $U_0^0$  and  $U_1^0$  decreases with rising diathermancy, as can be expected from the fact that the contribution of conduction to the heat transfer through the cloth diminishes.

For the diathermanous cloth, the agreement with the range of the two sets of calculations is quite good. The values for the opaque cloth, however, are better approximated by the solid curves than the dotted ones at short exposure times. The apparent necessity of assigning higher values to the heat transfer coefficients than those representing a stagnant air layer and natural convection at the front surface (case of  $U_0^0 = 0.1$  and  $U_1^0 = 2.0$ ) (McAdams, 14), may be explained by the fact that under rapid transient heating the transient heat transfer coefficients can be considerably higher than the values obtained under steady-state conditions (8, 13, 18). In addition,

movement of air in the pores of the cloth under a high temperature gradient may also contribute to the effective heat transfer coefficient.

Further possible influences are shown by Figures 1.20 - 1.24. Assumption of a small transmittance of the opaque cloth (although not revealed by spectrometer measurements) may raise the temperature response of the skin simulant considerably at low exposure times (Figure 1.20). A similar effect can be caused by a low residual moisture content of the "dry" cloth, whose desorption, migration and subsequent condensation on the surface of the relatively cool skin simulant will contribute to the energy transport. Figure 1.24 illustrates the variation due to 1.8% residual moisture content, calculated according to the moist cloth theory.

Last, the effect of a variation in the thermal conductivity of the cloth has been studied. In Figure 1.25  $(k/L)_c$  is raised by 30% over the value previously used. Here the dimensionless heat transfer coefficients are left constant (at 0.1 and 2.0), which implies that their dimensional equivalents  $U_o$  and  $U_i$ , too, are increased by 30% over their original values for natural convection and a stagnant air gap. This latter fact alone accounts for a rise in temperature. Thus if there is a contribution on  $(k/L)_c$  to the temperature rise at all, it must be rather small.

To reveal the influence of  $(k/L)_c$  further, some experiments have been carried out with a cylindrical skin simulant placed at a distance of 0.038 cm behind the cloth. These tests clearly indicate that the heat transfer through the stagnant air space in our system is much higher than can be predicted by an increased thermal conductivity in conjunction with the stagnant-air value of  $U_i$ .

Summarizing, it may be said that while slight effects may be due to transmittance and residual moisture in the dry cloth as well as its thermal conductivity, they appear unlikely. The major influence on the theoretical temperature response of the system is most probably effected by the choice of proper heat transfer coefficients. It seems necessary to base the theoretical solution on values of  $U_o$  and  $U_i$  higher than those related to steady-state natural convection and a stagnant air space. A rigorous confirmation of this would require further experimental investigation.

## VI. THEORETICAL - MOIST CLOTH OVER SKIN SIMULANT SYSTEM

### A. THE MATHEMATICAL MODEL

Based on the assumption that a linear relationship exists between the physical properties of the cloth fibers and that of water, an attempt was made to correlate the moist cloth data with the theoretical solution for the dry cloth-skin system using the calculated "pseudo" physical properties. The calculated theoretical temperature history was for lower than the experimental data. This suggested that the moisture in the cloth vaporized when exposed to high intensity radiation with part of the water vapor penetrating through the air gap and condensing on the cold skin simulant surface, thus resulting in a high temperature rise. A successful mathematical model must, therefore include the effect of moisture transport on the heat transfer process. Our proposed model assumes the following:

1. Mass transfer of moisture is caused by the molecular diffusion and bulk flow of vapor through the gas voids surrounding the cloth fibers, but not by liquid diffusion on the surface of or through pores in the cloth fibers.

2. The local moisture content (called "regain" in textile technology) of the cloth is at all times in equilibrium with the partial pressure of water vapor at the temperature of the local gas in the voids, i.e., the rate of equilibration is much faster than the vapor diffusion process.

3. Sensible heat transfer in the vapor phase is negligible compared with the heat conduction through the cloth and with the heat effects of adsorption and desorption of water on the cloth fiber.

4. The volume of air flowing through the cloth is negligible compared with that of the water vapor due to desorption and adsorption of water to and from the cloth fiber, i.e., air can be considered as a stagnant layer through which water vapor diffuses.

5. Other assumptions are the same as those for the dry cloth problem. An energy balance around a differential element of the cloth layer gives:

$$k_c \frac{\partial^2 T}{\partial x^2} = \rho_o (1 - f) C_c \frac{\partial T}{\partial \theta} + \lambda \rho_o (1 - f) \frac{\partial M}{\partial \theta} \quad (2.1)$$

or

$$\frac{\partial T}{\partial \theta} = \left(\frac{k}{C_p}\right)_c \frac{\partial^2 T}{\partial x^2} - \frac{\lambda}{C_c} \frac{\partial M}{\partial \theta} \quad (2.1a)$$

where  $\rho_c = \rho_o(1 - f)$  = bulk density of cloth, and the continuity equation for water can be written as:

$$-\frac{\partial}{\partial x} \left[ -\frac{gD}{(1 - y_1)} \frac{\partial y_1}{\partial x} \right] = \frac{\rho_c}{fM_1} \frac{\partial M}{\partial \theta} + \tilde{\rho} \frac{\partial y_1}{\partial \theta} \quad (2.2)$$

Since the bulk flow due to a total pressure gradient is neglected in this model, the total pressure is assumed to be constant at 1 atm., and the mole fraction of water vapor,  $y_1$ , can be replaced by the fractional partial pressure  $p/\pi$ . Equation (2.2) can be written as:

$$\frac{\rho}{\pi} \frac{\partial p}{\partial \theta} = D'' \frac{\partial^2 p}{\partial x^2} - \frac{\rho_c}{f} \frac{\partial M}{\partial \theta} \quad (2.2a)$$

where

$$D'' = \frac{gD\bar{M}}{(1 - \frac{p}{\pi}) \lambda RT}$$

$\rho$  = mass density of the gas phase,  $\mu\text{gm/cm}^3$

A third relationship can be obtained from assumption (2), thus

$$M = M(T, p)$$

and

$$\frac{\partial M}{\partial \theta} = \left(\frac{\partial M}{\partial T}\right)_p \frac{\partial T}{\partial \theta} + \left(\frac{\partial M}{\partial p}\right)_T \frac{\partial p}{\partial \theta} \quad (2.3)$$

Substituting (2.3) into (2.1a) and (2.2a), eliminating  $\partial p/\partial \theta$  from the two equations and making the assumption that  $\frac{\rho_c}{f} \left(\frac{\partial M}{\partial p}\right)_T \gg \frac{\rho}{\pi}$ , we obtain,

$$\frac{\partial T}{\partial \theta} = \left(\frac{k}{C_p}\right)_c \frac{\partial^2 T}{\partial x^2} - \left[ \frac{fD''\lambda}{C_c \rho_c} \right] \frac{\partial^2 p}{\partial x^2} \quad (2.4)$$

and

$$\frac{\partial p}{\partial \theta} = \left[ \frac{fD'' \left( 1 + \frac{\lambda}{C_c} \left( \frac{\partial M}{\partial T} \right)_p \right)}{\rho_c \left( \frac{\partial M}{\partial p} \right)_T} \right] \frac{\partial^2 p}{\partial x^2} - \left[ \frac{\alpha_c \left( \frac{\partial M}{\partial T} \right)_p}{\left( \frac{\partial M}{\partial p} \right)_T} \right] \frac{\partial^2 T}{\partial x^2} \quad (2.5)$$

Equations (2.4) and (2.5) represent the two equations describing the heat and mass transfer in the cloth layer.

For the skin simulant, we have,

$$\frac{\partial T}{\partial \theta} = \left( \frac{k}{C_p} \right)_s \frac{\partial^2 T}{\partial x_s^2} \quad (2.4a)$$

where the subscript s denotes skin simulant.

The boundary conditions are:

(1) At the front surface of the cloth:

$$(a) K_o (p_{x_c=0} - p_{surr}) = fD'' \left. \frac{\partial p}{\partial x_c} \right]_{x_c=0} \quad (2.6)$$

$$(b) I_o - U_o (T_{x_c=0} - T_{surr}) = -k_c \left. \frac{\partial T}{\partial x_c} \right]_{x_c=0} \quad (2.7)$$

(2) In the air gap between the cloth and the skin simulant, neglecting the heat capacity of the air:

(a) Material balance:

$$K_i (p_{x_c=L_c} - p_{x_s=0}) = -fD'' \left. \frac{\partial p}{\partial x_c} \right]_{x_c=L_c} \quad (2.8)$$

(b) Energy balance:

$$\begin{aligned} & -k_c \left. \frac{\partial T}{\partial x_c} \right]_{x_c=L_c} - K_i (p_{x_c=L_c} - p_{x_s=0}) \\ & = U_i (T_{x_c=L_c} - T_{x_s=0}) - K_i (p_{x_c=L_c} - p_{x_s=0}) \\ & = -k_s \left. \frac{\partial T}{\partial x_s} \right]_{x_s=0} \end{aligned} \quad (2.9)$$

## B. METHOD OF SOLUTION

### 1. Dimensionless Formulation of the Basic Equations

Unlike the case of the dry cloth-skin system, the moist-cloth problem does not lend itself to a generalized solution in dimensionless form. Not only is its solution non-linear with respect to irradiation intensity, but a general formulation would also require analytical expression of the hygroscopic equilibrium behavior of the cloth, so far only available in tabulated form. To describe this equilibrium, as well as the water vapor pressure curve, a number of dimensionless parameters would have to be introduced besides those needed for the heat and mass transfer coefficients, diffusivity, and the surrounding conditions.

The solution method developed is therefore not general, but is specific with respect to water vapor as the vaporizable component, the initial moisture content, the initial temperature and the irradiation intensity; i.e., the functions relating vapor pressure and moisture content are dealt with in absolute terms. Nevertheless, the calculations are carried out in dimensionless form, which not only provides an organizational aid but also allows for examination of the degree of nonlinearity as exhibited by the results.

The transformation groups for time, space, temperature, pressure and the transfer and diffusion coefficients are listed below:

$$T^0 = \frac{T_k}{T_o} \frac{L}{c}$$

dimensionless temperature group.

$$x_c^0 = \frac{x_c}{L_c}$$

dimensionless distance group, measured from the front surface of the cloth.

$$x_s^0 = \frac{x_s}{L_c} \cdot \frac{k_c}{k_s}$$

dimensionless skin-depth group.

$$\theta_c^0 = \left( \frac{k}{C_p} \right)_c \cdot \frac{\Delta \theta_c}{T_o}$$

dimensionless time group.

$$U_o^0 = \frac{U_o L_c}{k_c}$$

surface convective and radiant heat losses group.

$$U_i^0 = \frac{U_i L_c}{k_c}$$

convective heat transfer through air gap group.

$$\bar{K} = \sqrt{\frac{(kCp)_a}{(kCp)_c}} = \frac{\Delta x_c^0}{\Delta x_s^0}$$

property-ratio group.

$$P^0 = \frac{P}{P_0} - \frac{P_{surr}}{P_0}$$

dimensionless partial water vapor pressure group.  
(P is a convenient base pressure value, taken to be 1000, P<sub>surr</sub> the equilibrium partial pressure of water vapor at time zero.)

$$K_0^0 = - \frac{\lambda K_0 P_0}{I_0}$$

surface heat losses group due to moisture removal.

$$K_1^0 = - \frac{\lambda K_1 P_0}{I_0}$$

heat transfer group due to moisture transfer through the air gap.

$$D^0 = \frac{\lambda D^0 P_0}{L_c I_0}$$

heat transfer group due to moisture diffusion.

Using the above transformations, the differential equations (2.4, 2.4a, 2.5) become:

(a) For the cloth layer:

$$\frac{\partial T^0}{\partial \theta^0} = \bar{A} \frac{\partial^2 T^0}{\partial x_c^0{}^2} + \bar{B} \frac{\partial^2 P^0}{\partial x_c^0{}^2} \quad (2.4)'$$

$$\frac{\partial P^0}{\partial \theta^0} = \bar{C} \frac{\partial^2 T^0}{\partial x_c^0{}^2} + \bar{D} \frac{\partial^2 P^0}{\partial x_c^0{}^2} \quad (2.5)'$$

where

$$\bar{A} = 1.$$

$$\bar{B} = f D^0$$

$$\bar{C} = - \frac{\left(\frac{\partial M}{\partial T}\right)_P \cdot I_0 L_c}{\left(\frac{\partial M}{\partial P}\right)_T \cdot P_0 k_c}$$

$$\bar{D} = + \frac{f D^0 L_c C_c I_0}{k_c \lambda P_0} \left[ \frac{1}{\left(\frac{\partial M}{\partial P}\right)_T} + \frac{\lambda \left(\frac{\partial M}{\partial T}\right)_P}{C_c \left(\frac{\partial M}{\partial P}\right)_T} \right]$$

(b) For the skin:

$$\frac{\partial T^0}{\partial \theta^0} = \frac{\partial^2 T^0}{\partial X_s^0{}^2} \quad (2.4a)'$$

The boundary conditions (2.6, ... 2.9) are transformed into:

(a) At the outer surface of the cloth:

$$\text{Mass flux: } P_{x_c^0=0}^0 = 0 = (f(D^0/K_0)) \cdot \left. \frac{\partial P^0}{\partial X_c^0} \right|_{x_c^0=0} \quad (2.5)'$$

$$\text{Energy flux: } 1 - U_0^0 \cdot T_{x_c^0=0}^0 = \left. \frac{\partial T^0}{\partial X_c^0} \right|_{x_c^0=0} \quad (2.7)'$$

(c) In the air gap:

$$\text{Mass flux: } P_{x_c^0=1}^0 - P_{x_s^0=0}^0 = (f(D^0/K_1)) \cdot \left. \frac{\partial P^0}{\partial X_c^0} \right|_{x_c^0=1} \quad (2.8)'$$

$$\begin{aligned} \text{Energy flux: } & - \left. \frac{\partial T^0}{\partial X_c^0} \right|_{x_c^0=1} + K_1 (P_{x_c^0=1}^0 - P_{x_s^0=0}^0) \\ & = U_1^0 (T_{x_c^0=1}^0 - T_{x_s^0=0}^0) + K_1 (P_{x_c^0=1}^0 - P_{x_s^0=0}^0) \\ & = - \left. \frac{\partial T^0}{\partial X_s^0} \right|_{x_s^0=0} \end{aligned}$$

## 2. Difference Equations and Solution Algorithm

(a) Finite difference notation

In order to solve the system (2.4', 2.4a', 2.5), it is rewritten in the form of finite-difference equations. The variables involved now are lumped quantities, their values being assigned to discrete points in space and time, separated by intervals  $\Delta X_c^0$  (cloth),  $\Delta X_s^0$  (skin) and  $\Delta \theta^0$  (Figure 2.1). The subscripts  $j$  and  $n$  denote, respectively, a point in space and time. In particular, the subscript  $n$  denotes "present time";  $n-1$  refers to "past time",

and  $n+1$  to "future time".

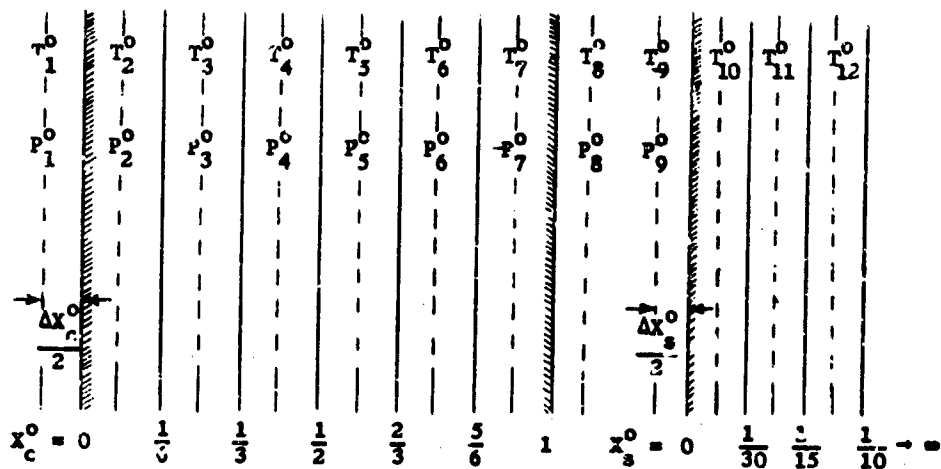


Figure 2.1

#### SLAB DIVISION FOR MOIST CLOTH-SKIN SIMULANT SYSTEM

The partial derivatives, *e r.* of the temperature distribution, in finite difference notation take the following form:

$$\left. \frac{\partial^2 T^0}{\partial x_c^2} \right|_{\substack{x_c^0 = j\Delta x_c^0 \\ \theta^0 = n\Delta\theta^0}} = \frac{T_{j-1,n}^0 - 2T_{j,n}^0 + T_{j+1,n}^0}{(\Delta x_c^0)^2}$$

abbr.:  $\frac{\Delta^2 T_{j,n}^0}{(\Delta x_c^0)^2}$  or  $T_{xxj,n}^0$  (2.10)

$$\left. \frac{\partial T^0}{\partial \theta^0} \right|_{\substack{x_c^0 = j\Delta x_c^0 \\ \theta^0 = n\Delta\theta^0}} = \frac{T_{j,n+1}^0 - T_{j,n}^0}{\Delta\theta^0}$$

abbr.:  $\frac{\Delta T_{j,n}^0}{\Delta\theta^0}$  or  $T_{\theta j,n}^0$  (2.11)

Thus, the governing difference equations are (with the abbreviations introduced above):

(1) For the cloth layer:

$$\frac{\Delta T^0}{\Delta \theta^0} = \bar{A} \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} + \bar{B} \frac{\Delta^2 P^0}{(\Delta X_c^0)^2} \quad (2.4)''$$

$$\frac{\Delta P^0}{\Delta \theta^0} = \bar{C} \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} + \bar{D} \frac{\Delta^2 P^0}{(\Delta X_c^0)^2} \quad (2.5)''$$

(2) For the skin:

$$\frac{\Delta T^0}{\Delta \theta^0} = \bar{A} \frac{\Delta^2 T^0}{(\Delta X_s^0)^2} \quad (2.4a)''$$

and the boundary conditions become:

(1) at the front surface of the cloth:

$$\text{Mass flux: } P_{x_c^0=0}^0 = (f(D^0/K_0^0)) \cdot \left. \frac{\Delta P^0}{\Delta X_c^0} \right|_{x_c^0=0} \quad (2.6)''$$

$$\text{Heat flux: } 1 - U_0^0 \cdot T_{x_c^0=0}^0 = - \left. \frac{\Delta T^0}{\Delta X_c^0} \right|_{x_c^0=0} \quad (2.7)''$$

(2) In the air gap:

$$\text{Mass flux: } P_{x_c^0=1}^0 - P_{x_s^0=0}^0 = - (f(D^0/K_1^0)) \cdot \left. \frac{\Delta P^0}{\Delta X_c^0} \right|_{x_c^0=1} \quad (2.8)''$$

or, if one assumes condensation to take place to the plane  $1/2 \Delta X_s^0$  above the skin surface and accordingly reduces the diffusional resistance across the air gap ( $1/K_1^0$ ) by that through half a skin increment:

$$P_{x_c^0=1}^0 - P_{x_s^0=0}^0 = - (f(D^0/K_1^0)) \cdot \left. \frac{\Delta P^0}{\Delta X_c^0} \right|_{x_c^0=1} \quad (2.8a)''$$

where

$$\left. \begin{aligned} P_{x_c^0=1}^0 &= \frac{P_7^0 + P_8^0}{2} \\ P_{x_s^0=0}^0 &= - \Delta X_s^0 / 2 = P_9^0 \\ \left. \frac{\Delta P^0}{\Delta X_c^0} \right|_{x_c^0=1} &= \frac{P_7^0 - P_8^0}{2} \end{aligned} \right\} \text{ in the 6-slice model of Figure 2.1.}$$

$$\begin{aligned}
 \text{Heat flux: } & - \frac{\Delta T^0}{\Delta x_c^0} \bigg|_{x_c^0=1} + K_i^0 (P_{x_c^0=1}^0 - P_{x_s^0=0}^0) \\
 & = U_i^0 (T_{x_c^0=1}^0 - T_{x_s^0=0}^0) + K_i^0 (P_{x_c^0=1}^0 - P_{x_s^0=0}^0) \\
 & = - \frac{\Delta T^0}{\Delta x_s^0} \bigg|_{x_s^0=0} \quad (2.9)''
 \end{aligned}$$

(b) Backward difference method

In solving difference equations the structure of the computing algorithm as well as the stability and accuracy of the solution depend on the choice of subscripts assigned to each of the derivatives. For example, in the case of the heat conduction equation,

$$\frac{\partial^2 T^0}{\partial x^0{}^2} = \frac{\partial T^0}{\partial \theta^0}$$

taking the second derivative in space at present time results in the "explicit" formulation:

$$\frac{T_{j+1,n}^0 - 2T_{j,n}^0 + T_{j-1,n}^0}{(\Delta x^0)^2} = \frac{T_{j,n+1}^0 - T_{j,n}^0}{\Delta \theta^0}$$

which at each point (j,n) contains only one unknown, since the distribution of  $T^0$  at time n is known.

If instead one chooses to take the second derivative at future time, one arrives at the so-called "backward difference" equation:

$$\frac{T_{j+1,n+1}^0 - 2T_{j,n+1}^0 + T_{j-1,n+1}^0}{(\Delta x^0)^2} = \frac{T_{j,n+1}^0 - T_{j,n}^0}{\Delta \theta^0}$$

which at each point (j,n+1) presents the three unknowns  $T_{j+1,n+1}^0$ ,  $T_{j,n+1}^0$ ,  $T_{j-1,n+1}^0$  and is also called "implicit".

Besides these methods, there are others involving both present and future time values in the evaluation of the next distribution (18). The formulation mentioned first is explicit in that the single unknown quantity

at each point  $(j,n)$  is readily obtainable. However, this method is known to possess a restriction on the solution stability. The second, backward difference formulation with three unknowns at  $(j,n)$  requires setting up a system of as many simultaneous equations as there are space points. Since the equations deal with subsequent space points, the unknowns appear in advancing positions and thus form a tridiagonal set of equations which can be solved by recursion after application of the boundary conditions. This procedure entails more computational work than the explicit method, but in the case of the heat conduction equation it is known to produce an unconditionally stable solution. A backward difference method was chosen, too, to solve the problem presented by equations (2.4", 2.4a", 2.5"). An investigation of the stability of the particular algorithm used has been carried out and is described in chapter VI, B, 5.

Whenever one of the equations is used to calculate implicitly the distribution of either variable at future time (subscript  $n+1$ ), the distribution of the other variable is its last known distribution. Furthermore, the two equations are used alternately in a pair of time steps, such that in the first step one first solves for  $T$ , then for  $P$ , and in the second step, first for  $P$ , then for  $T$ .

- a. Solve (2.4)" and (2.4a)" for  $T_{j,n+1}^0$  for all  $j$ ;  $T_{j,n}^0$  and  $P_{j,n}^0$  known
  - b. Solve (2.5)" for  $P_{j,n+1}^0$  for all  $j$ ;  $T_{j,n+1}^0$  and  $P_{j,n}^0$  known
  - c. Solve (2.5)" for  $P_{j,n+2}^0$  for all  $j$ ;  $T_{j,n+1}^0$  and  $P_{j,n+1}^0$  known
  - d. Solve (2.4)" and (2.4a)" for  $T_{j,n+2}^0$  for all  $j$ ;  $T_{j,n+1}^0$  and  $P_{j,n+2}^0$  known
- (2.12)

then replace  $n$  by  $n+2$ .

Details of the computing algorithm are described in Appendix C.

The main difference in solving for the temperature or pressure distribution is that the coefficients  $\bar{C}$  and  $\bar{D}$  in equation (2.5)", are dependent on temperature and pressure. Their present time values are determined at each time step preceding the solution of the equation set. This is done by means of a double interpolation (with entries  $T$  and  $p$ ) of tabulated values

for  $(\partial M/\partial T)_p$  and  $(\partial p/\partial T)_M$ , which are based on equilibrium data for moist cloth obtained by Urquhart and Williams (22).

### 3. Remarks on the Boundary Conditions and Variable Water Vapor Diffusivity

#### (a) Moisture condensation of the skin surface

The boundary condition (2.8)" relates the mass transfer at the inner cloth surface to the vapor diffusion through the air gap. In it,  $p_{x_s=0}^0$  is the water vapor pressure at the skin surface, or, more precisely, the saturated vapor pressure at the temperature of the skin surface, since the skin is taken to have no absorptivity for moisture. In calculating the pressure distribution, the above relation is used first, implying the assumption that there is condensed moisture on the skin. If this assumption is incorrect, (as revealed by a test of the pressure gradient at the air gap and a record of the moisture condensed), the pressure calculation is repeated once, with a simpler boundary condition stating that the moisture flux through the inner cloth surface is zero:

$$p_7^0 = p_8^0 \text{ (in the 6-slice model of Figure 2.1)}$$

A distinction has to be made in this context between the phases b and c of the alternating scheme (2.12), although both phases apply the same basic equations.

In phase b, the skin surface temperature at "future time"  $T_{x_s=0}^0, n+1$  is known and thus also  $p_{x_s=0, n+1}^0$ . In phase c, when  $n+2$  means future time, this is not true. The "present time" value  $T_{x_s=0, n+1}^0$  is therefore chosen as a trial value. If the ensuing calculation of temperatures in phase d does not confirm it closely enough, an improved value for the skin surface temperature is chosen and phases c and d are repeated until convergence is achieved.

#### (b) Treatment of dry cloth slices

At sufficiently high irradiation intensity, the evaporation of water and the moisture flow to the cooler interior of the system will eventually cause parts of the cloth to become dry, starting from the outer surface. A slice of the cloth is called dry when either its temperature rises above some fixed level (i.e.,  $180^\circ\text{C}$ ) or the relative humidity in it drops below a minimum (5%). The dry slices are now excluded from the pressure calculation based on the moisture equilibrium relationship. If, however, the equation

for the temperature calculation (2.4)" is to remain unaltered, some meaningful, if very low, pressure values must be assigned to the "dry" slices. The storage capacity of these slices for moisture can be considered negligible as long as they stay "dry". Therefore at these points the pressure values should not contribute to the temperature response as expressed by equations (2.4)"; the second derivative of pressure may be considered to be zero, which turns these equations into pure heat conduction equations. In other words, the pressure profile is to have a linear section, which is equivalent to stating that the values in question are only determined by the diffusion from the known vapor pressure in the first moist slice to the outside surface.

If  $m$  is the number of dry cloth slices, then  $P_1^0$  and  $P_{m+2}^0$  are related by a modification of the boundary condition (2.6)" which takes into account the lengthened path of diffusion to the boundary:

$$K_o^0 \cdot P_{x_c^0=0}^0 = fD^0 \cdot \left. \frac{\Delta P^0}{\Delta x_c^0} \right|_{x_c^0=0}$$

No dry slices:

$$P_1^0 = P_2^0 \cdot \frac{2fD^0 - K_o^0 \cdot \Delta x_c^0}{2fD^0 + K_o^0 \cdot \Delta x_c^0} \quad (2.6)''$$

$m$  slices dry:

$$P_1^0 = P_2^0 \cdot \frac{2fD^0 - K_o^0 \cdot \Delta x_c^0}{2fD^0 + (2m + 1)K_o^0 \cdot \Delta x_c^0} \quad (2.6)'''$$

(See Figure 2.2 below)

Accordingly, the pressures in the "dry" part of the cloth are found by interpolation.

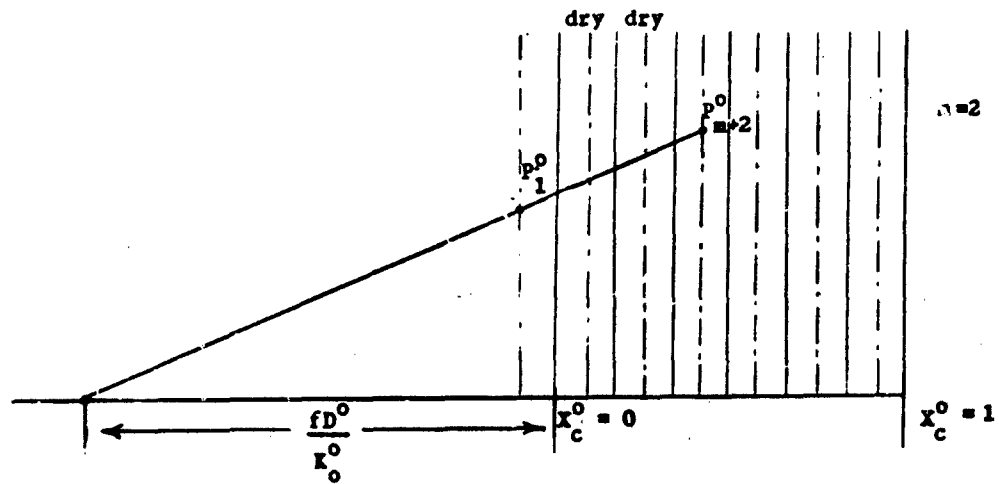


Figure 2.2

(c) The diffusivity of water vapor through air is given as a function of temperature:

$$D = 0.22 \left( \frac{T}{273} \right)^{3/2}$$

The effective coefficient of diffusion  $D^*$  can be calculated from  $D$  using an average temperature (e.g.,  $50^\circ\text{C}$ ):

$$D^* = \frac{g \bar{D}}{\left(1 - \frac{p_{av}}{p}\right) RT} \quad (2.13)$$

where  $g$  is the tortuosity factor.

The program allows for the use of either a fixed value of  $D^*$  or a variable one, to be determined from the local vapor pressure and temperature at each cloth slice and at each time step.

#### 4. Summary of the Computer Program

##### (a) Input

The program requires four groups of input data. The first type of data describes the moisture-temperature-water vapor pressure relationship for the

moist cloth. The functions

$$\left(\frac{\partial M}{\partial p}\right)_T = f(T, p)$$

and

$$\left(\frac{\partial p}{\partial T}\right)_M = f(T, p)$$

form tables with entries  $T$  and  $p$ . Their values are also listed in Table G.2. They are based on original data obtained by Urquhart and Williams, (22), which are compiled in (5).

The second group of data contains constants describing the properties of the physical system:

$$\begin{aligned} &U_c^0 \\ &U_i^0 \\ &fD^0 \cdot I_{\text{omax}} \\ &K_i^0 \cdot I_{\text{omax}} \\ &K_o^0 \cdot I_{\text{omax}} \\ &(L/k)_c \\ &(\lambda/k)_c \\ &(L^2 C_p / \kappa)_c \\ &T_{\text{crit}} \\ &(k C_p)_c \end{aligned}$$

The third group comprises constants referring to the properties of the mathematical model:

A tolerance for the trial value of the skin surface temperature rise

$$M_A = (\Delta X_c^0)^2 / \Delta \theta^0$$

$$\Delta X_c^0$$

$$\Delta X_s^0$$

The number of double time steps

An indicator for constant or variable water vapor diffusivity  
The number of single time steps between printouts  
The number of cloth slices  
A time mark for optional change of  $M_A$   
An alternate value for  $M_A$

Last, a number of parameters define "experimental" conditions, namely the surrounding temperature and relative humidity, the irradiation intensity, its duration and pulse shape:

$P_{surr}$

$T_{surr}$

An indicator for the type of irradiation pulse shape

$I_{max}$

The pulse width

The trapezoidal pulse shape parameter

#### (b) Output

The results of computations are presented as:

The dimensionless temperature distribution in and at the cloth and skin simulant

The dimensionless pressure distribution in and at the cloth as functions of dimensionless time.

As a by-product, the values of the variable coefficients in equation (2.5) are given as well as measures for the moisture loss due to evaporation at the cloth surface and condensation on the skin simulant.

A record of the number of cloth slices having dried out is kept, and optionally the value of the maximum critical enthalpy assumed by the skin is indicated.

#### (c) Program description

A common experience with any complete description of a sizeable computer program is that it tends to become as involved as the program itself appears at first glance. It is hoped, however, that the computing process is explained sufficiently by the description of the algorithm which forms the basic part

of the program (Appendix C) along with diagrams showing the flow of control through its main portions, a commentary on the purpose of the subroutines used and the program listings, all of which are included in Appendix E. The program in form of symbolic and binary cards may be obtained upon request from the files of the Fuels Research Laboratory, Chemical Engineering Department, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

### 5. Stability

A main distinction between the formulation of a differential equation in analytical or finite-difference terms arises from the fact that the latter formulation may be satisfied not only by one true solution but also by a number of so-called extraneous solutions contributing to the total calculated function. If these are not to disturb the solution of the problem, the condition to be imposed on them is that their amplitudes decay with time, i.e., that values of an extraneous solution  $u$  at a space point  $i$  at successive time steps  $n$  and  $n+1$  have an amplitude ratio or growth factor  $\xi \leq 1$ .

$$\xi = \frac{u_{i,n+1}}{u_{i,n}} \leq 1$$

This is the condition of stability of the solution process.

Whether a finite-difference method has the property of (unconditional or conditional) stability is determined by the structure of the particular computing algorithm chosen (see VI, B, 2), in conjunction with the coefficients of the differential equations. An investigation of the stability problem associated with the alternating explicit-implicit scheme used for the moist cloth-skin simulant system follows below\*. It results in a simple criterion for stability which is dependent only on the four coefficients of the equation system.

In the derivations below, a nomenclature exclusive to this chapter is used;  $T$ ,  $P$  and the coefficients  $\bar{A}$ ,  $\bar{B}$ ,  $\bar{C}$ ,  $\bar{D}$  only retain their meaning. The superscripts denoting "dimensionless" are dropped, and for the derivatives, the abbreviations (2.10, 2.11) of chapter VI, B, 2 are used.

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\* This study was done with the kind assistance of Professor P. L. Thibault Brian, Department of Chemical Engineering, M.I.T.

Temporarily, the system is assumed to be linear, i.e., to possess constant coefficients  $\bar{A}$ ,  $\bar{B}$ ,  $\bar{C}$ ,  $\bar{D}$ . The equations in question are

$$T_{\theta} = \bar{A}T_{xx} + \bar{B}P_{xx} \quad (3.1)$$

$$r_{\theta} = \bar{C}T_{xx} + \bar{D}P_{xx} \quad (3.2)$$

Assuming  $T$  and  $P$  to consist of separable functions,

$$T(x, \theta) = r(x) \cdot f(\theta) \quad (3.3)$$

$$P(x, \theta) = s(x) \cdot g(\theta) \quad (3.4)$$

the system becomes:

$$\bar{A}f \cdot (r''/r) + \bar{B}g \cdot (s''/s) = f' \quad (3.5)$$

$$\bar{C}f \cdot (r''/s) + \bar{D}g \cdot (s''/s) = g' \quad (3.6)$$

If the variables are truly separated, then the functions

$$(r''/r), (s''/s), (s''/r), \text{ and } (s''/s)$$

must be independent of  $x$ .

Setting  $(r''/r) = -\omega^2 = \lambda$  we find

$$r(x) = s(x) = e^{i\omega x} \quad (3.7)$$

We now solve for  $f(\theta)$  and  $g(\theta)$ .

$$\bar{A}\lambda f(\theta) + \bar{B}\lambda g(\theta) = f'(\theta) \quad (3.8)$$

$$\bar{C}\lambda f(\theta) + \bar{D}\lambda g(\theta) = g'(\theta) \quad (3.9)$$

From (3.10)

$$g(\theta) = \frac{f'(\theta) - \bar{A}\lambda f(\theta)}{\bar{B}\lambda} \quad (3.10)$$

$$g'(\theta) = \frac{f''(\theta) - \bar{A}\lambda f'(\theta)}{\bar{B}\lambda}$$

Substituting into (3.9) we find:

$$f''(\theta) - (\bar{A} + \bar{B})\lambda f'(\theta) + (\bar{A}\bar{D} - \bar{B}\bar{C})\lambda^2 f(\theta) = 0$$

Therefore,

$$f(\theta) = c_1 e^{\mu_1 \theta} + c_2 e^{\mu_2 \theta}$$

with

$$\begin{pmatrix} \mu_1 \\ \mu_2 \end{pmatrix} = (-\omega^2) \left\{ \frac{\bar{A} + \bar{B}}{2} \pm \sqrt{\left(\frac{\bar{A} + \bar{B}}{2}\right)^2 - (\bar{A}\bar{D} - \bar{B}\bar{C})} \right\}$$

Analogously, the solution for  $g(\theta)$  is,

$$g(\theta) = c_3 e^{\mu_1 \theta} + c_4 e^{\mu_2 \theta}$$

The total solution then is,

$$T(x, \theta) = \sum_k (c_1 e^{\mu_1 \theta} + c_2 e^{\mu_2 \theta}) (c_5 \cos \omega_k x + c_6 \sin \omega_k x) \quad (3.12)$$

$$P(x, \theta) = \sum_k (c_3 e^{\mu_1 \theta} + c_4 e^{\mu_2 \theta}) (c_5 \cos \omega_k x + c_6 \sin \omega_k x) \quad (3.13)$$

T and P are wave functions in distance. Their "growth" with time depends on the four coefficients as follows:

- if  $\bar{A}\bar{D} > \bar{B}\bar{C}$       T and P decay with time
- if  $\bar{A}\bar{D} = \bar{B}\bar{C}$       T and P are independent of time
- if  $\bar{A}\bar{D} < \bar{B}\bar{C}$       T and P increase with time

Since only the first case is physically meaningful, a finite-difference procedure to solve for T and P must also provide solutions that decay with time.

We define

$$T_{j,n} = T(x=j\Delta x, \theta=n\Delta \theta)$$

$$P_{j,n} = P(x=j\Delta x, \theta=n\Delta \theta)$$

$$r_j = e^{i\omega_j \Delta x}$$

In the finite-difference notation, we introduce as usual,

$$r'' = r_{j-1} - 2r_j + r_{j+1}$$

It follows, for the functions introduced in (3.5, 3.6)

$$(r''/r) = \frac{e^{i\omega(j-1)\Delta x} - 2e^{i\omega j\Delta x} + e^{i\omega(j+1)\Delta x}}{e^{i\omega j\Delta x}}$$

$$(r''/r) = e^{-i\omega\Delta x} - 2 + e^{i\omega\Delta x} = -4\sin^2(\omega\Delta x/2) \quad (3.14)$$

and likewise,

$$(r''/r), (r''/s), (s''/r), (s''/s) = -4\sin^2(\omega\Delta x/2)$$

Introducing the abbreviations,

$$\alpha = -4\bar{A} \frac{\Delta\theta}{(\Delta x)^2} \cdot \sin^2(\omega\Delta x/2)$$

$$\beta = -4\bar{B} \frac{\Delta\theta}{(\Delta x)^2} \cdot \sin^2(\omega\Delta x/2)$$

$$\gamma = -4\bar{C} \frac{\Delta\theta}{(\Delta x)^2} \cdot \sin^2(\omega\Delta x)$$

$$\delta = -4\bar{D} \frac{\Delta\theta}{(\Delta x)^2} \cdot \sin^2(\omega\Delta x)$$

we rewrite the equation system in the sequence to be used for its solution (see VI, B, 2):

$$-\alpha f_{n+1} - \beta s_n = f_{n+1} - f_n \quad (3.16a)$$

$$-\gamma f_{n+1} - \delta s_{n+1} = s_{n+1} - s_n \quad (3.16b)$$

$$-\gamma f_{n+1} - \delta s_{n+2} = s_{n+2} - s_{n+1} \quad (3.16c)$$

$$-\alpha f_{n+2} - \beta s_{n+2} = f_{n+2} - f_{n+1} \quad (3.16d)$$

This represents a double time step scheme in the second half of which the sequence of operations is inverted (thus "alternating"). We are interested

in determining its behavior over one entire double time step, i.e., in finding a relation between  $f_{n+2}$  and  $f_n$ , and likewise between  $g_{n+2}$  and  $g_n$ .

From (3.16a) is extracted,

$$f_{n+1} = \frac{f_n - \beta g_n}{1 + \alpha} \quad (3.17)$$

Substituting this into (3.16b) yields,

$$g_{n+1} = \frac{-\gamma}{(1 + \alpha)(1 + \delta)} \cdot f_n + \frac{\gamma\beta + 1 + \alpha}{(1 + \alpha)(1 + \delta)} \cdot g_n \quad (3.18)$$

Substituting these two expressions into (3.16c) results in

$$\begin{aligned} & -\gamma(2 + \delta)f_n - (\delta + 1)^2(\alpha + 1)g_{n+2} \\ & + [\beta\gamma(2 + \delta) + 1 + \alpha]g_n = 0 \end{aligned} \quad (3.19)$$

and into (3.16d) in

$$(1 + \alpha)^2 f_{n+2} - f_n + (1 + \alpha)\beta g_{n+2} + \beta g_n = 0 \quad (3.20)$$

Having eliminated all functions values at time  $n+1$ , we now actually consider the double time step as one period, rewriting the last equations:

$$\begin{aligned} & -\gamma(2 + \delta)f_n - (\delta + 1)^2(\alpha + 1)g_{n+1} \\ & + [\beta\gamma(2 + \delta) + 1 + \alpha]g_n = 0 \end{aligned} \quad (3.19a)$$

$$(1 + \alpha)^2 f_{n+1} - f_n + (1 + \alpha)\beta g_{n+1} + \beta g_n = 0 \quad (3.20a)$$

Next a relation is to be found for the time behavior of one of the solutions, i.e.,  $g_n$ , expressed as a growth factor

$$\xi = g_{n+1}/g_n$$

Thus the functions  $f$  are to be eliminated first; this is done most easily by substituting  $f_n$  from (3.19a) into (3.20a), hereafter also  $f_{n+1}$  from the

same equation, having increased the index by 1. The result is,

$$\underbrace{(1 + \alpha)^2(1 + \delta)^2 g^2}_{"a"} - \underbrace{\left\{ (1 + \alpha)^2 + \beta \gamma (2 + \alpha)(2 + \delta) + (1 + \delta)^2 \right\} g}_{"b"} \underbrace{+ 1}_{"c"} = 0 \quad (3.21)$$

The stability condition imposed on the function  $g$  is

$$g_{n+1}/g_n \leq 1$$

It is not necessary to go through the same derivation to find a corresponding relation for the growth factors associated with the function  $f$ . Consider the double time step to go from  $n+1$  to  $n+3$ , comprising the solution of equations (3.16c,d), i.e.,  $n+1$  to  $n+2$ , followed by that of equations (3.16a,b), i.e.,  $n+2$  to  $n+3$ .

$$\left. \begin{aligned} -\alpha f_{n+1} - \beta g_n &= f_{n+1} - f_n \\ -\gamma f_{n+1} - \delta g_{n+1} &= g_{n+1} - g_n \\ -\gamma f_{n+1} - \delta g_{n+2} &= g_{n+2} - g_{n+1} \\ -\alpha f_{n+2} - \beta g_{n+2} &= f_{n+2} - f_{n+1} \\ -\alpha f_{n+3} - \beta g_{n+2} &= f_{n+3} - f_{n+2} \\ -\gamma f_{n+3} - \delta g_{n+3} &= g_{n+3} - g_{n+2} \end{aligned} \right\} \begin{aligned} &\text{original double step} \\ &n \rightarrow n+2 \\ &\text{new double step} \\ &n+1 \rightarrow n+3 \end{aligned} \quad (2.12)$$

If for the moment we replace

T by P  
P by T  
 $\alpha$  by  $\delta^*$   
 $\delta$  by  $\alpha^*$   
 $\beta$  by  $\gamma^*$   
 $\gamma$  by  $\beta^*$   
f by  $g^*$   
g by  $f^*$

then the system  $n+1$  to  $n+3$  is formally identical with the original one. Therefore we know from the foregoing discussion the quantities  $a^*$ ,  $b^*$ ,  $c^*$  that will

be associated with the equation

$$a^* \frac{g_{m+2}^*}{g_m^*} + b^* \frac{f_{m+2}^*}{f_m^*} + c^* = 0 \quad (3.21)$$

or because of the replacement definition

$$a^* \frac{f_{m+2}}{f_m} + b^* \frac{f_{m+2}}{f_m} + c^* = 0 \quad (3.22a)$$

where  $a^*$ ,  $b^*$ ,  $c^*$  are expressed in terms of  $a^*$  ...  $\delta^*$ . Resubstituting  $\alpha^* = \delta$  etc., we obtain the terms in (3.20a) in terms of the original quantities  $\alpha$  ...  $\delta$ , only to find that they are identical with those in the growth factor relation (3.19) for  $g$ . This could be expected from the fact that the equation system and the algorithm for its solution are symmetric with respect to  $T$  and  $P$  (or  $f$  and  $g$ ).

It remains to be seen under what conditions the stability criterion, identical for  $f$  and  $g$ , is satisfied, i.e.,

$$|\xi| \leq 1 \text{ where } a\xi^2 + b\xi + c = 0 \text{ from equation (3.21)}$$

This can be transformed as follows:

$$\xi_{1,2} = -(b/2a) \pm \frac{\sqrt{b^2 - 4ac}}{2a} \leq 1$$

resulting in

$$-c \leq a + b$$

Using these terms as expressed in (3.21) we have,

$$\begin{aligned} -1 &\leq (1 + \alpha)^2(1 + \delta)^2 - (1 + \alpha)^2 \\ &\quad - \beta\gamma(2 + \alpha)(2 + \delta) - (1 + \delta)^2 \end{aligned}$$

From this follows:

$$-1 \leq (1 + 2\alpha + \alpha^2)(1 + 2\delta + \delta^2) - (1 + 2\alpha + \alpha^2) - \beta\gamma(2 + \alpha)(2 + \delta) - (1 + 2\delta + \delta^2)$$

or

$$0 \leq (2\alpha + \alpha^2)(2\delta + \delta^2) - \beta\gamma(2 + \alpha)(2 + \delta)$$

which reduces to

$$\frac{\beta\gamma}{\alpha\delta} \leq 1$$

Thus the condition of stability is satisfied whenever  $\overline{BC} / \overline{AD} \leq 1$ .

So far, we have assumed the coefficients  $\overline{A}$ ,  $\overline{B}$ ,  $\overline{C}$ , and  $\overline{D}$  to be constant. Since in fact  $\overline{C}$  and  $\overline{D}$  are evaluated anew at each time step by table interpolation, and  $\overline{B}$  can be either variable or held constant, one would have to ascertain that their values always fulfill the stability condition. A special subroutine was therefore written into an intermediate version of the computer program to test the criterion, which indeed was never violated during computations.

#### 6. Convergence

The question of convergence of the finite difference solution method bears upon two aspects of the problem:

- (a) Ultimate uniqueness of the finite difference solution
- (b) Expense of machine time versus accuracy

One is interested in determining the convergence of the finite-difference solution, when the difference net is refined, to the "true solution" that satisfies the finite difference system. (The true response of the physical system, as obtained experimentally, is valuable for comparison but not decisive for the consideration of convergence, since the mathematical abstraction implies simplifying assumptions). Unfortunately, no analytical solution of the system in question is available by which the accuracy of the calculated one could be determined. All one may ask for is ultimate convergence of the solution to a unique result, when finer steps in time and

space are taken. In the absence of general methods for establishing such behavior for coupled equations with coefficients depending on the response functions, a somewhat experimental approach was used to investigate it.

If one expresses the terms occurring in the finite difference equations in Taylor series forms, then the total truncation error for the two functions  $T^0$  and  $P^0$  comprises terms containing  $\Delta\theta^0$ ,  $(\Delta x_c^0)^2$  and  $(\Delta x_s^0)^2$ . It may be expected that the truncation error diminishes as these factors are reduced, as it does in simpler, linear systems so long as the condition for stability is obeyed. This latter requirement is in fact fulfilled by our system.

In order to observe convergence rather than prove it rigorously, calculations have been carried out to test the influence of different values of the intervals  $\Delta x_c^0$ ,  $\Delta x_s^0$  and  $\Delta\theta^0$ . First, the resulting response curves are expected to appear in the same sequence as the respective values of  $\Delta x_c^0$ ,  $\Delta x_s^0$  and/or  $\Delta\theta^0$ . Second, the rate of change of these curves is expected to become smaller as successively smaller finite differences are used, i.e., they should converge against a final function. Figures 2.7a,b illustrate the results of these calculations, i.e., the temperature response of the skin obtained at constant irradiation intensities of  $I_{\text{max}} = 0.5$  and  $1.0 \text{ cal/cm}^2\text{sec}$  and dimensionless step widths,

$$\Delta x_c^0 = 1/2, 1/6 \text{ and } 1/18,$$

$$\Delta x_s^0 = 1/10, 1/30, 1/90 \text{ (resp.)}$$

$$\Delta\theta^0 = 0.0031 \dots 0.25$$

For comparison, the temperature responses of the cloth are also depicted for the case of  $I_{\text{max}} = 0.5 \text{ cal/cm}^2\text{sec}$ , (Figure 2.7c).

Inspection of the calculated results shows that the curves for the skin temperature lie in the expected order with respect to each other. (Note that the sequence may be ascending or descending as the truncation error may change its sign with time).

A similar behavior was observed for the cloth temperatures, at least over a time range until  $\theta^0 = 2.0$  (Figure 2.7c).

Furthermore, it appears that successive refinement of  $\Delta x_c^0$ ,  $\Delta x_s^0$  and

$\Delta\theta^0$  results in a progressively smaller variation of the curves. For  $I_{\text{omax}} = 0.5 \text{ cal/cm}^2\text{sec}$  the case of  $\Delta X_c^0 = 1/18$  was not computed. At  $I_{\text{omax}} = 1.0 \text{ cal/cm}^2\text{sec}$  however, the refinement of intervals in fact leads to convergence in that the response obtained with  $\Delta X_c^0 = 1/6$  and  $\Delta\theta^0 = 0.00556$  very precisely reproduces that obtained with  $\Delta X_c^0 = 1/18$  and  $\Delta\theta^0 = 0.0031$ , within the low time range until  $\theta^0 = 1.0$ .

The agreement found from these trial calculations certainly has to be taken cum grano salis. In particular, the comparison with the case of finest step widths has not been carried out over a very large range of time, first since this alone would have required excessive amounts of machine time, and second, because one can hardly expect a perfect reproduction over such a range from a system with slight built-in discontinuities, such as the effect of cloth slices drying out. (The approximative treatment of those cloth slices, which might introduce slight deviations, must make itself felt more strongly in the 18-slice model than with 2 or 6 slices, simply since the condition applies to a larger number of such slices as time goes on).

For practical purposes one has to make a comparison between the accuracy of the computed solution and the expense of machine time required to obtain it. The amount of computer time used per time step strongly depends on the fineness of the slices into which the continuum is conceptually divided, and on the length of time intervals, since the former affects the size of the equation system to be solved, while the latter is immediately related to the progression on the real time scale. The attempt at finding experimentally the degree to which a somewhat "unique" or final solution is gained by refining the space-time mesh leads one to believe that the 2-slice model does not provide sufficient accuracy, producing deviations of up to 10% from the 6-slice case. On the other hand, not much accuracy is gained by preferring 18-slices over 6. As far as computer time is concerned, this is a fortunate balance. The actual amounts of computer time required per second of real time are given in Appendix E.

#### 7. Time-variant Irradiation Intensity

In the earlier studies of a mathematical model to describe the moist cloth-skin system the intensity of irradiation was assumed to be constant.

This represents in fact the case of the experiments carried out at MIT; here an exposure shutter was kept open for a certain time interval and then closed rapidly, thus forming a square wave of irradiation.

The situation is different in the case of a thermonuclear explosion, where the intensity of irradiation is time-variant, exhibiting a very pronounced peak value and a long decaying section. (An analytical expression for this intensity distribution was given by Batter, (23)).

Thus the temperature-pressure-time response of the system will be quite different; in particular it may be expected that an irradiation of constant intensity much smaller than the peak intensity of a thermonuclear pulse will produce a given temperature rise in the skin. At constant irradiation, temperature rises monotonously and the moisture migrates to the cooler interior of the system, partly condensing on the skin surface, and although the moisture on the skin may later vaporize, there is no reversal of heat flow during irradiation. With an irradiation pulse of finite duration and energy, on the other hand, the temperature rise will eventually be followed by a decay, first in the cloth, later also on the skin surface and in the interior of the skin. Furthermore, it can be expected that there will be a reversal of the heat flow and with it will be associated a reversal of the moisture flow.

In order to show these differences between the responses to constant and time-variant irradiation as well as to allow a comparison of theoretical results with those obtained from experiments that actually involved a square wave, the mathematical method has been set up to accept a variable irradiation intensity as a boundary condition.

This facility allows for four cases of intensity distributions:

- Step function
- Square wave
- Trapezoidal wave
- Thermonuclear explosion pulse

It is introduced as follows:

The irradiation intensity affects only the heat boundary condition at the

outer cloth surface

$$I_o = U_o (T_{x_c=0} - T_{surr}) = -k_o \left. \frac{\partial T}{\partial x_c} \right|_{x_c=0} \quad (2.7)$$

or in dimensionless finite-difference terms:

$$1 - U_o^o \cdot T_{x_c^o=0}^o = \left. \frac{\Delta T^o}{\Delta x_c^o} \right|_{x_c^o} \quad (2.7)^n$$

Note that elsewhere in the formulation of the dimensionless system  $I_o$  is used also, but merely as a reduction factor for dimensionless notation. If one still retains some characteristic value of intensity, such as the maximum of a pulse distribution, as a reference value, one is free to introduce into the boundary condition a term expressing the relative irradiation intensity  $I_o(\theta)/I_{o\max}$ :

$$I_o(\theta^o)/I_{o\max} - U_o^o \cdot T_{x_c^o=0}^o = \left. \frac{\Delta T^o}{\Delta x_c^o} \right|_{x_c^o=0}$$

This value is computed at each time step, preceding the solution for the temperature distribution.

#### (a) Description of irradiation pulses

The maximum irradiation intensity is prescribed in absolute terms (cal/cm<sup>2</sup>sec). Since the program used a dimensionless time scale throughout, all characteristic extensions of pulses in time are prescribed in dimensionless terms, (Figure 2.3).

For the squarewave, one quantity  $\theta_{char}^o$  suffices. The time scale of the trapezoidal pulse requires two quantities:  $\theta_{er}^o$  defining the end of its first ramp, and  $\theta_{char}^o$  the end of the pulse.

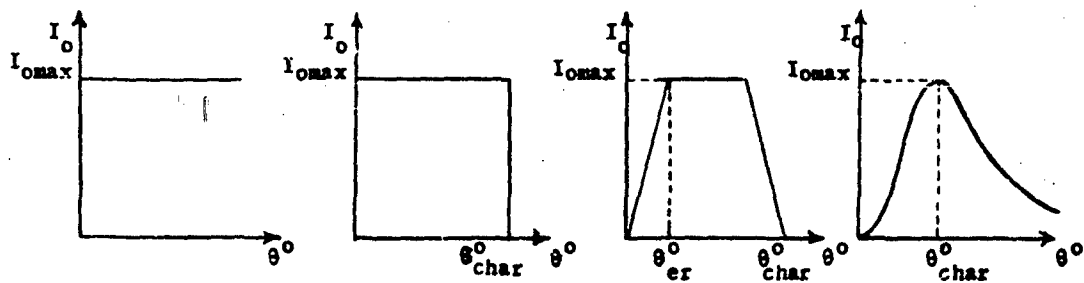


Figure 2.3

### IRRADIATION PULSE SHAPES

The thermonuclear explosion pulse requires one characteristic value  $\theta_{\text{char}}^0$ , locating the peak of the distribution, and a normalized shape function (20) indicated in Table 2.1 (see for example, Figure 2.20).

Table 2.1

### THERMONUCLEAR PULSE INTENSITY DISTRIBUTION

| Region<br>$\theta^0/\theta_{\text{char}}^0$ | Relative intensity<br>$I_0(\theta^0)/I_{0\text{max}}$            | Energy delivered at time $\theta^0$<br>(cal/cm <sup>2</sup> sec)                                                                                             |
|---------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 0 - 0.3                                     | $0.565(\theta^0/\theta_{\text{char}}^0)$                         | $I_{0\text{max}} \cdot \theta_{\text{char}}^0 \cdot 0.2825(\frac{\theta^0}{\theta_{\text{char}}^0})$                                                         |
| 0.3 - 0.65                                  | $1.72(\frac{\theta^0}{\theta_{\text{char}}^0}) - 0.347$          | $I_{0\text{max}} \cdot \theta_{\text{char}}^0 [0.0521 + 0.86(\frac{\theta^0}{\theta_{\text{char}}^0})^2 - 0.347(\frac{\theta^0}{\theta_{\text{char}}^0})]$   |
| 0.65 - 1.4                                  | $1.0 - 1.42[(\frac{\theta^0}{\theta_{\text{char}}^0}) - 1.05]^2$ | $I_{0\text{max}} \cdot \theta_{\text{char}}^0 [-0.49 + (\frac{\theta^0}{\theta_{\text{char}}^0}) - 0.473(\frac{\theta^0}{\theta_{\text{char}}^0} - 1.05)^2]$ |
| 1.4 - 10.0                                  | $1.434(\frac{\theta^0}{\theta_{\text{char}}^0})^{-1.64}$         | $I_{0\text{max}} \cdot \theta_{\text{char}}^0 [2.696 - 2.24(\frac{\theta^0}{\theta_{\text{char}}^0})^{-0.64}]$                                               |

For comparison, the program verifies the areas of pulses, i.e., the radiation energies delivered.

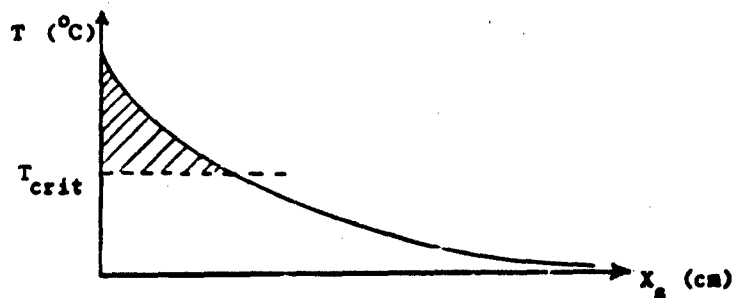
(b) Remark on the square wave

In computing the response to a square wave input, a slight difficulty is sometimes encountered at the end of the pulse. The sudden termination of irradiation leaves in the above mentioned boundary condition only the term for the heat losses. Since a surface temperature value is taken to govern the outward heat flow during an entire time step, the size of time steps may have to be reduced at this point so as not to simulate too large a heat loss during the beginning of the relaxation period. At a later time, when the surface temperature has dropped, the original interval size can be resumed. The occurrence of this disturbing effect depends on whether a sufficiently high surface temperature has been reached at the end of the pulse. A convenient way of changing the time step size by altering the modulus  $(\Delta x_c^0)^2 / \Delta \theta^0$  is provided in the program.

The effect described does not occur in the cases of a trapezoidal or thermonuclear pulse shape, where the process is sufficiently smooth.

8. Burn Severity Correlation

Different ways of relating the temperature response of the irradiated cloth-skin system to the severity of a resulting burn have been dealt with in former studies, (3, 5). Among these, a correlation based on the concept of a critical base temperature and a constant skin enthalpy increase appeared most promising. It states that a burn of given severity is effected by a certain minimum value of that part of the skin enthalpy which lies above a critical temperature level, (see sketch below).



This criterion has been tested earlier in particular by comparing University of Rochester data on mild 2+ burns with the results of skin simulant experiments. Here the maximum of the critical enthalpy (i.e., the shaded area in the above plot) was taken to occur at the time at which the measured temperature closest to the skin simulant surface reached a maximum, (effected by a square wave of irradiation). Temperature distributions were plotted, extrapolated towards the skin simulant surface and their area above  $T_{crit}$  measured. A constant thermal energy increase of  $0.89 - 0.93 \text{ cal/cm}^2$  above a critical temperature of  $53^\circ\text{C}$  was found to agree with most of the University of Rochester data.

The same procedure can be applied to temperature distributions obtained from theoretical calculations. It is more practical, however, to include this evaluation in the computing program, as the entire temperature history is available to it and in particular because this provides a more precise way of finding that distribution which yields the maximum value in time of the critical enthalpy:

$$(hCp)_s \cdot \int_0^{x_s} (T - T_{crit}) (T_{(x_s, \theta)} - T_{crit}) dx_s = f(\theta) \quad (4.1)$$

(When a pulse of irradiation is applied, the maximum value need not be associated with the maximum skin surface temperature, as the temperatures in the interior of the skin simulant may still continue to rise while the irradiation intensity and the skin simulant surface temperature begin to decrease).

The computer program described in this report is set up to calculate by means of a Simpson-rule integration the maximum critical enthalpy attained at any time during the process. The quantities  $(hCp)_s$  and  $T_{crit}$  are to be prescribed as input parameters.

The temperature distribution in the skin depends strongly on the assumptions made for the heat and mass transfer coefficients, which can only be defined within a certain tolerance. Since the burn correlation integral represents only the top part of the area under a temperature profile, it should be kept in mind that its value is influenced even more by the choice

of these coefficients. Nevertheless, with this restriction, it appears useful to obtain in this direct way the information regarding the burn correlation that the theoretical solution is able to supply. Moreover, the facility can be used to find the maximum total heat content of the skin simulant if the critical temperature is given the value of the surrounding temperature.

### C. DISCUSSION OF RESULTS

Earlier studies (5) have shown that the theoretical solutions obtained for a system involving diathermanous cloth tend to agree better with experimental observations than those found for an opaque cloth layer. This is true for the case of dry cloth as well as for that of moist cloth, and may be explained by the direct admittance of part of the heat received, into the interior of the system. The purpose of extensive computer calculations devoted to the opaque cloth situation was fourfold:

First, the convergence of the numerical solution with refinement of the difference-net was tested. The results of these calculations are discussed in Chapter VI, B, 6.

Next, a number of computations was designed to show the influence of the transfer coefficient,  $U_0$ ,  $U_1$ ,  $K_0$ ,  $K_1$  and the water vapor diffusivity  $D^*$  on the theoretical response as well as its agreement with experimental results for constant irradiation levels  $I_0 = 0.5 - 3.96 \text{ cal/cm}^2\text{sec}$ ,  $30^\circ\text{C}$  and 80% relative humidity.

A further aim was to investigate the type of response obtained under time-variant irradiation of various pulse shapes and equal total energy, at maximum intensity levels  $I_{\text{omax}} = 0.3 - 1.0 \text{ cal/cm}^2\text{sec}$ ,  $30^\circ\text{C}$  and 80% relative humidity, using one set of transfer coefficients.

A last group of calculations was carried out in order to test the agreement between a number of experimental results from square-wave, short exposure irradiation and the theoretical solutions obtained with identical irradiation, temperature and relative humidity conditions, ( $I_{\text{omax}} = 1.0, 1.4 \text{ and } 2.6 \text{ cal/cm}^2\text{sec}$ ;  $19^\circ\text{C}$ ; 65% relative humidity). The transfer coefficients

and the diffusivity were varied in these tests. Furthermore, some theoretical results for the diathermanous cloth case in comparison with experimental curves are presented.

### 1. Numerical Values used in the Computations

The values of the parameters used are summarized below. A complete reference, in particular on the estimation of the transfer coefficients, is given in (5).

#### (a) Properties of the cloth:

$$\begin{aligned}\rho_o &= 1.57 \text{ gm/cm}^3 \text{ for cellulose} \\ \rho_c L_c &= 0.0273 \text{ gm/cm}^2 \text{ for } \phi \text{ oz. standard cotton sateen} \\ L_c &= 0.043 \text{ cm (measured)} \\ f &= 1 - (\rho_c/\rho_o) = 0.594 \\ C_c &= 0.34 \text{ cal/gm}^\circ\text{C} \\ k_c &= 1.62 \cdot 10^{-4} \text{ cal/cm sec}^\circ\text{C, based on } (L/k)_c = 266 \text{ cm}^2\text{sec}^\circ\text{C/cal} \\ D'' &= 0.105 \text{ } \mu\text{gm/cm sec mm Hg at an average temperature of } 50^\circ\text{C and} \\ &\quad \text{with a tortuosity factor of } g = 1/2.4 \text{ (see VI, B, 3)}\end{aligned}$$

#### (b) Properties of the skin simulant: see V, C, 1.

#### Transfer Coefficients:

The following estimates were used as a basis:

#### Surface heat transfer coefficient:

$$\begin{aligned}\text{A dimensionless value } U_o^0 &= 0.1 \text{ was used, corresponding to} \\ U_o &= 18.6 \cdot 10^{-3} \text{ cal/cm}^2\text{sec}^\circ\text{C}\end{aligned}$$

#### Air gap heat transfer coefficient:

$$U_1^0 = 3.0, \text{ corresponding to } U_1 = 3.76 \cdot 10^{-3} \text{ cal/cm}^2\text{sec}^\circ\text{C}$$

#### Surface moisture transfer coefficient:

$$K_o = 0.2 \mu\text{gm/cm}^2\text{sec mm Hg}$$

#### Air gap moisture transfer coefficient (effective):

$$K_1 = 14.4 \mu\text{gm/cm}^2\text{sec mm Hg}$$

The variations applied to the transfer coefficients are discussed in the following sections.

#### Heat of desorption:

$$\lambda = 650 \text{ cal/gm H}_2\text{O}$$

In all of the computations, the 6-slice model was used with a modulus  $M_A = 5$  and a skin/cloth property ratio group  $\tilde{R} = 5$ .

## 2. Constant Irradiation - Influence of Transfer Coefficients and Diffusivity; Comparison with Experiments

The estimates of the parameters  $U_0$ ,  $U_1$ ,  $K_0$ ,  $K_1$  and  $D^*$  have been established in (5). Considerable tolerance has to be allowed for these values, particularly regarding the effective water vapor diffusivity  $D^*$  and the mass transfer coefficients.  $D^*$  is subject to an uncertainty due to the tortuosity factor which may range between 1 and 0.2 or less. It also enters into the derivation of the mass transfer coefficient for the air gap. The theoretical results vary rather strongly with changes in the choice of all these parameters, especially at long exposure times.

In fact, once it has been shown that the experimental results can be reproduced closely by a calculation, the comparison between theoretical and experimental responses may be looked at as a method to find values of the coefficients rather than as a check on the validity of the analytic model.

The following discussion concerns calculations involving a surrounding temperature of 30°C and relative humidity of 80%.

Figure 2.10 shows the dimensionless skin simulant temperature response at simulated depths  $X_0^0 = 0.05$  and 0.15 as a function of dimensionless time. At an irradiation intensity  $I_0 = 0.83 \text{ cal/cm}^2\text{sec}$ , the transfer coefficients are varied through the range:

$$\begin{aligned} U_0^0 &= 0.1 \dots 0.025 & \text{or} & & U_0 &= (3.76 \dots 0.94) \cdot 10^{-4} \text{ cal/cm}^2\text{sec} \\ U_1^0 &= 5.0 \dots 10.0 & \text{or} & & U_1 &= (18.6 \dots 37.2) \cdot 10^{-4} \text{ cal/cm}^2\text{sec} \\ & & & & K_0 &= 0.2 \dots 0.05 \text{ } \mu\text{gm/cm}^2\text{mm Hg} \\ & & & & K_1 &= 14.4 \dots 3.6 \text{ } \mu\text{gm/cm}^2\text{mm Hg} \end{aligned}$$

The effective diffusion coefficient  $D^*$  is held at a constant value of  $D^* = 0.105 \text{ } \mu\text{gm/cm sec mm Hg}$  (except where indicated to be variable). It is seen that  $K_0$ ,  $K_1$  and  $U_1$  have the strongest influence, while the surface

heat transfer coefficient only affects the solution at longer exposure times.

Figures 2.11 and 2.12, based on Figure 2.10, present a comparison with the experimental response, determined also at  $I_0 = 0.83 \text{ cal/cm}^2\text{sec}$ . Two cases having different transfer coefficients are given. The experimental curves describe the temperature at simulated depths  $X_0^0 = 0.028, 0.038$  and  $0.122 \text{ cm}$  (thermocouple locations).

The theoretical curves referring to these same depth values have been obtained from cross-plots of the calculated data. It appears that a not too drastic alteration from the original estimates for the transfer coefficients (by factors  $1/2$  for  $U_1$  and  $1/4$  for  $U_0, K_0$ , and  $K_1$ ) leads to quite good agreement with the measured temperatures.

Figure 2.13, also at  $I_0 = 0.83 \text{ cal/cm}^2\text{sec}$ , shows the variation introduced when variable diffusivity values  $D''$ , based on equation (2.13), are used in the calculations instead of a fixed average value. This does not seem to improve the agreement in the above case; in other examples, however, which are discussed later (VI,C, 4) the refinement has indeed led to a better approximation, which means a different combination of transfer coefficients may be needed here for closer agreement.

In Figure 2.14 the influence of an increased value of  $U_1$  and decreased ones for  $U_0, K_0$  and  $K_1$  is shown again for an irradiation intensity  $I_0 = 0.5 \text{ cal/cm}^2\text{sec}$ .

Figures 2.15, 2.16, and 2.17 present a comparison with the experimental response at intensities  $0.5, 1.26$ , and  $3.96 \text{ cal/cm}^2\text{sec}$ . The irregular appearance of the experimental curves at  $I_0 = 1.26$  stems from a partly scorched cloth layer. The cases of  $I_0 = 0.5$  and  $1.26$  show rather good agreement, with the theoretical curves being slightly too steep at longer times. At  $I_0 = 3.96$  the position of the calculated curves is high from the beginning. It appears that in all of these cases the application of a variable diffusivity (according to equation 2.13), with transfer coefficients in the range indicated on the figures, would have yielded a considerably better reproduction of the experimental response.

A comparison between the temperature responses of the moist and dry, opaque cloth systems is drawn in Figures 1.11 (experimental) and 2.18

(theoretical). The two figures are not precisely analogous in that they refer to slightly different skin simulant depths ( $x_s = 0.028$  cm and to  $x_s^0 = 0.05$  @  $x_s = 0.014$  cm). Yet they show that the theoretical response for the larger intensities lacks the pronounced change in slope occurring in the experimental moist cloth curves prior to their intersection with the curve for the dry cloth. In the logarithmic plots, too, this discrepancy is displayed by the slopes of the theoretical curves which are too steep at longer times.

The role of moisture in the system contributes greatly to the heat transport towards the skin simulant, but only initially. Eventually, the pressure gradients in the cloth reverse their direction (which can be read from the numerical results), leaving conduction as the only mode of heat transmission into the interior of the system. An inspection of the above figures suggests that this effect is not simulated strongly enough by the theory. The reason may be sought in the neglect of bulk flow of water vapor, in our model, but it is also possible that refinement is needed for the treatment of completely dry parts of the cloth which so far involves the assumption of a partially linear pressure profile.

Deviations between theory and experiments as discussed above are less striking in the case of a isothermanous (moist or dry) cloth, for which an analogous comparison based on earlier studies (5) is given in Figures 1.12 and 2.19.

So far, the theoretical results have been judged by the response at small skin depths relatively close to each other (0.028 and 0.038 cm). At larger depths (0.122 cm) a deviation is common to most cases, which cannot be neglected. It may be accounted for by the fact that the value used exclusively for the skin/cloth property ratio  $\sqrt{(kCp)_s / (kCp)_c} = 5.0$  is the one based on the dry cloth system and need not hold exactly true for the moist cloth situation; this would distort the simulated skin depth scale. As yet the effect has not been tested.

The water vapor diffusivity  $D'$  has not been given alternate (constant) values in the calculations, since it affects the results mainly in the short-time range, while the major deviations of the calculated responses still occur at longer times.

The preceding discussions concern only the predominant parameters among those not known precisely. Their influences at least can be established by the use of the computing program. The effects of further variations, e.g., of the tortuosity factor occurring both in  $D''$  and  $K_1$ , of the cloth heat conductivity  $k_c$  and  $\tilde{R}$ , as well as the surrounding temperature and relative humidity can likewise be determined, requiring a large but not excessive amount of computer time. In order to define a narrower range for the first group of parameters ( $U_0$ ,  $U_1$ ,  $K_0$ ,  $K_1$ ,  $D''$ ) however, not only a considerable number of calculations would be needed but also a larger set of experiments repeated under each condition.

### 3. Time-Variant Irradiation - Influence of Pulse Shapes

A set of calculations has been carried out in order to observe qualitatively the response variation with irradiation pulses of different shapes. In order to provide some common basis for comparison, the areas of the pulses (i.e., the total irradiation energies) are kept the same within each of two groups. The first group is based on the total energy delivered by a thermonuclear pulse distribution with peak intensity  $I_{\text{omax}} = 0.5 \text{ cal/cm}^2\text{sec}$  and peak-time  $\theta_{\text{char}}^0 = 0.5$  until  $\theta^0 = 5.0$ ; this energy equals  $0.545 \text{ cal/cm}^2\text{sec}$  (its dimension stems from the use of a dimensionless time scale but absolute intensity). The second group uses a thermonuclear pulse with peak intensity  $I_{\text{omax}} = 1.0 \text{ cal/cm}^2\text{sec}$  as a basis, with an area of  $1.09 \text{ cal/cm}^2\text{sec}$  until  $\theta^0 = 5.0$ .

Square and trapezoidal waves at different irradiation intensity levels and the thermonuclear pulse are used as input forms. The latter, for convenience, shall be referred to as the "true pulse". The other conditions assumed and common to all of these calculations are: surrounding temperature  $30^\circ\text{C}$ , relative humidity 80%, and transfer coefficients and constant water vapor diffusivity as stated in VI, C, 1.

The results of the first group of runs are shown in Figure 2.20. The four cases presented are the true pulse with peak at  $0.5 \text{ cal/cm}^2\text{sec}$ , a square wave distribution with intensity level  $I_{\text{omax}} = 0.5 \text{ cal/cm}^2\text{sec}$ , a square and trapezoidal wave both with  $I_{\text{omax}} = 0.3 \text{ cal/cm}^2\text{sec}$ ; these distributions are indicated in the upper part of Figure 2.20. The lower part

of the graph shows the respective temperature responses of the skin simulant at simulated depths  $X_s^0 = 0.0167$  and  $0.15$ . In order to permit a comparison, the temperatures are given in reduced, but not dimensionless form, i.e., as value of  $T^0 \cdot I_{0max}$  ( $= \Delta T \cdot (k/L)_c$ ).

It is not surprising that the square wave with  $I_{0max} = 0.5 \text{ cal/cm}^2\text{sec}$  yields a higher temperature response than the true pulse of same intensity level. However, the latter response shows values still considerably lower than those produced by the square and trapezoidal waves at 60% of its peak intensity, ( $0.3 \text{ cal/cm}^2\text{sec}$ ) near the skin simulant surface as well as in its interior.

Figure 2.21 shows the results of the second group of calculations, comparing the true pulse function of maximum level  $1.0 \text{ cal/cm}^2\text{sec}$  with trapezoidal waves at  $I_{0max} = 1.0$  and  $0.6 \text{ cal/cm}^2\text{sec}$ , a square wave with  $I_{0max} = 0.6$  and  $0.4 \text{ cal/cm}^2\text{sec}$ , and the case of constant irradiation intensity  $1.0 \text{ cal/cm}^2\text{sec}$ . The temperature response  $T^0 \cdot I_{0max}$  is given for one depth value  $X_s^0 = 0.0167$ . As in the first group, the square and trapezoidal waves not only at  $0.6$  but even at  $0.4 \text{ cal/cm}^2\text{sec}$  lead to much higher skin simulant temperatures than the true pulse. This can be attributed to the fact that the latter irradiation distribution yields a faster rise of the cloth surface temperature and of the water vapor pressure near the cloth surface than square and trapezoidal waves at lower intensity levels, thus increasing the heat and moisture losses at the system surface. Furthermore, the reversal of the pressure gradient in the cloth takes place at an earlier time with the true pulse so that during the section of decaying irradiation intensity the conductive heat transfer to the skin simulant is counteracted by the moisture transport directed outward.

In none of the cases described do the temperature gradients in cloth and skin reverse their direction, so that within the calculated time range the decay of temperatures in the skin simulant is only due to the mass transfer from its surface to the cloth. Naturally, the temperatures in its interior keep rising for some time while the surface temperature has begun to drop.

These conditions can be read clearly from the numerical results; they may only be stated here in passing since a complete representation of the

results would require too much space. Reference is made though to the logarithmic plots of the skin simulant temperature responses of all the cases, given for simulated depths up to  $X_s^0 = 0.95$  in Figures 3.8 through 3.16, Appendix F.

#### 4. Time-Variant Irradiation - Comparison with Experiments

It is clear from previous discussions that a rather wide range of experiments is required to serve as a yardstick, if the capacity of the mathematical analysis to model our physical system is to be examined. The number of physical coefficients which are subject to an estimation only underlines this necessity. In the effort to come to a closer agreement between theoretical predictions and experimental evidence, the judgement of how well the model reproduces the situation and the "improvement" of those parameters are intertwined, thus making the judgment somewhat relative.

The examples for a theoretical approximation of the measured response described before have left some uncertainty regarding which of the five most important parameters are to be altered and to what degree. They applied to a constant irradiation input, i.e., to cases in which the entire process develops in one direction. A more rigid test for the model may be formed by a pulse input, where the direction of events ultimately is reversed, even to the extent that part of the cloth layer will dry out first and later attain moisture again.

Some calculations serving such a test have been executed, with conditions matching those of experiments. All of them were done with a surrounding temperature of 19°C, and 65% relative humidity.

The first group of these computations applied to a square wave irradiation of intensity level 1.0 cal/cm<sup>2</sup>sec and 4 seconds exposure time ( $\theta_{char}^0 = 1.62$ ). In the calculations presented by Figures 2.22 through 2.24, constant values  $D'' = 0.105$   $\mu\text{gm/cm sec mm Hg}$  and  $U_0^0 = 0.1$  ( $U_0 = 3.76 \cdot 10^{-4}$  cal/cm<sup>2</sup>sec°C) are used, while the other transfer coefficients are varied in the ranges:

$$U_1^0 = 2.5 - 10.0 \quad \text{or} \quad U_1 = (9.3 - 37.2) \cdot 10^{-3} \text{ cal/cm}^2\text{sec}^\circ\text{C}$$

$$K_0 = 0.05 - 0.2 \quad \mu\text{gm/cm}^2\text{sec mm Hg}$$

$$K_1' = 3.6 - 14.4 \quad \mu\text{gm/cm}^2\text{sec mm Hg}$$

(The combinations are indicated on the plots).

Neither the positions nor the shapes of the curves referring to 3 simulated skin depths appear quite satisfactory. Additional trial runs in the above range of parameter values (not presented here) have not yielded any better agreement. It is to be noted that the cloth is recorded by the program to become dry throughout after  $\theta^0 = 1.6$  ( $\approx 4$  seconds, i.e., at the end of the pulse). In the cases quoted first, half of the cloth is dry already at  $\theta^0 \approx 0.95$ . Obviously the test is hampered by the fact that 65% relative humidity may be low enough to produce a situation where the moist-cloth theory finally applies only to a very small section of the cloth, namely just the last slice out of six slices, while the dry part is manipulated according to the procedure described in V, B, 3.

It is suspected that the water vapor diffusivity must not be excluded from our parameter trial procedure. In fact, one calculation carried out with variable diffusivity (according to equation 2.13) and the "original" values for the transfer coefficients (VI, C, 1) yields much better agreement between theory and experiment, if not beyond the maximum of the temperature functions, (Figure 2.25). It seems that further improvement can be achieved by not too severe variations of the heat or mass transfer coefficients from their original estimated values, while using variable diffusivity.

Considering the required expense of machine time however, the effort had to be limited to a few trials.

The situation looks more favorable in a second pair of calculations involving a square wave of intensity  $I_{\text{max}} = 1.4 \text{ cal/cm}^2\text{sec}$  and two seconds exposure time.

In the case recorded in Figure 2.26, a constant diffusivity  $D^0 = 0.105 \text{ } \mu\text{gm/cm sec mm Hg}$  is used, while Figure 2.27 depicts the response when  $D^0$  is variable. For  $U_0, U_1, K_0, K_1$  the original estimates are used. Again it appears that the assumption of a fixed average diffusivity should not be made. As before, the cloth dries out rapidly while irradiated, until only two out of six slices are left moist (contrasted with one in the previous example, which may explain the discrepancy in agreement with the experiment there). In the subsequent relaxation period, the cloth becomes moist throughout, nourished from the condensed moisture on the skin simulant surface.

Thus considering the fact that the computation has to treat the system as a composite dry-moist system during almost the entire period, the results mentioned last could be considered remarkable. While the reversal of moisture flow can be detected readily from the numerical results, the temperature gradient in the cloth and skin simulant - except in the outermost half-slice of the cloth - does not change its direction, so that the only outward heat flow in the system interior during the relaxation period is constituted by the action of the moisture transport. This observation holds true for all pulse responses computed so far.

#### 5. Remark on the Burn Severity Correlation

In the calculations discussed above, the integral (4.1) designed to serve as a basis for the correlation of burn severity has been evaluated. As expected, its maximum occurs at some time after the surface temperature of the skin simulant is highest. The results also show that the value of the integral varies more than do the temperatures obtained when transfer coefficients etc. are changed. For example, while the skin simulant temperatures at and near the surface vary by about 9% between the curves of Figures 2.22 and 2.24, the integral changes its value by about 24%. This indicates that a fairly high reliability of the calculated temperature profiles is required to define the critical skin enthalpy closely enough, if it is to be applied to a correlation with experimental burn data.

### VII. SUMMARY AND CONCLUSIONS

The temperature response of a system composed of a skin simulant covered by dry or moist cloth and exposed to radiative heating has been studied experimentally and theoretically.

The mathematical analysis adequately describes the behavior of the dry-cloth-skin simulant system. The response to constant or time-variant irradiation can be constructed on the basis of general solutions both for opaque and diathermanous cloth.

The theoretical model for the moist cloth-skin simulant system is based on molecular diffusion of water vapor as the only mode of moisture transfer, thus neglecting bulk flow of water vapor and other simplifying

assumptions. It is designed for an opaque cloth layer but could be altered to apply to diathermanous cloth as well by a method analogous to that developed for the dry cloth case. The theoretical formulation is not general but requires new computer calculations for any set of specific conditions. Either constant or time-variant irradiation intensities are acceptable as boundary conditions; the latter may be a square wave, trapezoidal wave or a thermonuclear explosion pulse distribution. It also takes into account the complete drying of part of the cloth layer which can always be expected in reality.

This model yields solutions which agree fairly well with experimental results both for constant and time-varying irradiation. Uncertainties are inherent mainly in the values of heat and mass transfer coefficients and the water vapor diffusivity. Both further experiments and calculations extending over a range of these parameters could serve to determine better estimates for their values and thus improve the capability of the computing system for predicting the system behavior more accurately.

With the above reservations the variation in the temperature responses to irradiation of different distribution forms can be established clearly. The model can serve as a tool for inspection of the influences caused not only by the transfer coefficients, but by other conditions such as the surrounding temperature, relative humidity and properties of the cloth. The numerical results permit the observation of phenomena which cannot be detected experimentally, such as the direction and rate of moisture flow and the process of drying out of the cloth.

The solution includes a measure for the "critical enthalpy" of the cloth, which can be related to the severity of burns. This criterion is most sensitive to slight variations of the theoretical temperature response and deserves further testing.

The study of the influences on the heat transfer by chemical reactions in the irradiated cloth, by the structure of the fabric and moisture-retaining additives still are open paths for further research into the protection from burns.

## APPENDIX A

### NOMENCLATURE

|                  |                                                                                                                                            |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| $\bar{A}$        | Coefficient in partial differential equation                                                                                               |
| $\bar{B}$        | Coefficient in partial differential equation                                                                                               |
| $C$              | Mass heat capacity, cal/ $\mu\text{gm}^\circ\text{C}$                                                                                      |
| $\bar{C}$        | Coefficient in partial differential equation                                                                                               |
| $D$              | Diffusion coefficient = $D_p$ gm mol/cm sec                                                                                                |
| $D'$             | Average diffusion coefficient = $D/(1-\gamma_{av})$ gm mol/cm sec                                                                          |
| $D''$            | Corrected mass diffusion coefficient through cloth = $gD'\bar{M}/w$<br>$\mu\text{gm/cm sec mm Hg}$                                         |
| $\mathcal{D}$    | Diffusivity, $\text{cm}^2/\text{sec}$                                                                                                      |
| $\bar{D}$        | Coefficient in partial differential equation                                                                                               |
| $f$              | Volume fraction of voids in cloth, dimensionless                                                                                           |
| $g$              | Tortuosity factor for the diffusion through cloth                                                                                          |
| $I$              | Intensity of incident radiation, cal/ $\text{cm}^2\text{sec}$                                                                              |
| $I_0$            | Intensity of unreflected radiation, cal/ $\text{cm}^2\text{sec}$ ; constant, unless specified<br>as time-variant                           |
| $I_{\text{max}}$ | Characteristic intensity level of unreflected radiation, cal/ $\text{cm}^2\text{sec}$ ;<br>(used whenever $I_0$ specified as time-variant) |
| $I_x$            | Intensity of radiation at depth $x$ , cal/ $\text{cm}^2\text{sec}$                                                                         |
| $k$              | Thermal conductivity, cal/ca sec $^\circ\text{C}$                                                                                          |
| $K$              | Mass (moisture) transfer coefficients, $\mu\text{gm/cm}^2\text{sec}^\circ\text{C}$                                                         |
| $L$              | Thickness, cm                                                                                                                              |
| $M$              | Moisture content of cloth, wt. $\text{H}_2\text{O}/100$ wt. dry cloth                                                                      |
| $\bar{M}$        | Molecular weight                                                                                                                           |
| $M_A$            | Modulus                                                                                                                                    |

|                |                                                                                |
|----------------|--------------------------------------------------------------------------------|
| p              | Partial pressure, mm Hg                                                        |
| P <sub>0</sub> | Base pressure used in connection with dimensionless transformation, mm Hg      |
| p <sup>0</sup> | Dimensionless partial pressure                                                 |
| R              | Universal gas constant, cm <sup>3</sup> mm Hg/g mol <sup>0</sup> K             |
| $\tilde{R}$    | Property ratio = $\Delta X_C^0 / \Delta X_S^0 = \sqrt{(kCp)_S / (kCp)_C}$      |
| t              | Time, sec                                                                      |
| T              | Temperature, <sup>0</sup> C except when specified as <sup>0</sup> K            |
| T <sub>0</sub> | Base temperature, <sup>0</sup> C                                               |
| u              | Function                                                                       |
| U              | Overall heat transfer coefficient, cal/cm <sup>2</sup> sec <sup>0</sup> C      |
| w <sub>j</sub> | Right hand sides of tridiagonal equation system for finite difference solution |
| x              | Distance or depth, cm                                                          |
| x <sup>0</sup> | Dimensionless depth                                                            |
| y              | Mole fraction, dimensionless                                                   |

Greek:

|            |                                                                                           |
|------------|-------------------------------------------------------------------------------------------|
| $\alpha_c$ | Thermal diffusivity of cloth                                                              |
| $\beta_j$  | Left hand side coefficients of tridiagonal equation system for finite difference solution |
| $\gamma$   | Extinction coefficient, cm <sup>-1</sup>                                                  |
| $\Delta$   | Finite increment                                                                          |
| $\phi_j$   | Right hand sides of tridiagonal equation system for finite difference solution            |
| $\theta$   | Exposure or irradiation time, sec                                                         |
| $\lambda$  | Heat of desorption, cal/ $\mu$ gm (numerically negative)                                  |
| w          | Total pressure, mm Hg                                                                     |

$u_j$  Left hand side coefficients of bidiagonal equation system for finite difference solution  
 $\rho$  Mass density,  $\mu\text{gm}/\text{cm}^3$   
 $\rho_0$  Mass density of cellulose or solid,  $\text{gm}/\text{cm}^3$   
 $\tilde{\rho}$  Molal density,  $\text{gm mol}/\text{cm}^3$   
 $\sum$  Summation  
 $\tau$  Transmittance  
 $\varphi$  Function

Subscripts:

$c$  Cloth  
 char Characteristic abscissa in irradiation pulse  
 cond Moisture condensation  
 crit Critical value (temperature)  
 er Characteristic abscissa in trapezoidal irradiation pulse  
 evap Moisture evaporation  
 $i$  Air gap between cloth and skin simulant except when used to denote  $i$  components  
 $j$  Depth planes  
 $n$  Time increments  
 $o$  Cloth surface unless specified otherwise  
 $s$  Skin simulant  
 surr Surroundings  
 $A, B, \dots$  Depth planes

first subscript : space

second subscript : time

Superscripts:

o Dimensionless groups

## APPENDIX B

### METHOD OF SOLUTION - DRY CLOTH OVER SKIN SIMULANT SYSTEM

#### A. OPAQUE CLOTH

With the dimensional transformations (1.8) introduced in the main section and with the finite-difference notations:

$$\left. \frac{\partial^2 T^0}{\partial X_c^2} \right|_{\substack{X_c^0 = j \cdot \Delta X_c^0 \\ \theta^0 = n \Delta \theta^0}} \approx \frac{T_{j-1,n}^0 - 2T_{j,n}^0 + T_{j+1,n}^0}{(\Delta X_c^0)^2} = \frac{\Delta^2 T^0}{(\Delta X_c^0)^2}$$

$$\left. \frac{\partial T^0}{\partial \theta^0} \right|_{\substack{X_c^0 = j \cdot \Delta X_c^0 \\ \theta^0 = n \Delta \theta^0}} \approx \frac{T_{j,n+1}^0 - T_{j,n}^0}{\Delta \theta^0}$$

the problem of the opaque-cloth-skin system (equations 1.1 - 1.3) can be stated in dimensionless terms as follows:

#### 1. Basic Equations:

(a) For the cloth layer:

$$\frac{\Delta T^0}{\Delta \theta_c^0} = \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} \quad (1.1)'$$

(b) For the skin simulant:

$$\frac{\Delta T^0}{\Delta \theta_s^0} = \frac{\Delta^2 T^0}{(\Delta X_s^0)^2} \quad (1.3)'$$

where  $\Delta \theta_c^0 = \Delta \theta_s^0 = \Delta \theta^0$  if the modulus  $(\Delta X^0)^2 / \Delta \theta^0$  is taken to be the same in both the cloth and skin simulant, which implies that the ratio of space intervals becomes:

$$\frac{\Delta x_c^0}{\Delta x_s^0} = \sqrt{\frac{(kCp)_s}{(kCp)_c}} = R \quad (1.9)$$

## 2. Boundary Conditions:

(a) At the outer surface of the cloth:

$$\left. \frac{\Delta T^0}{\Delta x_c^0} \right|_{x_c^0=0} = - \frac{(1/U_0^0) - (T_{x_s^0=0}^0 - T_{surr}^0)}{(1/U_0^0)} \quad (1.4)'$$

(b) At the inner surface of the cloth and the skin surface:

$$-\left. \frac{\Delta T^0}{\Delta x_c^0} \right|_{x_c^0=1} = \frac{T_{x_c^0=1}^0 - T_{x_s^0=0}^0}{(1/U_1)} = -\left. \frac{\Delta T^0}{\Delta x_s^0} \right|_{x_s^0=0} \quad (1.5)'$$

## 3. Numerical Solution - Modified Schmidt Technique

Cloth and skin simulant are divided into slices of width  $\Delta x_c^0$  and  $\Delta x_s^0$ , respectively. The reference planes for temperature are located at the center of the slices and also half a slice beyond the surfaces of the cloth and skin simulant (see Figure 1.2). This convention is known to produce a better approximation to the true solution than taking the surfaces as reference planes (14, 19, 20). A scheme having two cloth slices is used below for demonstration.

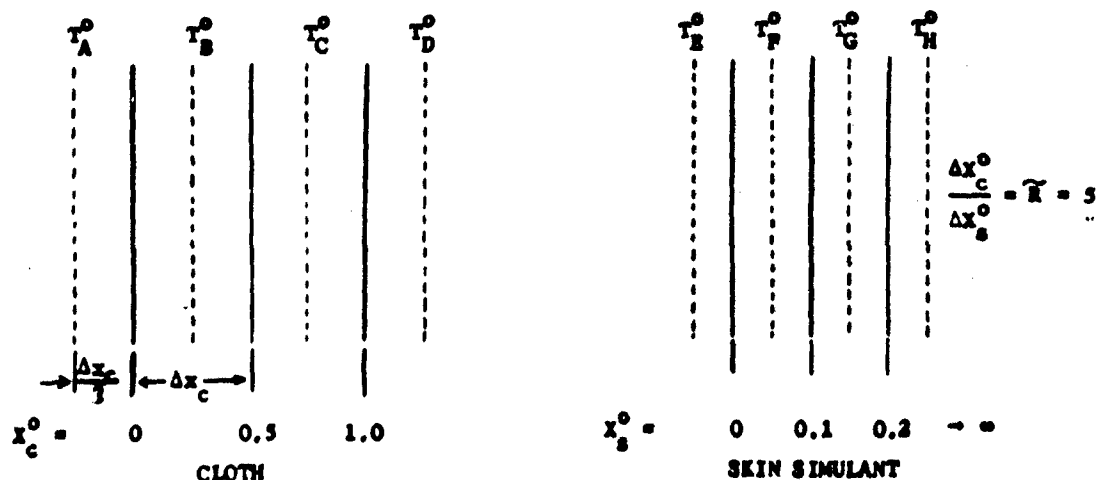


Figure 1.2

The calculation of a temperature distribution starts with the temperature value at plane A, for which the boundary condition (1.4)' can be written as:

$$T_{A,n+1} = \frac{(1/U_o^0) - T_{B,n}^0}{(1/U_o^0) + (\Delta x_c^0/2)} \cdot \Delta x_c^0 + T_{B,n}^0 \quad (n \text{ initially zero}) \quad (1.4)''$$

where  $(T_A^0 + T_B^0)/2 = T_{x_c=0}^0$  and  $T_{\text{surr}}^0 = 0$ . This relation is illustrated by Figure 1.3.

Next, the temperature values inside the cloth are computed according to equation (1)', which may be written as:

$$(T_{C,n}^0 - T_{B,n}^0) - (T_{B,n}^0 - T_{A,n}^0) = \frac{(\Delta x_c^0)^2}{\Delta \theta^0} \cdot (T_{B,n+1}^0 - T_{B,n}^0)$$

This relation can be simplified considerably if the modulus  $(\Delta x_c^0)/\Delta \theta^0$  is taken to be 2, as proposed by Schmidt:

$$T_{B,n+1}^0 = \frac{T_{A,n}^0 + T_{C,n}^0}{2}$$

or generally,

$$T_{j,n+1}^0 = \frac{T_{j-1,n}^0 + T_{j+1,n}^0}{2}$$

where j may denote any slice within the cloth. In particular, this formulation allows for a graphical interpretation of the process, (Figure 1.3).

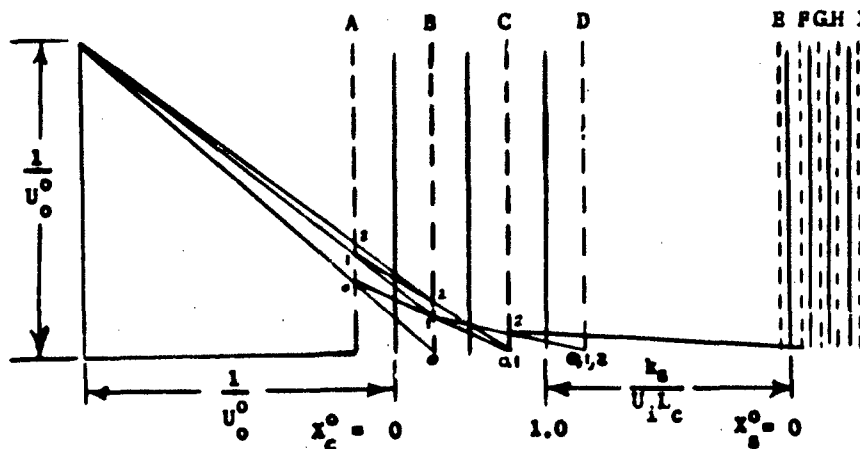


Figure 1.3

At the planes above the inner cloth surface and the skin surface (D and E for the 2-slice model) the temperatures at time  $n+1$  are obtained by means of the boundary condition (1.5)', which in reordered form yields:

$$T_{D,n+1}^0 = \frac{(T_{C,n}^0 - T_{F,n}^0) \frac{1}{U_1^0} + \frac{\Delta x_a^0 - \Delta x_c^0}{2}}{\frac{1}{U_1^0} + \frac{\Delta x_a^0 + \Delta x_c^0}{2}} + T_{F,n}^0$$

and similarly

(1.5)''

$$T_{E,n+1}^0 = \frac{(T_{C,n}^0 - T_{F,n}^0) \frac{\Delta x_s^0}{2}}{\frac{1}{U_1^0} + \frac{\Delta x_c^0}{2} + \frac{\Delta x_s^0}{2}} + T_{F,n}^0$$

These relations can also be verified graphically if the planes  $x_c^0 = 1$  and  $x_s^0 = 0$  are separated by a distance  $1/U_1^0$  (Figure 1.4); the temperature distribution throughout the system can then be drawn continuously.

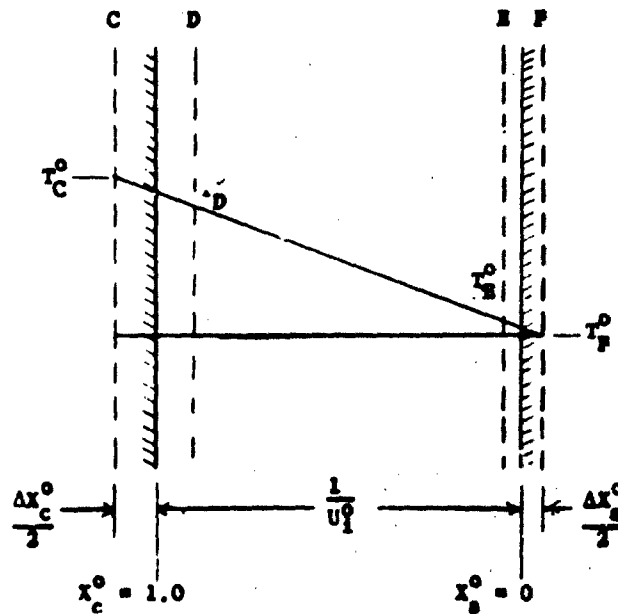


Figure 1.4

The conduction of heat into the interior of the skin is governed by equation (1.3)'. Using the modulus  $(\Delta x_s^0)^2 / \Delta \theta^0 = 2$  for the skin simulant, the same simple formulation is obtained as for the cloth equation:

$$T_{j,n+1}^0 = \frac{T_{j-1,n}^0 + T_{j+1,n}^0}{2} \quad (1.3)''$$

It is to be noted here that the method outlined above is a modification of the one originally proposed by Schmidt (19, 20). In applying the boundary condition (1.4), Schmidt's method properly states that at time 0,  $T_{x_c=0}^0 = T_{surr}^0 = 0$  at the outer cloth surface. However, in the next step, the calculation of  $T_{B,1}^0$ , all the space between the planes A and B is implicitly assumed to have the heat capacity of cloth. In the modified technique described, this error is partly compensated for by the assumption (in boundary condition 1.4'') of  $T_{B,0}^0 = T_{surr}^0 = 0$  at time 0 and the neglect of heat capacity in the half-slice from the surface to plane B, which leads to a closer approximation to the true solution.

#### 4. Stability and Accuracy

It is known for this particular type of computing algorithm that the solution is both stable and convergent with refinement of the intervals if the modulus is larger than or equal to 2, (18).

Comparative solutions using the 2- and 6-slice models and a modulus  $M = 2$  (in order to retain the simplicity of the computing scheme) have shown that the accuracy is improved only in the low-time range ( $\theta^0 \leq 1$ , corresponding approximately to  $\theta^0 \leq 2.5$  sec of real time) by the finer mesh. Therefore the calculations are best started using the 6-slice model and then continued with the 2-slice model.

Further details of the method are described in (4).

### **B. DIATHERMANOUS CLOTH**

#### 1. Basic Equations

The basic equations governing the case of diathermanous cloth can be transformed into the following dimensionless and finite-difference form:

(a) For the cloth layer:

$$\frac{\Delta T^0}{\Delta x_c^0} = \frac{\Delta^2 T^0}{(\Delta x_c^0)^2} - \frac{\Delta(e^{-\gamma L_c} x_c^0)}{\Delta x_c^0} \quad (1.2)'$$

(b) For the skin simulant:

(identical with the opaque cloth case)

$$\frac{\Delta T^0}{\Delta x_s^0} = \frac{\Delta^2 T^0}{(\Delta x_s^0)^2} \quad (1.3)'$$

again with  $\Delta \theta_c^0 = \Delta \theta_s^0 = \Delta \theta^0$  and  $\Delta x_c^0 / \Delta x_s^0 = \gamma$ . Thus the only new term introduced is a heat source  $-\frac{\Delta(e^{-\gamma L_c} x_c^0)}{\Delta x_c^0}$  at each cloth increment.

In using the finite-difference model, it is assumed that the amount of radiant energy absorbed in the center of each slice of the cloth is distributed according to the Beer-Lambert law. Inspection of this distribution shows this to be justified for cloth of high diathermancy, where the radiant energy decreases nearly linearly across the cloth. With a cloth of low diathermancy, however, the decay of intensity is much stronger near the exposed surface of the cloth. Therefore a better assumption is that the fraction of incident radiation absorbed by the first cloth slice is absorbed at the front surface (analogous to the opaque cloth case).

The boundary condition at the front surface thus appears different according to either assumption.

## 2. Boundary Condition at the Front Cloth Surface

(a) High diathermancy

$$\left. \frac{\Delta T^0}{\Delta x_c^0} \right|_{x_c^0=0} = U_0^0 (T_{x_c^0=0}^0 - T_{\text{surf}}^0) \quad (1.6a)'$$

(b) Low diathermancy

$$\left. \frac{\Delta T^0}{\Delta x_c^0} \right|_{x_c^0=0} = - \frac{\frac{1}{U_0^0} (\Delta e^{-\gamma L_c} x_c^0) - (T_{x_c^0=0}^0 - T_{\text{surf}}^0)}{\frac{1}{U_0^0}} \quad (1.6b)'$$

Also for low diathermancy, the radiation term disappears from the equation for the first increment:

$$\left. \frac{\Delta T^0}{\Delta \theta^0} \right|_{x_c^0=0} = \frac{\Delta^2 T^0}{(\Delta x_c^0)^2} \quad (1.2a)'$$

### 3. Boundary Conditions in the Air Gap

(a) Between the back surface of the cloth and the air gap:

$$\left. - \frac{\Delta T^0}{\Delta x_c^0} \right|_{x_c^0=1} = \frac{T_{x_c=1}^0 - T_{x_a=0}^0}{\frac{1}{U_1}} \quad (1.7a)'$$

(b) Between the air gap and the skin simulant:

$$\left. \frac{\Delta T^0}{\Delta x_s^0} \right|_{x_s^0=0} = - \frac{\frac{1}{U_1}(e^{-\gamma L_c}) - (T_{x_c=0}^0 - T_{x_c=1}^0)}{\frac{1}{U_1}} \quad (1.7b)'$$

The evaluation of this problem follows the same path as that of the opaque case, except that the independent variable  $\frac{\Delta(e^{-\gamma L_c x_c^0})}{\Delta x_c^0}$  has to be evaluated for each cloth increment.

As a consequence, the solution will be specific with respect to the value  $\gamma L_c$ .

### 4. Simplified General Solution for Diathermanous Cloth

Since the system is linear, however, it is in fact possible to arrive at a generalized solution eliminating the need to calculate anew for different diathermancies.

The response to any one intensity can be considered to be the weighted sum of a number of solutions, in each of which a unit of radiant energy is assumed to be absorbed in one particular cloth increment only. The weighting factors to be applied then are the fractions of the incident radiation that are associated with each increment by the given distribution, i.e.,  $\Delta(e^{-\gamma L_c x_c^0})_j$ .

Thus as many basic solutions are required as there are planes in

which absorption is assumed, (which needs not coincide with the number of conceptual slices in the cloth). In particular, a method was proposed in which absorption is taken to occur at three locations only, resulting in three basic curves or solutions:

Curve I represents the case of absorption of a unit of radiant energy at the exposed surface of the cloth, which is equivalent to the opaque cloth solution.

Curve II represents the case of unit absorption at  $X_c^0 = 0.75$ , and

Curve III represents that of absorption at the surface of the skin simulant. For this method, the equations in finite difference form become:

Curve I: identical with opaque cloth case.

Curve II:

1. For the cloth layer:

(a) Any increment other than that associated with  $X_c^0 = 0.75$

$$\frac{\Delta T^0}{\Delta \theta^0} = \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} \quad (1.2a)'$$

(b) The cloth increment whose centerline is at  $X_c^0 = 0.75$

$$\frac{\Delta T^0}{\Delta \theta^0} = \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} + \frac{1}{\Delta X_c^0} \quad (1.2b)'$$

2. For the skin simulant:

$$\frac{\Delta T^0}{\Delta \theta^0} = \frac{\Delta^2 T^0}{(\Delta X_s^0)^2} \quad (1.3)'$$

3. Boundary conditions at the front surface of the cloth:

$$\left. \frac{\Delta T^0}{\Delta X_c^0} \right|_{X_c^0=0} = U_0^0 (T_{X_c^0=0}^0 - T_{\text{sur}}^0) \quad (1.6a)'$$

4. Boundary conditions in the air gap:

$$-\left. \frac{\Delta T^0}{\Delta X_c^0} \right|_{X_c^0=1} = U_1^0 (T_{X_c^0=1}^0 - T_{X_s^0=0}^0) \quad (1.7a)'$$

$$= \left. \frac{\Delta T^0}{\Delta X_s^0} \right|_{X_s^0=0} \quad (1.7b)'$$

Curve III:

1. For all increments of the cloth layer:

$$\frac{\Delta T^0}{\Delta \theta^0} = \frac{\Delta^2 T^0}{(\Delta X_c^0)^2} \quad (1.2a)'$$

2. For the skin simulant:

$$\frac{\Delta T^0}{\Delta \theta^0} = \frac{\Delta^2 T^0}{(\Delta X_s^0)^2} \quad (1.3)'$$

3. Boundary condition at the front surface of the cloth:

$$\left. \frac{\Delta T^0}{\Delta X_c^0} \right|_{X_c^0=0} = U_0^0 (T_{X_c^0=0}^0 - T_{\text{sur}}^0) \quad (1.6a)'$$

4. Boundary condition: in the air gap:

(a) Between the back surface of the cloth and the air gap:

$$-\left. \frac{\Delta T^0}{\Delta X_c^0} \right|_{X_c^0=1} = U_1^0 (T_{X_c^0=1}^0 - T_{X_s^0=0}^0) \quad (1.7a)'$$

(b) Between the air gap and the surface of the skin simulant:

$$-\left. \frac{\Delta T^0}{\Delta X_s^0} \right|_{X_s^0=0} = \frac{\frac{1}{U_1^0} (T_{X_c^0=0}^0 - T_{X_c^0=1}^0)}{\frac{1}{U_1^0}} \quad (1.7b)'$$

The total response resulting from any particular diathermancy can be obtained from contributions of the three curves by applying to them a weighting factor according to the fractions of radiant energy absorbed at the three discrete locations:

$$T_{YL}^0 = \left[ e^{-\gamma L_c X_c^0} \right]_{X_c^0=0.5}^{X_c^0=1} \cdot T_I^0 + \left[ e^{-\gamma L_c X_c^0} \right]_{X_c^0=1.0}^{X_c^0=0.5} \cdot T_{II}^0 + \left[ e^{-\gamma L_c X_c^0} \right]_{X_c^0=\infty}^{X_c^0=1.0} \cdot T_{III}^0 \quad (1.9)$$

A solution in which radiant energy is assumed to be absorbed in each cloth slice (according to equation 2') can be expected to be more accurate than the scheme described above. Calculations of such a solution for the 6-slice model, however, have shown that the gain in accuracy is in fact small and would not justify the increase in computing effort over that required by the general three-curve solution method.

# APPENDIX C

## SOLUTION ALGORITHM - MOIST CLOTH - SKIN SIMULANT SYSTEM

In the following description the cloth is assumed to be conceptually divided into six slices of width  $\Delta x_c^0$  and the skin is assumed to have an infinite number of slices  $\Delta x_s^0$  (Figure 2.1).

The  $T^0$ - and  $P^0$  values associated with these are taken at their mid-points. Points 1, 8 and 9 are located above the cloth and skin surfaces at distances  $\Delta x_c^0/2$  and  $\Delta x_s^0/2$ , respectively.

With the derivatives written out and the unknowns separated to the left hand sides, the equations governing the four phases of the alternating solution scheme are:

$$\begin{aligned} \bar{A} T_{j-1,n+1}^0 - (2\bar{A} + M_A) T_{j,n+1}^0 + \bar{A} T_{j+1,n+1}^0 = \\ - \bar{B} (P_{j-1,n}^0 - 2P_{j,n}^0 + P_{j+1,n}^0) - M_A \cdot T_{j,n}^0 \end{aligned} \quad (2.14)$$

$$\begin{aligned} \bar{D} P_{j-1,n+1}^0 - (2\bar{D} + M_A) P_{j,n+1}^0 + \bar{D} P_{j+1,n+1}^0 = \\ - \bar{C} (T_{j-1,n+1}^0 - 2T_{j,n+1}^0 + T_{j+1,n+1}^0) - M_A \cdot P_{j,n}^0 \end{aligned} \quad (2.15)$$

$$\begin{aligned} \bar{D} P_{j-1,n+2}^0 - (2\bar{D} + M_A) P_{j,n+2}^0 + \bar{D} P_{j+1,n+2}^0 = \\ - \bar{C} (T_{j-1,n+1}^0 - 2T_{j,n+1}^0 + T_{j+1,n+1}^0) - M_A \cdot P_{j,n+1}^0 \end{aligned} \quad (2.16)$$

$$\begin{aligned} \bar{A} T_{j-1,n+2}^0 - (2\bar{A} + M_A) T_{j,n+2}^0 + \bar{A} T_{j+1,n+2}^0 = \\ - \bar{B} (P_{j-1,n+2}^0 - 2P_{j,n+2}^0 + P_{j+1,n+2}^0) - M_A \cdot T_{j,n+1}^0 \end{aligned} \quad (2.17)$$

$$\bar{A} = 1$$

Both skin and cloth are treated in the same calculating system, such that equations (2.15) and (2.16) are only evaluated for points  $j$  in the cloth. Whenever in equations (2.14) and 2.17)  $j$  denotes a point in the skin, the pressure term is dropped and the space interval  $\Delta x_c^0$  replaced by  $\Delta x_s^0$ .

As an example, the first phase of the alternating solution scheme shall be described. Equation 2.14 is applied to the entire set of points in the cloth, which is verified identically by lines 2 ... 6 of the system Figure 2.5. At the cloth and skin surfaces, the boundary conditions are to be taken into account. Thus as  $j = 1$ , the unknown  $T_{1,n+1}^0$  is temporarily substituted by means of  $T_{2,n+1}^0$  and the boundary condition 2.7"

$$1 - U_0^0 (T_{x_c^0=0}^0) = \frac{\Delta T^0}{\Delta x_c^0} \bigg|_{x_c^0=0}$$

equivalent to

$$T_{1,n+1}^0 = \frac{2\Delta x_c^0}{2 + U_0^0 \Delta x_c^0} + \frac{U_0^0 \Delta x_c^0 - 2}{U_0^0 \Delta x_c^0 + 2} \cdot T_{2,n+1}^0 \quad (2.7a)''$$

which modifies both the left and right hand sides of the first equation (line 0 - line 1 in Figure 2.5).

The temperatures  $T_{7,n+1}^0 \dots T_{10,n+1}^0$  near the surfaces confining the air gap are related through boundary condition (2.9)''', which can be written as,

$$T_{8,n+1}^0 = \frac{(T_{7,n+1}^0 - T_{10,n+1}^0) \left[ \frac{1}{U_1^0} + \frac{\Delta x_s^0 - \Delta x_c^0}{2} \right] + \frac{\Delta x_c^0 \Delta x_s^0}{2} K_1 \left[ \frac{P_7^0 + P_8^0}{2} - P_9^0 \right]}{\frac{1}{U_1^0} + \frac{\Delta x_s^0 + \Delta x_c^0}{2}} \quad (2.9a)'''$$

as well as

$$T_{9,n+1}^0 = \frac{(T_{7,n+1}^0 - T_{10,n+1}^0) \Delta x_s^0 + \left[ \frac{\Delta x_c^0 \Delta x_s^0}{2} + \frac{\Delta x_s^0}{U_1^0} \right] K_1 \left[ \frac{P_7^0 + P_8^0}{2} + P_9^0 \right]}{\frac{1}{U_1^0} + \frac{\Delta x_s^0 + \Delta x_c^0}{2}} + T_{10,n+1}^0 \quad (2.9b)'''$$

After reordering, these relations match the general scheme applied in the

system (Figure 2.5) and from lines 7 and 8.

Last, equation (2.4a)<sup>m</sup> is applied to all of the points in the skin, which is considered semi-infinite. At the start, i.e., at time zero, the equations are written down for a small, arbitrary number of points in the skin, since initially  $T_{\text{skin}}^c = 0$ . In this way, a tridiagonal system of equations is formed. The expressions for all of the coefficients appearing in the middle diagonal and for the right hand sides are listed in Figure 2.5.

Next, the system is solved by successive elimination. Dividing the first equation by a factor  $v_1 = \beta_1$  and adding to the second equation, one obtains:

$$\underbrace{-(\beta_2 - (1/v_1))}_{v_2} \cdot T_{3,n+1}^0 + T_{4,n+1}^0 = -((w_1/v_1) + \varphi_2) = -w_2$$

Dividing this by  $v_2 = (\beta_2 - 1/v_1)$  and adding to the third yields,

$$\underbrace{-(\beta_3 - 1/v_2)}_{v_3} \cdot T_{4,n+1}^0 + T_{5,n+1}^0 = -((w_2/v_2) + \varphi_3) = -w_3$$

etc.

This elimination scheme, carried throughout the system, results in a bidiagonal set of equations (Figure 2.6), the coefficients and right hand sides of which follow the relations:

$$v_1 = \beta_1$$

$$v_i = \beta_{i-1}/v_{i-1}, \quad i = 2 \dots 6, 9 \dots$$

$$w_1 = \varphi_1$$

$$w_i = w_{i-1}/v_{i-1}, \quad i = 2 \dots 6, 9 \dots$$

Equations (2.9a)<sup>m</sup> and (2.9b)<sup>m</sup> are brought to match the bidiagonal pattern

by means of a linear combination of the 6th, 7th, and 8th lines, resulting in

$$\begin{aligned}
 v_7 &= \frac{(v_6 Q - 1)(1 - S) + (1 - Q)}{v_6 S(1 - Q)} \\
 v_8 &= \frac{v_6 v_7 S - 1}{v_6 v_7 (S - 1)} \\
 w_7 &= \frac{w_6(Q - S) + v_6 [(1 - S)QH - (1 - Q)SR]}{v_6 S(1 - Q)} \\
 w_8 &= \frac{w_6 + v_6 SR \left[ \frac{P_7^0 + P_8^0}{2} - P_9^0 \right] + w_7/v_7}{v_6 (S - 1)}
 \end{aligned}$$

where

$$\begin{aligned}
 Q &= \frac{(2/U_1^0) + \Delta X_s^0 + \Delta X_c^0}{(2/U_1^0) + \Delta X_s^0 - \Delta X_c^0} \\
 S &= \frac{(1/U_1^0) + (\Delta X_c^0 + \Delta X_s^0)/2}{\Delta X_s^0} \\
 QH &= \frac{\Delta X_c^0 \wedge X_s^0}{(2/U_1^0) + \Delta X_s^0 - \Delta X_c^0} \cdot K_1^0 \\
 SR &= (\Delta X_c^0/2 + 1/U_1^0) K_1^0
 \end{aligned}$$

The bidiagonal system is solved by backward substitution, yielding the future time temperature values  $T_{j,n+1}^0$ . Starting with the last equation, in the interior of the skin, we get

$$\begin{aligned}
 T_{M+1,n+1}^0 &= T_{M+2,n+1}^0 + w_M/v_M \\
 T_{M,n+1}^0 &= T_{M+1,n+1}^0 + w_{M-1}/v_{M-1} \\
 &\vdots \\
 T_{j,n+1}^0 &= T_{j+1,n+1}^0 + w_{j-1}/v_{j-1}
 \end{aligned}$$

until  $j = 2$ .  $T_{j,n+1}^0$  results from the boundary condition (2.7)". At the point  $M+2$  in the skin simulant, the temperature is zero. After each time step, the number of points  $M$  and thus the size of the equation system is increased by one, accounting for the propagation of the temperature profile into the skin simulant.

The three remaining phases of the alternating scheme (2.12), namely those based on equations (2.15 - 2.17), in principle follow the same path as outlined above. In treating the implicit evaluation of future time pressures, the elimination of  $P_{1,n+1}^0$  is done by means of the boundary condition (2.8)". The boundary condition (2.9)" for the pressure in the air gap enters into the 7th equation of the tridiagonal system, which has a constant size corresponding to the number of cloth slices.

# APPENDIX D

## MASS AND HEAT BALANCE - MOIST CLOTH - SKIN SIMULANT SYSTEM

A means of testing the internal consistency of the computation is provided by the indication of the (cumulative) amounts of moisture lost due to evaporation at the front surface of the cloth and condensation at the skin simulant surface.

A mass balance can be set up as follows:

$$M_{\text{evaporation}} + M_{\text{condensation}} + M_{\text{cloth, final}} = M_{\text{cloth, initial}}$$

From equation (2.6)\* follows:

$$M_{\text{evap}} = K_o \Delta \theta \sum_n \left[ \frac{P_1 + P_2}{2} \right]$$

The sum of the surface pressure values, taken over all n past time steps, is recorded as

$$\text{"SURF LOSS"} = \sum_n \left[ \frac{P_1^o + P_2^o}{2} \right]$$

with  $\Delta \theta = \Delta \theta^o \cdot (L^2 \rho C / k)_c \cdot n$ ;  $M_A = (\Delta x_c^o)^2 / \Delta \theta^o$ , the surface loss of moisture is

$$M_{\text{evap}} = P_o K_o \cdot \frac{M_A}{(\Delta x_c^o)^2} \cdot (L^2 \rho C / k)_c \cdot (\text{SURF LOSS}) (\mu g H_2O / cm^2) \quad (5.1a)$$

The moisture flux through the inner cloth surface is given by:

$$\text{moisture flux}_{(\text{air gap})} = K_1 \cdot \left[ \frac{P_7 + P_8}{2} - P_9 \right] \quad (5.2)$$

(taking the 6-slice model as an example)

The program evaluates

$$\text{"COND"} = \sum \left[ \frac{P_7^o + P_8^o}{2} - P_9^o \right]$$

Thus the total amount of moisture condensed is given by

$$M_{\text{cond}} = P_o K_i \cdot \frac{M_A}{(\Delta x_c)^2} \cdot (L^2 \rho C / k_c) \cdot (\text{COND}) \quad (\mu\text{gmH}_2\text{O}/\text{cm}^2) \quad (5.2a)$$

The remaining moisture content of the cloth is constructed as

$$M_{\text{cloth, final}} = \rho_c L_c \sum_{i=1}^I M(T_i, P_i) \quad (\mu\text{gmH}_2\text{O}/\text{cm}^2) \quad (5.3)$$

(i counting the number of cloth slices)

A heat balance may also be established; however, the integrals required (over the surface temperature gradients and over the enthalpy fluxes due to moisture evaporation) are not evaluated by the program and would have to be calculated from the printed results.

APPENDIX B  
COMPUTER PROGRAM DESCRIPTION

A. FUNCTION OF MAIN- AND SUBPROGRAMS

The MAIN-program and subroutines are written in FORTRAN - and FAP-language and can be run at any IBM 709 - installation (16K or 32K) under FMS control. The explicit subroutines are:

SUBP  
DOUBIN  
DTAD, TAB  
PULSE  
IARA  
CHANGE  
F2PM

All other subroutines are FMS 709 library programs.

1. MAIN Program

The flow of control is shown in Figure 2.7.

Any number of data sets, can be handled in one run.

First, the equilibrium data for cloth are read in, to be used for all data sets.

Next, a set of data is read. The calculation starts with the determination of the relative irradiation intensity followed by phase (a) of the alternating scheme (2.12), which establishes the distribution of temperatures. Based on the new temperature values, the variable coefficients C and D of equation (2.5)' are found by interpolation of the tabulated data.

Hereafter, phase (b) is solved for the pressure profile, assuming that the boundary condition (2.6)' is valid, which implies condensation of moisture on the skin surface. A test for this condition follows. If it shows no condensation, the pressure calculation is repeated assuming

this subroutine determines the relative irradiation intensity  $I_o(\theta^0)/I_{o\max}$  and records it.

#### 5. PARA

The input parameters pertaining to irradiation intensity and pulse shape are interpreted and printed in dimensionless and absolute terms.

#### 6. ERG

This subroutine computes, at the end of a run, the total irradiation energy received in the cases of a step function or a thermonuclear pulse, (equations of Table 2.1).

#### 7. CHANGE

With CALL CHANGE(1), the purpose of this subprogram is threefold:

1. To record the number of dry cloth slices.
2. Optional: to determine the maximum of the heat content of the skin above a given critical temperature level, attained at any time (equation 4.1).
3. Optional: to vary the size of time steps at prescribed dimensionless times by means of altering the modulus  $M_A$ . Any number of such changes is possible. The use of this procedure lies in the facility to reduce the time step size near the end of a square wave of irradiation, and to increase it at a later time again. - Any new value for  $M_A$  must be a multiple of the original one. The functions 2 and 3 are only activated by special data cards.

#### B. MACHINE TIME CONSUMPTION

The amount of machine time used per time step depends mainly on the number of cloth slices, since the determination of pressure profiles requires most of the work. The approximate expense of computer time is given below:

| <u>No. of Cloth Slices</u> | <u>Machine Time / Double Time Step (Sec.)</u> |
|----------------------------|-----------------------------------------------|
| 2                          | > 2                                           |
| 6                          | 2 - 2.6                                       |
| 18                         | 4 - 5                                         |

Using the 6-slice model with a modulus  $M_A = 5.0$ , a double time step is  $2\Delta\theta^0 = 0.0111$ , which corresponds to  $2\Delta\theta = 0.0272$  sec (with  $\theta/\theta^0 = (L^2\rho C/k)_c = 2.45$ ). The ratio of the machine time scale to the real time scale is,

$$\frac{\text{machine time}}{\text{real time}} \approx 70 - 95$$

in other words, a second of real time requires 1.2 - 1.6 minutes of computer time.

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|     |                                                                     |          |
|-----|---------------------------------------------------------------------|----------|
|     | GAMA(1)=GAMA(NR)+G                                                  | MAI10203 |
|     | DO 86 J=NR,NR                                                       | MAI10205 |
| 86  | GAMA(1)=GAMA(1)-1/GAMA(1)-1                                         | MAI10204 |
|     | GAMA(NR)=1+1/W-1/GAMA(NR)                                           | MAI10209 |
|     | DELTIME=CC(MR)                                                      | MAI10206 |
|     | DO 90 J=NR,NR                                                       | MAI10207 |
| 90  | DELTIME(1)=DELTIME(1)/GAMA(1)-1/CC(1)                               | MAI10208 |
|     | DELTIME(N)=DELTIME(N)/GAMA(NR)+W                                    | MAI10209 |
|     | PINAC=21+DELTIME(N)+1/GAMA(NR)                                      | MAI10210 |
|     | DO 95 I=NR,NR                                                       | MAI10211 |
|     | J=NAC-1=NAL                                                         | MAI10212 |
| 95  | P(J)=2-DELTIME(J)+P(J)+1/GAMA(J)                                    | MAI10213 |
|     | P(1)=G(PNR)                                                         | MAI10214 |
|     | IF(MR=1) 2,92,93                                                    | MAI10215 |
| C   | INTERPOLATE PRESSURE PROFILE IN DRY SLICES                          | MAI10216 |
|     | PACT=(PINR)-P(1)/PNR                                                | MAI10217 |
|     | DO 96 I=1,NR                                                        | MAI10218 |
| 96  | P(I)=(1+I)-1+PACT                                                   | MAI10219 |
| 92  | COM1=(PINR=21+PINR(N)=0)-P(NR=3)                                    | MAI10220 |
|     | IF (COM1) 96,98,100                                                 | MAI10221 |
| 96  | IF (ISUM2) 65,65,100                                                | MAI10222 |
| C   | P CALC COMPLETED, MOVE T TO TA, P TO PA                             | MAI10223 |
| 100 | NR=NR                                                               | MAI10224 |
|     | DO 102 I=1,NR                                                       | MAI10225 |
| 102 | TA(I)=T(1)                                                          | MAI10226 |
|     | DO 103 I=1,NR                                                       | MAI10227 |
| 103 | PA(I)=P(1)                                                          | MAI10228 |
|     | EVAP=(P(1)-P(2))/0.5 *EVAP                                          | MAI10229 |
| C   | PRINT OUT FOR MAIN PROGRAM                                          | MAI10230 |
|     | TIME=TIME+ZETA                                                      | MAI10231 |
| C   | RECORD DRY CLOTH SLICES. INTEGRATE MAR, CRT, HEAT CONTENT OF SLICES | MAI10232 |
| C   | CHANGE MODULO AND TIME STEP IF PRESCRIBED                           | MAI10233 |
|     | CHARGE=CHARGE(1)                                                    | MAI10234 |
|     | NR=NR+1                                                             | MAI10235 |
|     | IF (INT-NR) 116,116,115                                             | MAI10236 |
| 116 | PRINT 500,TIME,TIME,NR,1,20,1,TIME,NR,NTC,NTG,TA(1)                 | MAI10237 |
|     | IF(PINR=1,21)EVAP,GUM2,CNC(1)=0,1,10,1,CMB(1)=0,1,10                | MAI10238 |
|     | NR=NR                                                               | MAI10239 |
| 115 | CALL SUBP                                                           | MAI10240 |
|     | NR=NR+1                                                             | MAI10241 |
|     | IF(NR=NRSTEP) 4005,4005,119                                         | MAI10242 |
| C   | INDICATE END IF DRY-OUT                                             | MAI10243 |
| 118 | 40-STEP                                                             | MAI10244 |
|     | CALL CHARGE(1)                                                      | MAI10245 |
| C   | COMPUTE TOTAL ENERGY IN LABS OF STEP FUNCTION OR TRUE DATA          | MAI10246 |
| 119 | CALL ARG                                                            | MAI10247 |
|     | RUN OUT UNUSED CHARGE-CARDS,IF ANY                                  | MAI10248 |
|     | CALL CHARGE(2)                                                      | MAI10249 |
|     | GO TO 982                                                           | MAI10250 |
|     | END                                                                 | MAI10251 |

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C SUBROUTINE SUBP                                SUBP0000
C IMPLICIT P EXPLICIT T MULATION                SUBP0001
C000 DIMENSION ALPH(1000),AA(18),T(1000),TA(1000),PIZZ(1),PAIZ(1),    SUBP0002
C1BEFAT(1000),CMB(11),CMB(11),COFC(18),COFBI(18),GAMBI(1),GAMB(1),    SUBP0003
C2DALT(19),CCLB(18),DV(18),T(19),C(18),    SUBP0004
C3TEMP(18),P(18),Q(18),COF(10),Z(19),P(10),Z(1)    SUBP0005
C701 COMMON TEMP,PRES,AA,IMP,T,TA,ALPH,BETA,P,AA,CC,GAMMA,GAMB,TA,    SUBP0006
C1LNC,CMB,COFC,COF,T,ALP,ALP,ALP,ALP,SUMZ,EVAP,DV,DP,CIO,CLE,CAP    SUBP0007
C2DVC,CHGA,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0008
C3CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0009
C4CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0010
C5SHAPET,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0011
C6CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0012
C7CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,CH,    SUBP0013
C8COMMON PAUT,PAUA    SUBP0014
C9 FORMAT STATEMENTS    SUBP0015
C1001 F(10H)TIME =F(8.0/30H TEMPERATURE IN CLOTH AND SKIN 11PT,    SUBP0016
C1110/30H 11PT/30H SKIN 11PT/30H    SUBP0017
C1210H PRESSURE =Z(19.2/10H WUP LOSS=P(10.0/30H COND=P(10.0/30H C    SUBP0018
C310P(3.2/30H D 10P(3.0)    SUBP0019
C505 FORMAT(17H CYCLE P(3.0)    SUBP0020
C606 NEXT TIME INCREMENT    SUBP0021
C707 OPTIONAL DIFFUSIVITY CALC    SUBP0022
C801 GO TO 1002/005/1/0    SUBP0023
C902 DO 803 1=1,NIC    SUBP0024
C1003 DVP(1)=DV    SUBP0025
C1104 GO TO 9    SUBP0026
C1205 DO 804 1=NIC    SUBP0027
C1306 DVP(1)=DVP(2),P(1)=P(1)+P(2)/P(1),P(2)=P(2)+P(1)    SUBP0028
C1407 CALL DOUBLE INTERPOLATION SUBPROGRAM    SUBP0029
C1508 DO 8 1=NIC,NIC    SUBP0030
C1609 CALL DOUBLE INTERPOLATION SUBPROGRAM    SUBP0031
C1710 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0032
C1812 CALL DCM,TA(1)=1,PA(1)=1,DMP,COF(1)    SUBP0033
C1913 CMB(1)=DVP(1)/DVP(1)+COF(1)/COF(1)+COF(1)/COF(1)    SUBP0034
C2014 CMB(1)=CMB(1)/CMB(1)    SUBP0035
C2105 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0036
C2206 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0037
C2307 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0038
C2408 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0039
C2509 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0040
C2610 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0041
C2711 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0042
C2812 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0043
C2913 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0044
C3014 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0045
C3115 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0046
C3216 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0047
C3317 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0048
C3418 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0049
C3519 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0050
C3620 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0051
C3721 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0052
C3822 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0053
C3923 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0054
C4024 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0055
C4125 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0056
C4226 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0057
C4327 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0058
C4428 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0059
C4529 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0060
C4630 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0061
C4731 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0062
C4832 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0063
C4933 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0064
C5034 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0065
C5135 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0066
C5236 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0067
C5337 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0068
C5438 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0069
C5539 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0070
C5640 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0071
C5741 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0072
C5842 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0073
C5943 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0074
C6044 CMB(1)=10/CLE/1000,COF(1)=1    SUBP0075

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[illegible]



|      |                                    |                               |          |
|------|------------------------------------|-------------------------------|----------|
|      | REN TO COMMON-8 WHEN K=5           |                               |          |
|      | REN Y TABLE FLOATS FROM COMMON-9   |                               |          |
|      | REN TO COMMON-14                   |                               | TAB 0010 |
|      | REN ON OV OR UNDER FLOW OR DLT     |                               | TAB 0011 |
|      | REN ORIGINAL ARG IN ACC            |                               | TAB 0012 |
|      | REN 1 LIST (8) IF SOLN IS GOOD     |                               | TAB 0013 |
|      | REN 2 LIST (8) IF ERROR            |                               | TAB 0014 |
|      | REN LIST (11) LOCATION OF LIST (1) |                               | TAB 0015 |
|      | REN LIST (12) LOCATION OF X TABLE  |                               | TAB 0016 |
|      | REN LIST (13) LOCATION OF Y TABLE  |                               | TAB 0017 |
|      | REN LIST (4)=DEL X                 |                               | TAB 0018 |
|      | REN LIST (5)=DEL Y                 |                               | TAB 0019 |
|      | REN LIST (6)=C                     |                               | TAB 0020 |
|      | REN LIST (7)=P                     |                               | TAB 0021 |
|      | REN LIST (8)=SUCCESSFUL, 2-UNREY   |                               | TAB 0022 |
| TAB  | LFTN                               |                               | TAB 0023 |
|      | TRA J71                            |                               | TAB 0024 |
| J1   | CLA 0-1                            | A=LOC OF X TABLE              | TAB 0025 |
| J2   | HOR                                | CHS IF X(1)=1 LESS THAN X(1)  | TAB 0026 |
|      | CAS 81                             | X1 HAS SIGN ADJUSTED          | TAB 0027 |
|      | TRA J9                             | X LESS THAN X(1)              | TAB 0028 |
|      | TRA J9                             | X(1)=1                        | TAB 0029 |
| J6   | TXI J71-1-0                        | X GREATER THAN X(1)=0-DELTA X | TAB 0030 |
| J7   | TXI J82-2-0                        | D=DELTA Y                     | TAB 0031 |
| J8   | TXI J11-1-0                        | A=DELTA X                     | TAB 0032 |
| J9   | CLA K2                             | A=DELTA Y                     | TAB 0033 |
|      | LST                                | LOC OF X IN ADDRESS           | TAB 0034 |
|      | TRA J13                            | X EVER                        | TAB 0035 |
|      | TRA J26                            | X UOD                         | TAB 0036 |
| J13  | CLA 0-1                            | A=LOC OF Y TABLE              | TAB 0037 |
|      | PSB COMMON                         | LOCATION OF X                 | TAB 0038 |
|      | ASP                                |                               | TAB 0039 |
|      | STO COMMON-2                       | ERASABLE                      | TAB 0040 |
| J17  | TXI J18-1-0                        | D=DELTA X                     | TAB 0041 |
| J18  | CLA 0-1                            | A=LOC OF Y TAB                | TAB 0042 |
|      | PSB COMMON                         |                               | TAB 0043 |
|      | ESP                                |                               | TAB 0044 |
|      | PSB COMMON-2                       |                               | TAB 0045 |
|      | TXI J25                            | X CLOSER TO X(1)              | TAB 0046 |
| J23  | TXI J24-1-0                        | DECREMENT SAME AS J6          | TAB 0047 |
| J23A | TXI J23B-1-0                       | DECR DELTA                    | TAB 0048 |
| J23B | TXI J23C-1-0                       | DECR DELTA                    | TAB 0049 |
| J24  | TXI J24-1-0                        | X CLOSER TO X(1)=1-D=DELTA X  | TAB 0050 |
| J25  | TXI J25-1-0                        | D=DELTA Y                     | TAB 0051 |
| J26  | TXI J27-1-0                        | -X(1)/DELTA X=-X(1)/2 DELTA X | TAB 0052 |
| J27  | TXI J28-2-0                        | -X(1)/DELTA Y=-X(1)/2 DELTA Y | TAB 0053 |
| J28  | LAD K14                            | X(1)=0-0 X(1)                 | TAB 0054 |
| J29  | CLA COMMON                         |                               | TAB 0055 |
| J30  | PSB 0-1                            | A=LOC OF X TABLE              | TAB 0056 |
|      | STO COMMON-2-0                     | D=DELTA X                     | TAB 0057 |
| J31  | TXI J32-1-0                        |                               | TAB 0058 |
| J32  | TXI J29-0-1                        |                               | TAB 0059 |
|      | LAD K1-0                           |                               | TAB 0060 |
| J34  | CLA 0-2                            | A=Y TABLE                     | TAB 0061 |
|      | STO COMMON-0-0                     |                               | TAB 0062 |
| J36  | TXI J37-0-0                        | D=DELTA Y                     | TAB 0063 |
| J37  | TXI J38-0-1                        |                               | TAB 0064 |
|      | LAD K-1                            | X=0-0-0                       | TAB 0065 |
| J39  | DCI                                | BEGIN ALITER INTERPOLATION    | TAB 0066 |
| J40  | TOV J41                            |                               | TAB 0067 |
| J41  | PSB 0-1                            |                               | TAB 0068 |
| J42  | POA 0-2                            |                               | TAB 0069 |
| J43  | TOV J44                            |                               | TAB 0070 |
| J44  | CLA COMMON-2-2                     |                               | TAB 0071 |
|      | PSB COMMON-3-1                     |                               | TAB 0072 |
|      | STO COMMON-2                       |                               | TAB 0073 |
|      | LDO COMMON-0-1                     | ERASE: X(1)=X(1)+1            | TAB 0074 |
|      | POP COMMON-2-2                     |                               | TAB 0075 |
|      | STO K1                             | ERASE: Y(1)=X(1)+1            | TAB 0076 |
|      | LMO COMMON-3-1                     |                               | TAB 0077 |
|      | POP COMMON-0-2                     |                               | TAB 0078 |
|      | CHS                                |                               | TAB 0079 |
|      | PSB K1                             |                               | TAB 0080 |
|      | TOV J47                            |                               | TAB 0081 |
|      | TOV J48                            |                               | TAB 0082 |
| J48  | POP COMMON-2                       |                               | TAB 0083 |
|      | TOV J47                            |                               | TAB 0084 |
|      | STO COMMON-0-2                     |                               | TAB 0085 |
|      | TXI J43-2-1                        |                               | TAB 0086 |
|      | TXI J42-1-1                        |                               | TAB 0087 |
|      | DCI                                |                               | TAB 0088 |
|      | TRA J47                            |                               | TAB 0089 |
|      | CLA BENE                           | DIVIDE CHECK ON               | TAB 0090 |
| J49  | STO 0                              | PREPARE NORMAL EXIT           | TAB 0091 |
|      | CLA COMMON-0                       | A=LIST (8)                    | TAB 0092 |
|      | LMO REG1-1                         |                               | TAB 0093 |
|      | LMO REG2-2                         |                               | TAB 0094 |
|      | LMO REG4-4                         |                               | TAB 0095 |
|      | EPH                                |                               | TAB 0096 |
|      | TRA J48                            |                               | TAB 0097 |
| J47  | CLA COMMON                         |                               | TAB 0098 |
|      | STO COMMON-0                       |                               |          |



|                 | ADDRESS OF X TABLE |          |
|-----------------|--------------------|----------|
| CLA -1.0        |                    | TAB 0113 |
| ARS 18          |                    | TAB 0114 |
| STA J1          |                    | TAB 0115 |
| STA J13         |                    | TAB 0116 |
| STA J18         |                    | TAB 0117 |
| STA J30         |                    | TAB 0118 |
| STA J137        |                    | TAB 0119 |
| STA J139        |                    | TAB 0120 |
| CLA -2.0        |                    | TAB 0121 |
| ARS 18          |                    | TAB 0122 |
| STA J34         |                    | TAB 0123 |
| CLA -3.0        |                    | TAB 0124 |
| STO K           |                    | TAB 0125 |
| ADD DONE        |                    | TAB 0126 |
| STO K1          |                    | TAB 0127 |
| SUB DONE        |                    | TAB 0128 |
| ARS 18          |                    | TAB 0129 |
| STA K2          |                    | TAB 0130 |
| CLA -3.0        |                    | TAB 0131 |
| STO J6          |                    | TAB 0132 |
| STO J17         |                    | TAB 0133 |
| STO J26         |                    | TAB 0134 |
| STO J31         |                    | TAB 0135 |
| STO J23A        |                    | TAB 0136 |
| CLA -0.0        |                    | TAB 0137 |
| STO J7          |                    | TAB 0138 |
| STO J25         |                    | TAB 0139 |
| STO J36         |                    | TAB 0140 |
| STO J23B        |                    | TAB 0141 |
| LDO K+1         |                    | TAB 0142 |
| LDO DONE+1.1    |                    | TAB 0143 |
| MPY -3.0        |                    | TAB 0144 |
| ALS 17          |                    | TAB 0145 |
| STO COMMON-2    |                    | TAB 0146 |
| COM             |                    | TAB 0147 |
| ADD DONE        |                    | TAB 0148 |
| STO J26         |                    | TAB 0149 |
| LDO DONE+1.1    |                    | TAB 0150 |
| MPY -0.0        |                    | TAB 0151 |
| ALS 17          |                    | TAB 0152 |
| STO COMMON-0    |                    | TAB 0153 |
| COM             |                    | TAB 0154 |
| ADD DONE        |                    | TAB 0155 |
| STO J27         |                    | TAB 0156 |
| CLA K2          |                    | TAB 0157 |
| LBT             |                    | TAB 0158 |
| TRA J126        |                    | TAB 0159 |
| TRA J130        |                    | TAB 0160 |
| CLA COMMON-2    |                    | TAB 0161 |
| ADD -3.0        |                    | TAB 0162 |
| STO COMMON-2    |                    | TAB 0163 |
| CLA COMMON-0    |                    | TAB 0164 |
| ADD -0.0        |                    | TAB 0165 |
| STO COMMON-0    |                    | TAB 0166 |
| CLA -0.0        |                    | TAB 0167 |
| SUB DONE        |                    | TAB 0168 |
| LRS 35          |                    | TAB 0169 |
| MPY -3.0        |                    | TAB 0170 |
| ALS 17          |                    | TAB 0171 |
| SUB COMMON-2    |                    | TAB 0172 |
| STO J6          |                    | TAB 0173 |
| STO J23         |                    | TAB 0174 |
| CLA 0           |                    | TAB 0175 |
| LDO J17+1       |                    | TAB 0176 |
| PSB 0.1         |                    | TAB 0177 |
| TPJ J144        |                    | TAB 0178 |
| CLA MDP         |                    | TAB 0179 |
| STO J2          |                    | TAB 0180 |
| CLA COMMON      |                    | TAB 0181 |
| T- J140         |                    | TAB 0182 |
| C- C40          |                    | TAB 0183 |
| STO J2          |                    | TAB 0184 |
| CLA COMMON      |                    | TAB 0185 |
| CHS             |                    | TAB 0186 |
| STO K1          |                    | TAB 0187 |
| CLA 0.0         |                    | TAB 0188 |
| SUB SEVEN       |                    | TAB 0189 |
| ARS 18          |                    | TAB 0190 |
| STA J61         |                    | TAB 0191 |
| LDO COMMON-2.1  |                    | TAB 0192 |
| LDO COMMON-0.2  |                    | TAB 0193 |
| CLA -0.0        |                    | TAB 0194 |
| SUB K1          |                    | TAB 0195 |
| THZ J1          |                    | TAB 0196 |
| POX 0.1         |                    | TAB 0197 |
| PDX 0.2         |                    | TAB 0198 |
| TRA J28         |                    | TAB 0199 |
| CLA LOCATE      |                    | TAB 0200 |
| TRA J+4         |                    | TAB 0201 |
| PZE 0.0+0       |                    | TAB 0202 |
| K1 PZE 0.0+0    |                    | TAB 0203 |
| 72 PZE 0.0+0    |                    | TAB 0204 |
| K1 PZE          |                    | TAB 0205 |
| PZE 0.0+1       |                    | TAB 0206 |
| PZE 0.0+2       |                    | TAB 0207 |
| PZE 0.0+1       |                    | TAB 0208 |
| PZE 0.0+1       |                    | TAB 0209 |
| CHS CHS         |                    | TAB 0210 |
| SEVEN PZE 0.0+7 |                    | TAB 0211 |
| REG1 PZE        |                    | TAB 0212 |
| REG2 PZE        |                    | TAB 0213 |
|                 |                    | TAB 0214 |
|                 |                    | TAB 0215 |

ADDRESS OF X TABLE

ACC HAS DELTA X

DELTA Y IN ACC

(AK/2) DELTA X

(AK/2) DELTA Y, TEMP ERAS

K EVEN

K ODD

\*STAB.DETERMINE DIRECTION OF MONOTONICITY A(1)-K(2)

LOCATING SUB ROUTINE 0.0+0 C+0.0+1 0.0+0 K WITH ADJUSTED SIGN

TAB197.1

TAB191.1

TAB190.1

TAB190.2

TAB190.3

TAB190.4

TAB190.5

TAB 195

TAB 0216  
TAB 0417  
TAB 0218  
TAB 0219

[illegible]

P-22-000001  
 P-22-000002  
 P-22-000003  
 P-22-000004  
 P-22-000005  
 P-22-000006  
 P-22-000007  
 P-22-000008  
 P-22-000009  
 P-22-000010  
 P-22-000011  
 P-22-000012  
 P-22-000013  
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 P-22-000097  
 P-22-000098  
 P-22-000099  
 P-22-000100



[illegible]

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1BETA(1000),CMC(18),CHD(18),COFC(18),COFD(18),GAM(18),GAMA(18), ERG 0004
2DELTA(18),CCI(18),DVP(18),F(18),TS(18), ERG 0005
3L(18),TEMP(18),PRES(18),DPT(18),DPT(18),DPT(18),DPT(18),DPT(18), ERG 0006
901 COMMON TEMP,PRES,DPT,DPT,TATA,ALPH,BETA,P,PA,AA,CC,GAM,GAMA,DELTA, ERG 0007
1CMC,CMF,COFC,COFD,P,TS,ALPO,ALPS,ALP,SMZ,EVAP,DVP,CIO,CLK,CAP, ERG 0008
2DVC,CHN,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG,GG, ERG 0009
3TMP,TD,AL,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA,AA, ERG 0010
4KPLSE,TCHAR,VOYM,ENDHND,ENDCSD,TDIS,ANSTEP,TAUDIN, ERG 0011
5SNAPET,CKD,NS,SC,DV,PD,CKRED,CK,RF,2H,2S,CRITT,CKI,COM,UI,UD, ERG 0012
6ACOMA,ENERGO,ENERGA,ENORHA,ENDCSA,TENDAS,TENDCH,TEND,TPEND,ANSTEP, ERG 0013
COMMON PFAC,PRSA ERG 0014
GO TO (1,100,100,2),KPLSE ERG 0015
1 ENERGO=CIO*TIME ERG 0016
3 ENERGA=ENERGO*TAUDIN ERG 0017
PRINT 516 ERG 0018
916 FORMAT(6H DIMENSIONLESS ABSOLUTE ERG 0019
XTIME SCALE ) ERG 0020
PRINT 521,ENERGO,ENERGA ERG 0021
521 FORMAT(21H TOTAL ENERGY =,F8.4,13H CAL/CMSEC ,F8.4,13H CAL/ ERG 0022
ACM2) ERG 0023
100 RETURN ERG 0024
2 IF (TDIS-.3) 10,10,11 ERG 0025
10 ENERGO=L(10)*TCHAR*.2879*TDIS**2 ERG 0026
GO TO 3 ERG 0027
11 IF (TDIS-.65) 12,12,13 ERG 0028
12 ENERGO=CIO*TCHAR*(.082125+.06*TDIS**2-.347*TDIS) ERG 0029
GO TO 3 ERG 0030
13 IF (TDIS-1.4) 14,14,15 ERG 0031
14 ENERGO=CIO*TCHAR*(-.4093483*TDIS+.373333*TDIS-1.051003) ERG 0032
GO TO 3 ERG 0033
15 ENERGO=CIO*TCHAR*(2.695877-2.240625*TDIS+(-.641) ERG 0034
GO TO 3 ERG 0035
END ERG 0036

```

```

* PAD
COUNT 4
ENTRY (F2PM) F2PM 1
* BURNY (F2PM) F2PM 2
(F2PM) CALL EXIT F2PM 3
END F2PM 4

```

# APPENDIX F

## SUMMARY OF COMPUTER SOLUTIONS ON MOIST CLOTH - SKIN SIMULANT SYSTEM

The theoretical results for the temperature response of the moist opaque cloth - skin simulant system are summarized in the following diagrams. The listings of the numerical solutions and the master diagrams are in the files of the Fuels Research Laboratory, Department of Chemical Engineering, MIT.

For reference see List of Figures.

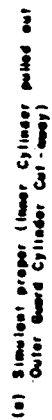


FIG. 1.6 SKIN SIMULANT NO. 11 B

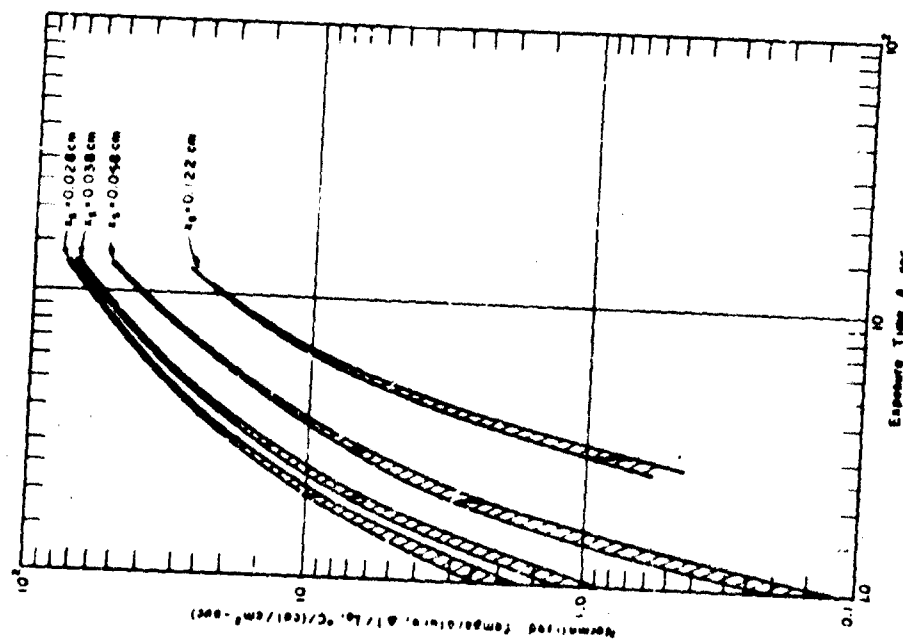


FIG 17 EXPERIMENTAL RESULTS ON DRY OPAQUE (DEEP BLACK, BLACK, DARK GRAY) CLOTH - SKIN SIMULANT SYSTEM

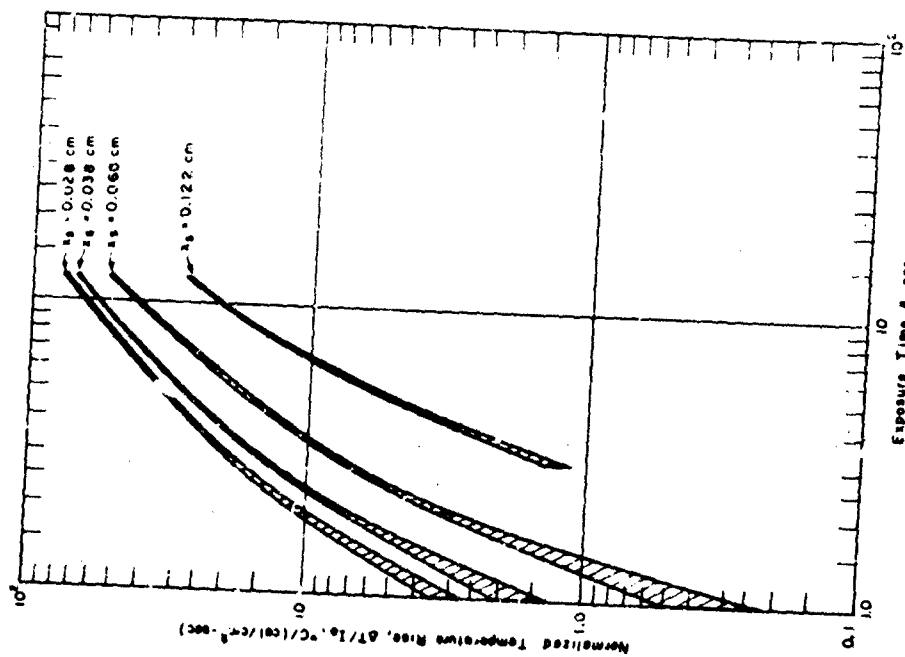


FIG 18 EXPERIMENTAL RESULTS ON DRY MEDIUM GRAY CLOTH - SKIN SIMULANT SYSTEM

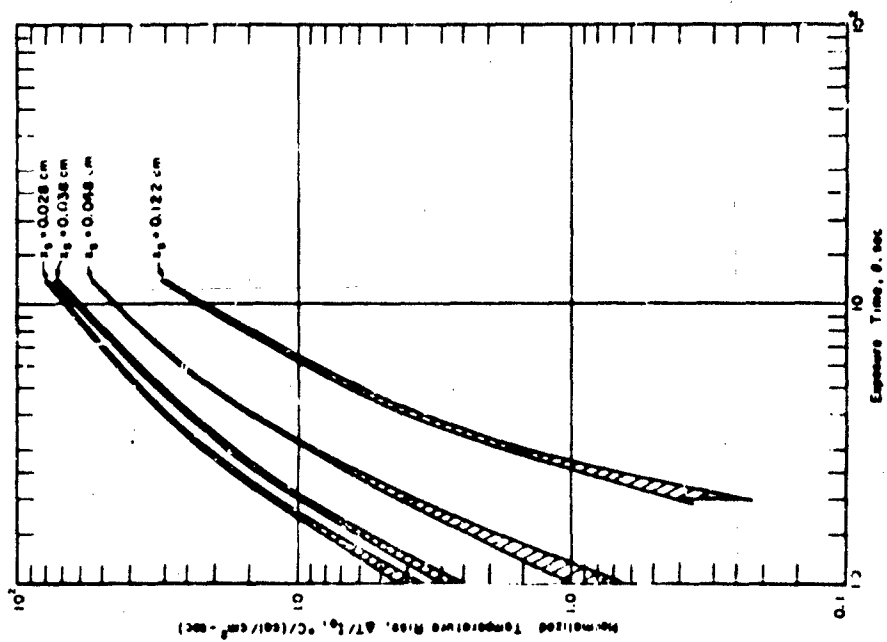


FIG. 9 EXPERIMENTAL RESULTS ON DRY LIGHT GREY CLOTH-SKIN SIMULANT SYSTEM

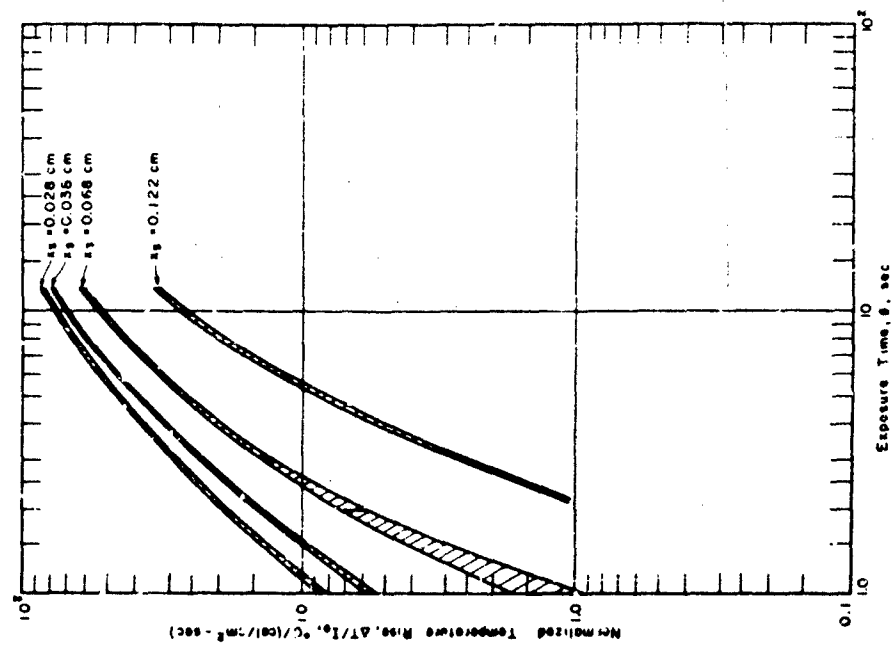


FIG. 10 EXPERIMENTAL RESULTS ON DRY WHITE (WITH CMC) CLOTH-SKIN SIMULANT SYSTEM

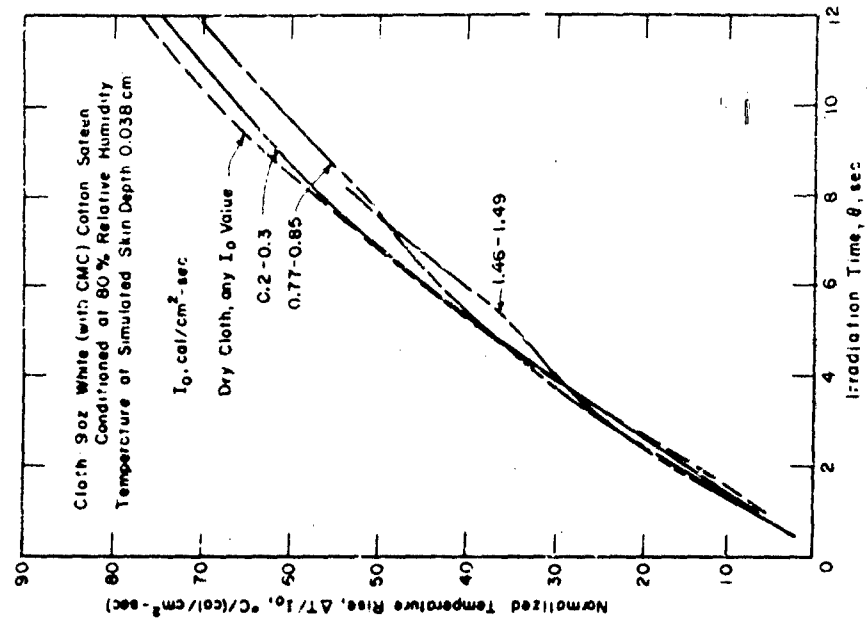


FIG. 1N HEAT TRANSFER TO SKIN SIMULANT THROUGH MOIST OPAQUE CLOTH

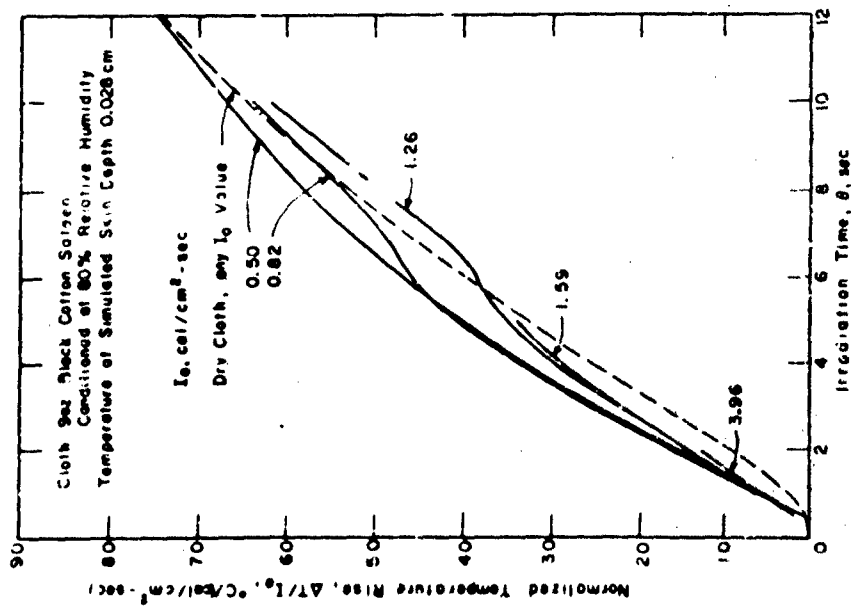


FIG. 1I2 HEAT TRANSFER TO SKIN SIMULANT THROUGH MOIST DIATHERMANOUS CLOTH

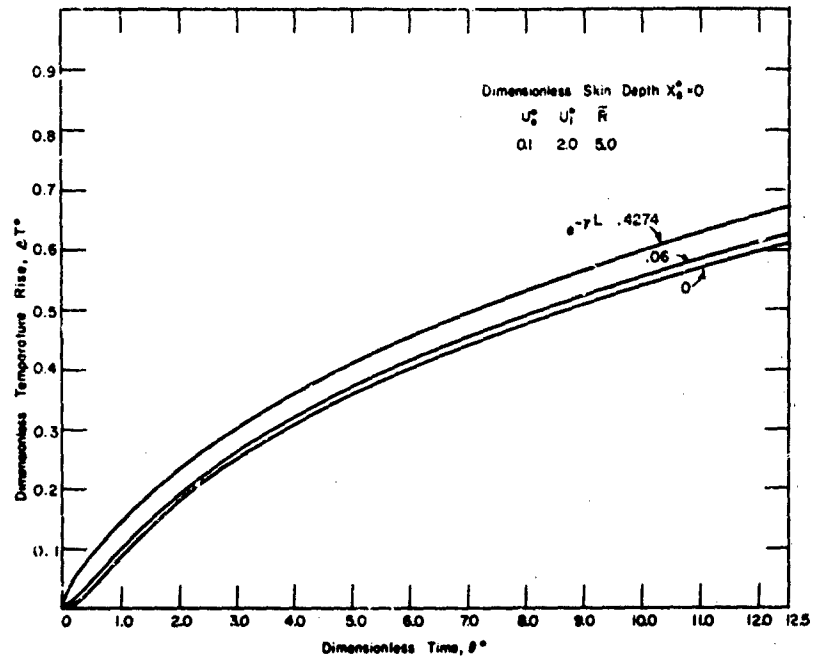


FIG. 1.13 EFFECT OF CLOTH DIATHERMANCY ON THE HEAT TRANSFER TO THE SKIN SIMULANT

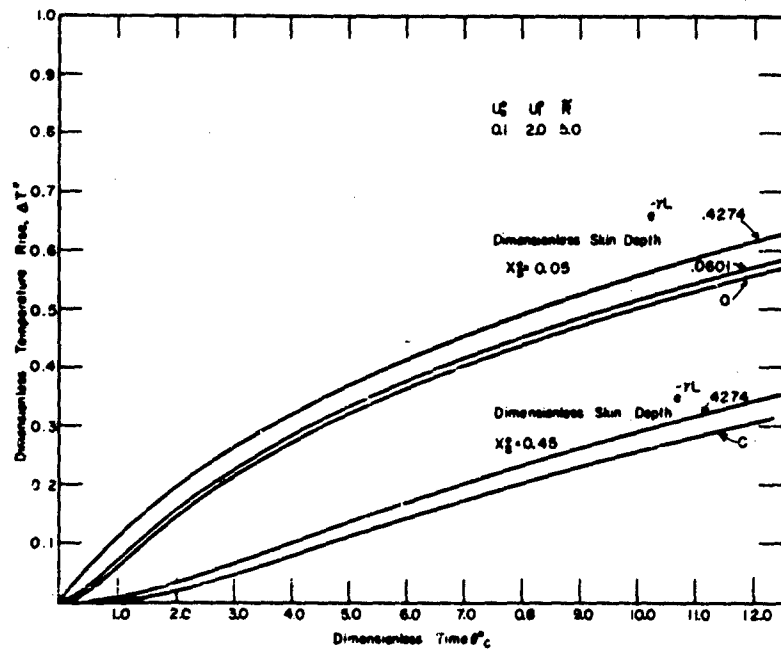


FIG. 1.14 EFFECT OF CLOTH DIATHERMANCY ON THE HEAT TRANSFER TO THE SKIN SIMULANT

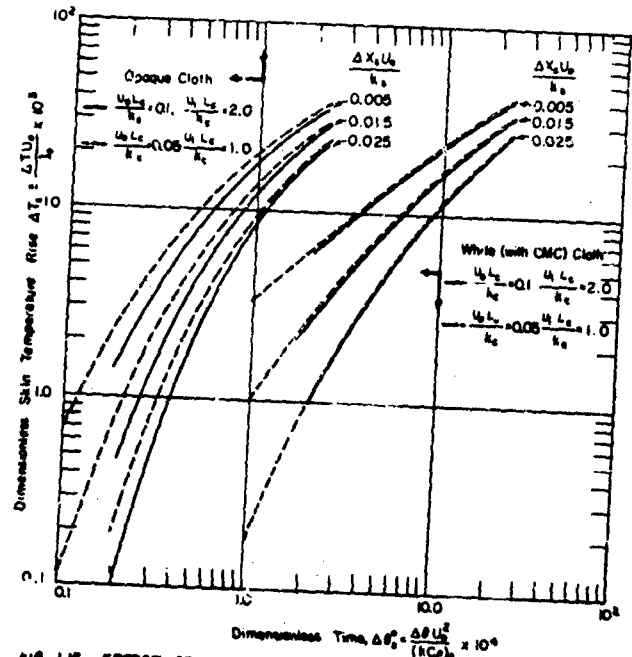


FIG. 1.15 EFFECT OF DOUBLING THE THERMAL CONDUCTANCE OF CLOTH ON THE HEAT TRANSFER TO THE SKIN SIMULANT.

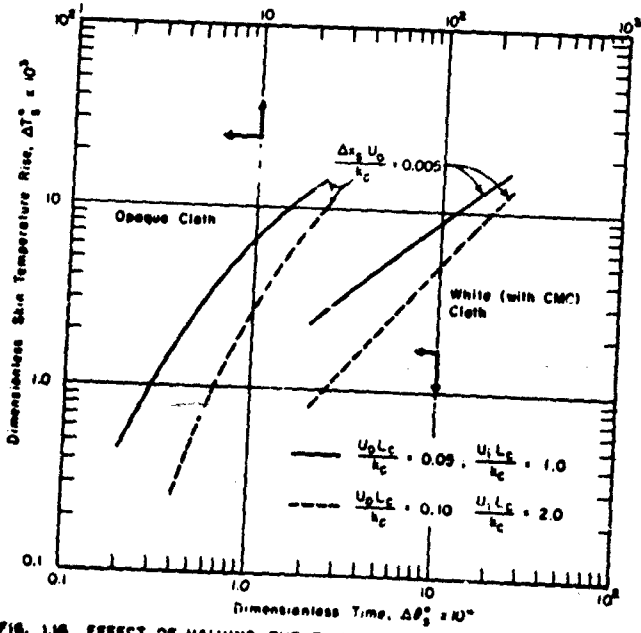


FIG. 1.16 EFFECT OF HALVING THE THICKNESS OF CLOTH ON THE HEAT TRANSFER TO THE SKIN SIMULANT

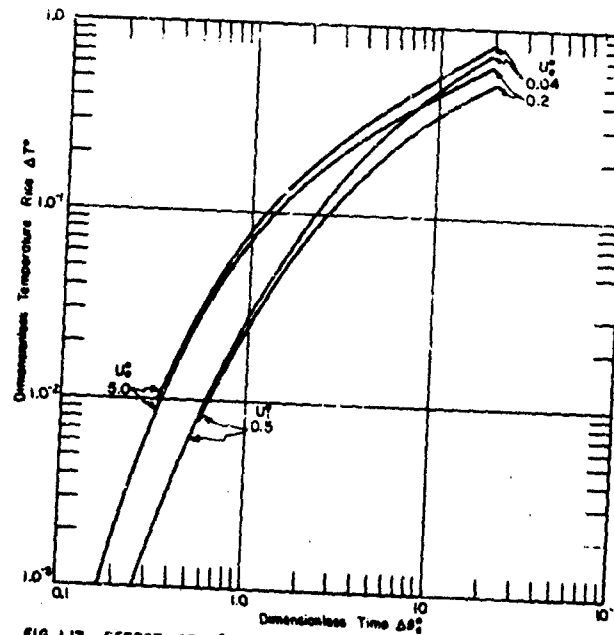


FIG 1.17 EFFECT OF  $U_c$  AND  $U_f$  ON THE HEAT TRANSFER TO SIMULANT THROUGH DRY OPAQUE CLOTH

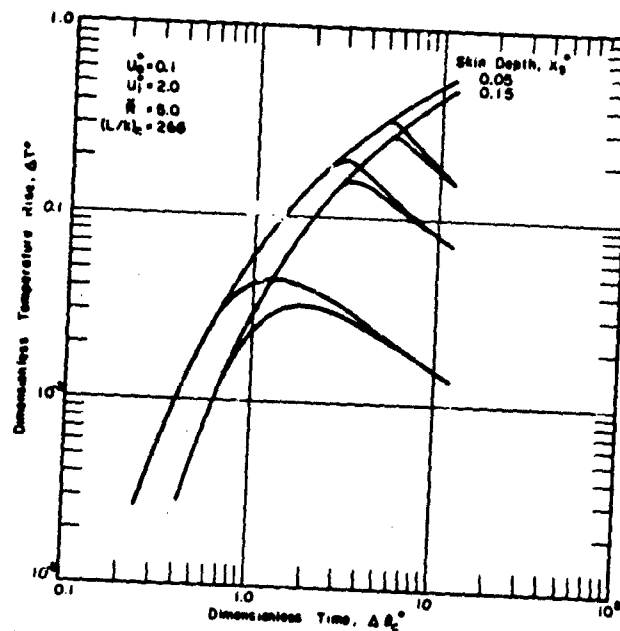


FIG 1.18 TEMPERATURE RESPONSE IN SKIN SIMULANT DURING AND AFTER IRRADIATION. SYSTEM: DRY OPAQUE CLOTH IN "CONTACT" WITH SKIN SIMULANT

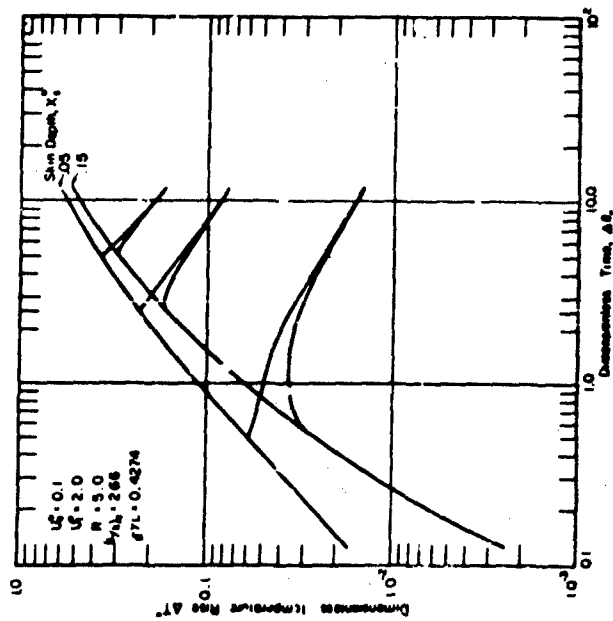


FIG. 118 TEMPERATURE RESPONSE IN SKIN SIMULANT DURING AND AFTER IRRADIATION. SYSTEM: DRY WHITE (WITH CMG) CLOTH IN "CONTACT" WITH SKIN SIMULANT

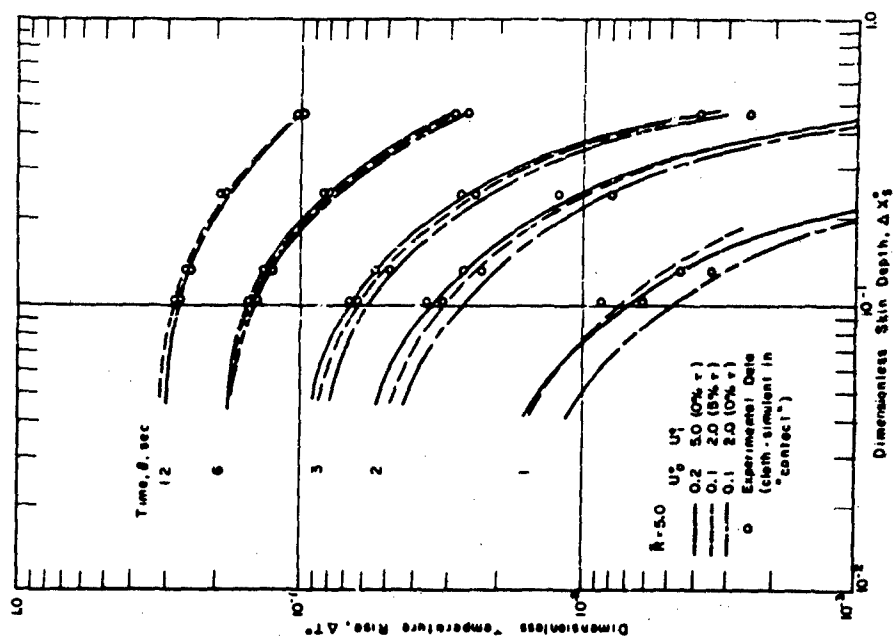


FIG. 120 COMPARISON OF EXPERIMENTAL RESULTS ON DRY OPAQUE CLOTH-SKIN SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF  $U_0$ ,  $U_1$  AND  $\tau$

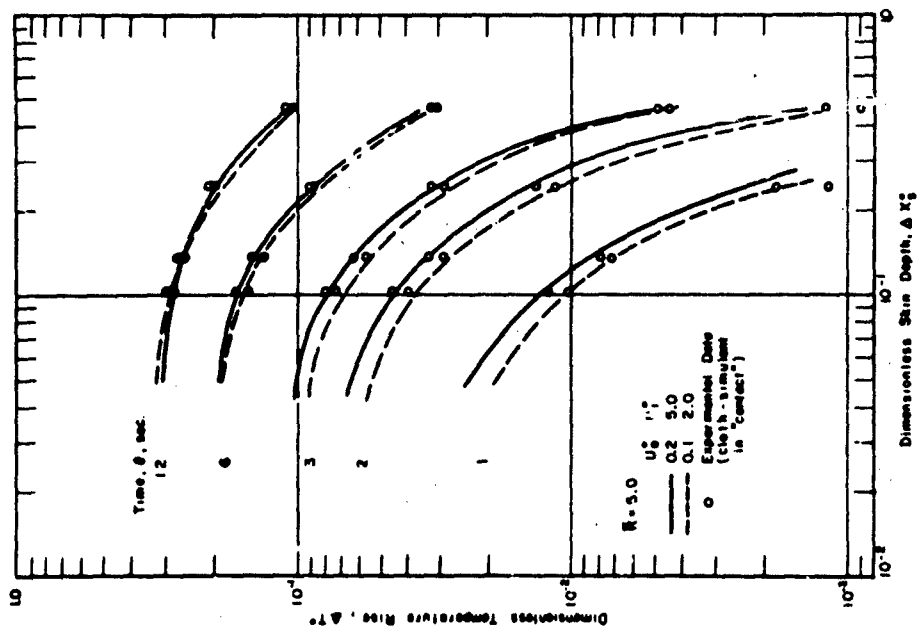


FIG. 123 COMPARISON OF EXPERIMENTAL RESULTS ON DRY MEDIUM GRAY CLOTH-SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF  $u_s$  AND  $u_t$

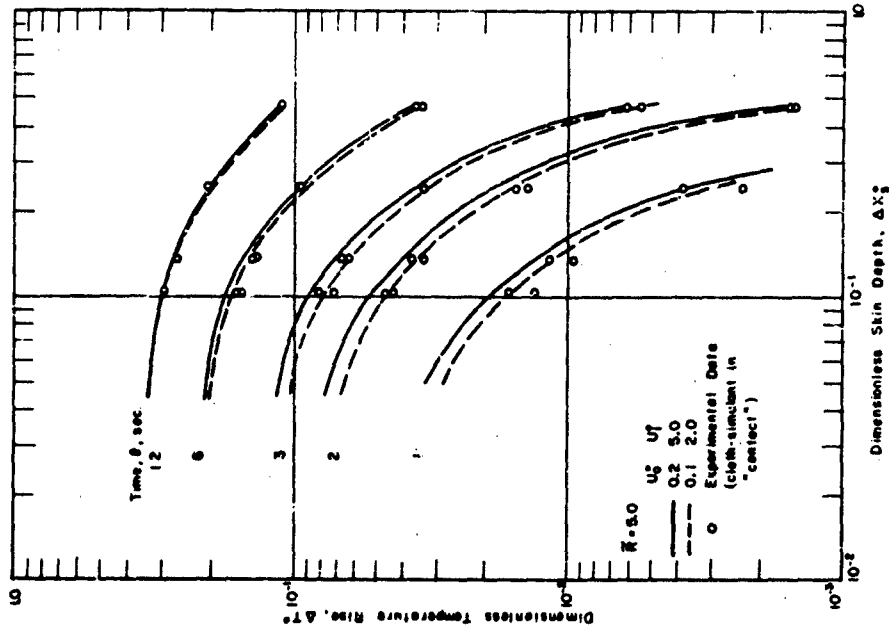


FIG. 122 COMPARISON OF EXPERIMENTAL RESULTS ON DRY LIGHT GRAY CLOTH-SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF  $u_s$  AND  $u_t$

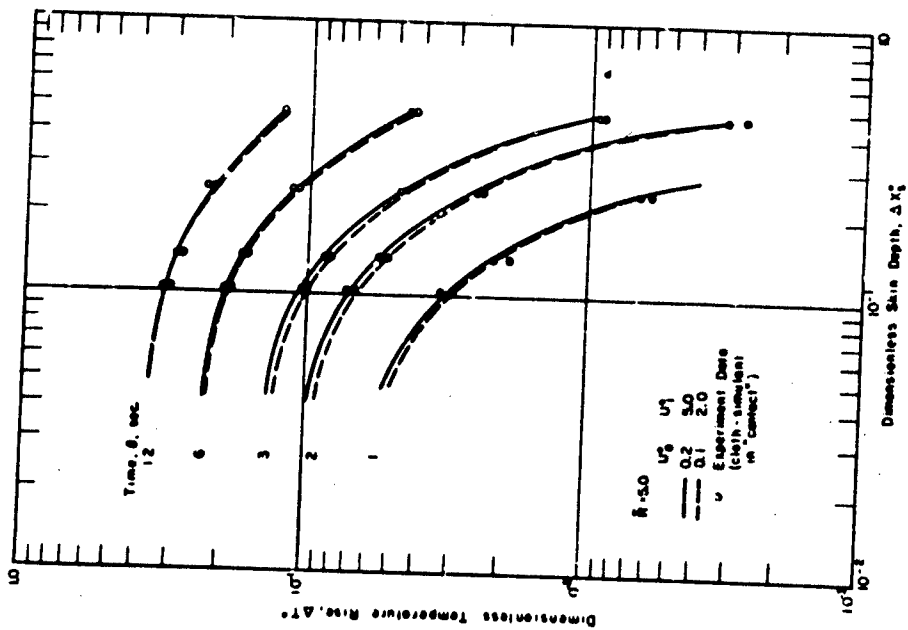


FIG. 123 COMPARISON OF EXPERIMENTAL RESULTS ON DRY WHITE (WITH CMC) CLOTH-SKIN SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF  $U_0$  AND  $U_1$

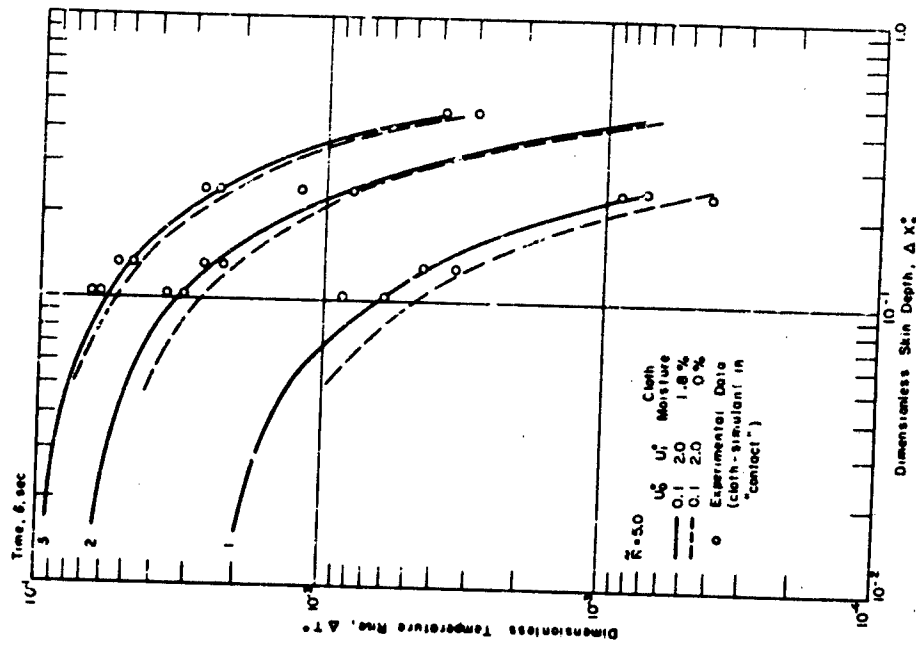


FIG. 124 COMPARISON OF EXPERIMENTAL RESULTS ON DRY OF AQUE CLOTH-SKIN SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF RESIDUAL MOISTURE IN CLOTH

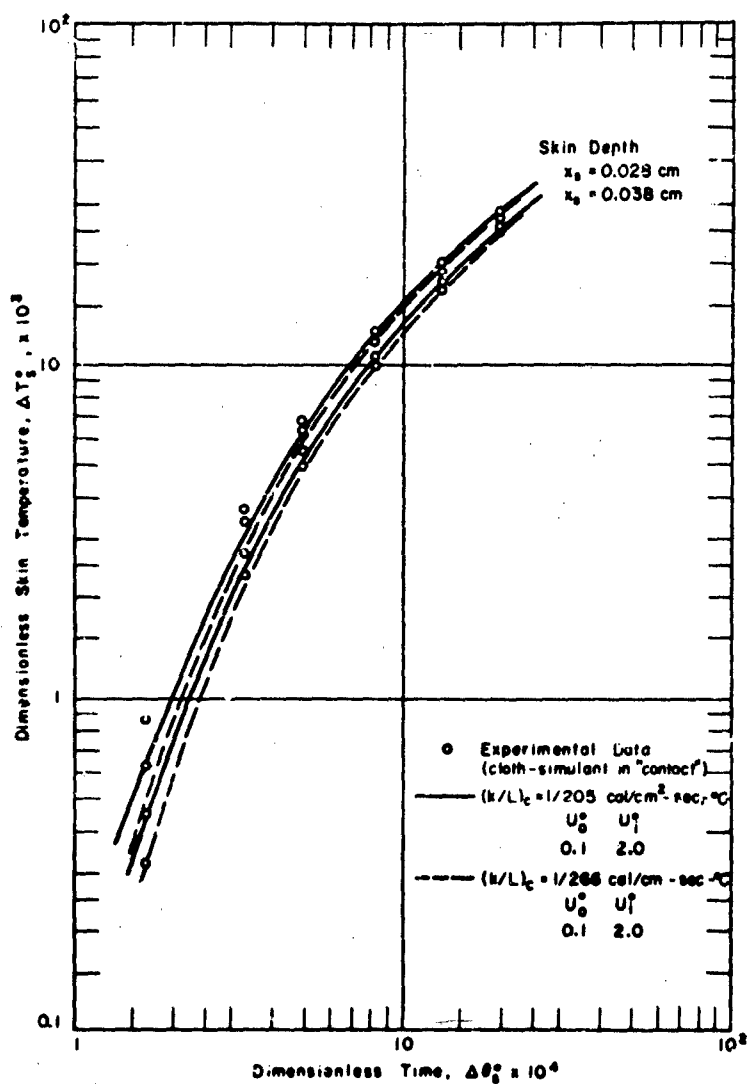


FIG 128 COMPARISON OF EXPERIMENTAL RESULTS ON DRY OPAQUE CLOTH-SKIN SIMULANT SYSTEM WITH THEORETICAL ANALYSIS. EFFECT OF THERMAL CONDUCTANCE OF CLOTH.

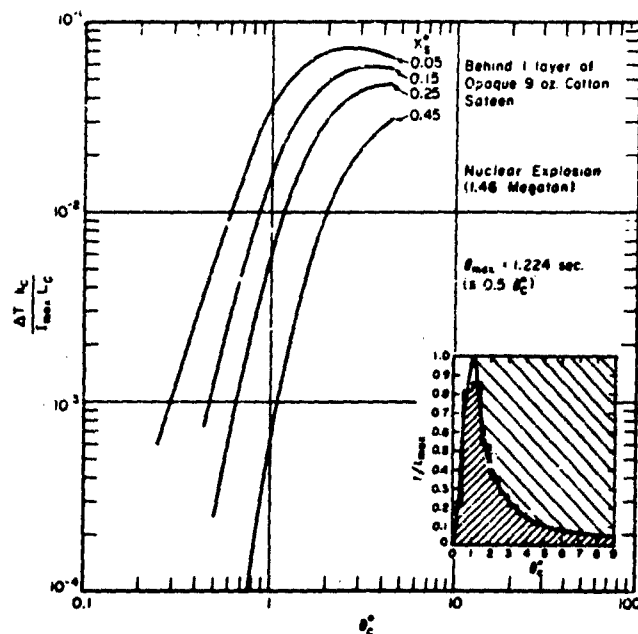


FIG. 1.26 TEMPERATURE RESPONSE IN CLOTHED SKIN SIMULANT EXPOSED TO NON-SQUARE WAVE RADIATION (NUCLEAR EXPLOSION PULSE)

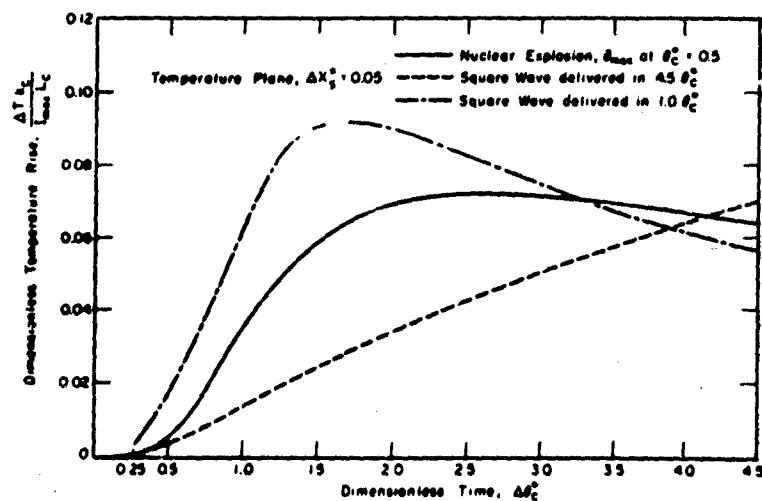


FIG. 1.27 COMPARISON OF TEMPERATURE RESPONSE IN CLOTHED SKIN IRRADIATED BY SQUARE WAVE RADIATION AND RADIATION FROM A NUCLEAR EXPLOSION

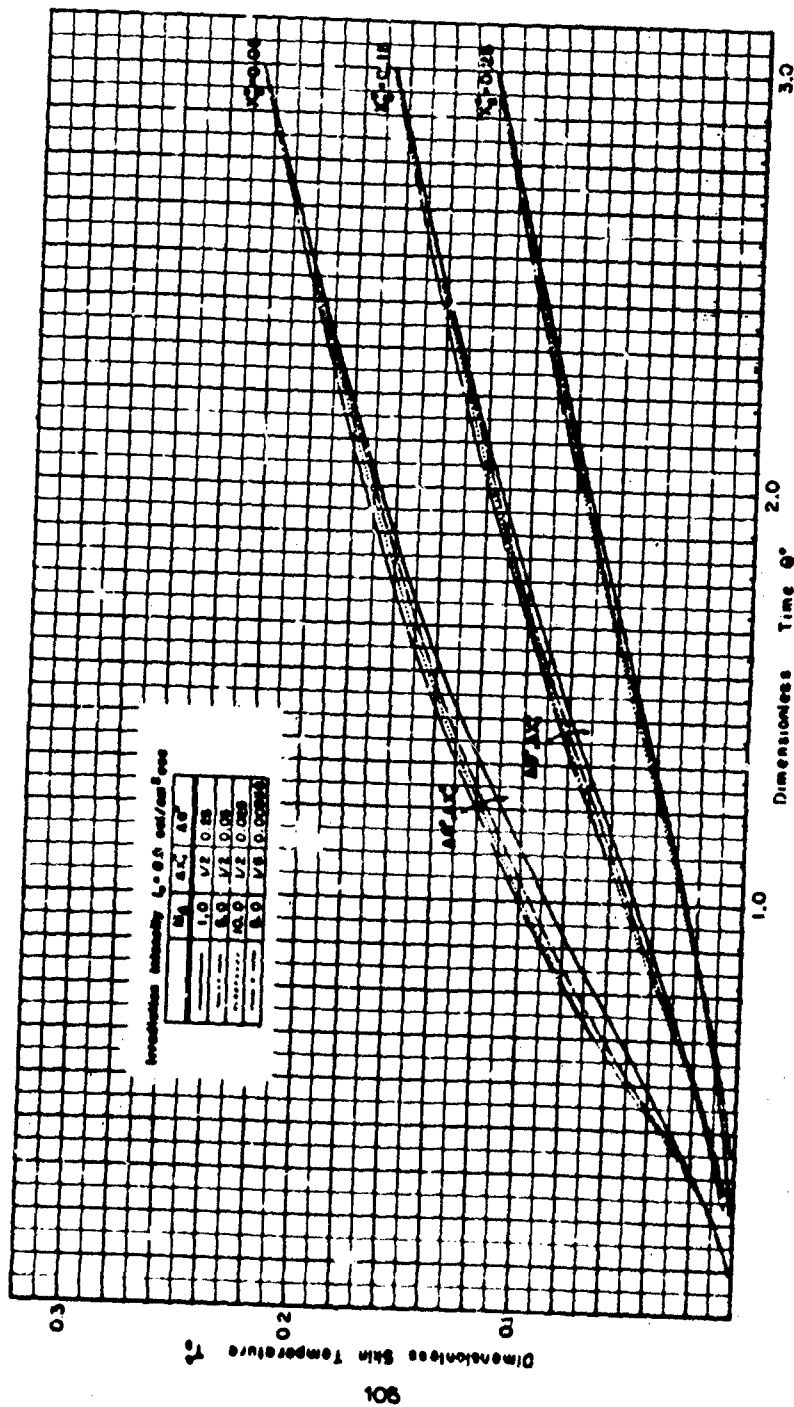


FIG. 2.4a CONVERGENCE OF THEORETICAL SOLUTION.  
EFFECT OF  $Ma$ ,  $h$ ,  $h'$ , AND  $h''$  ON TEMPERATURE RESPONSE OF  
SKIN SIMULANT.

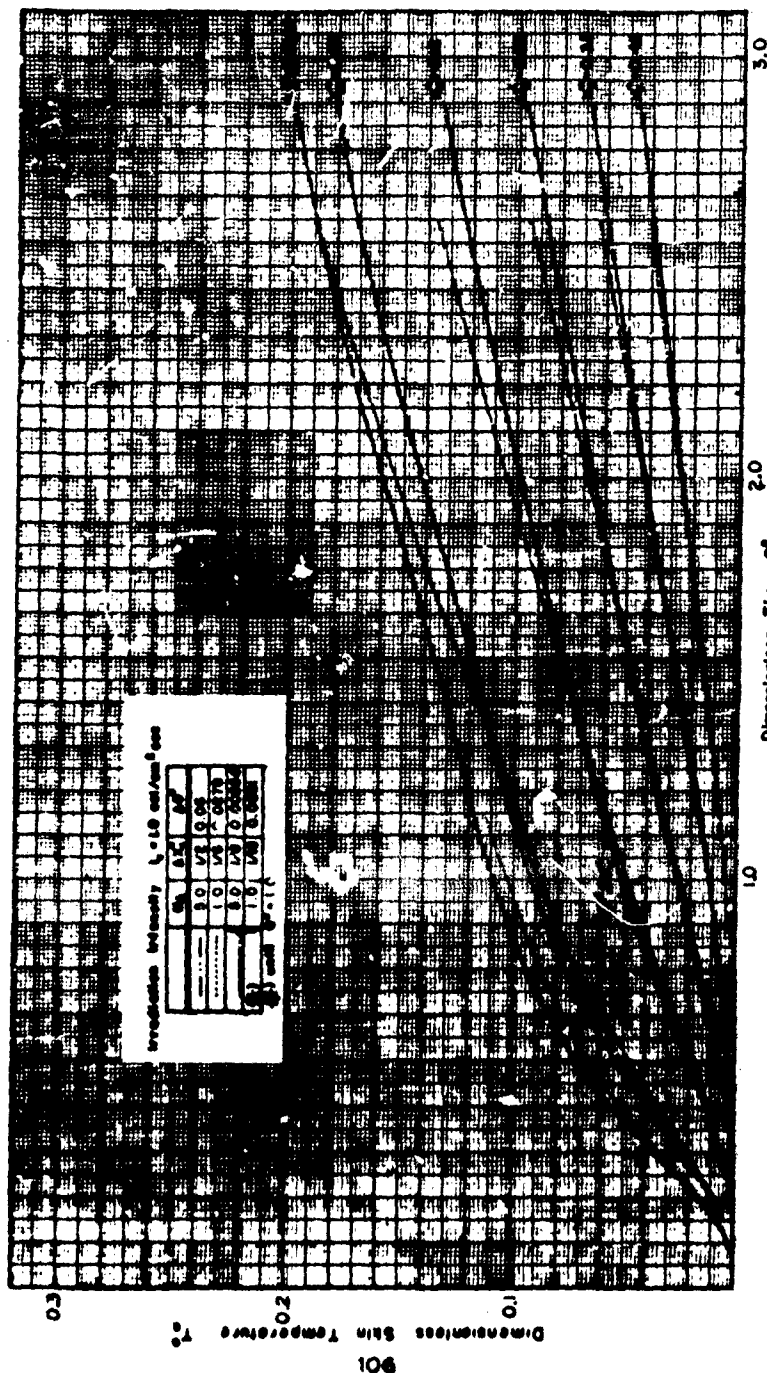


FIG. 2.46 CONVERGENCE OF THEORETICAL SOLUTION.  
EFFECT OF  $q$ ,  $\Delta T$  AND  $\Delta \theta$  ON TEMPERATURE RESPONSE OF  
SKIN SIMULANT.

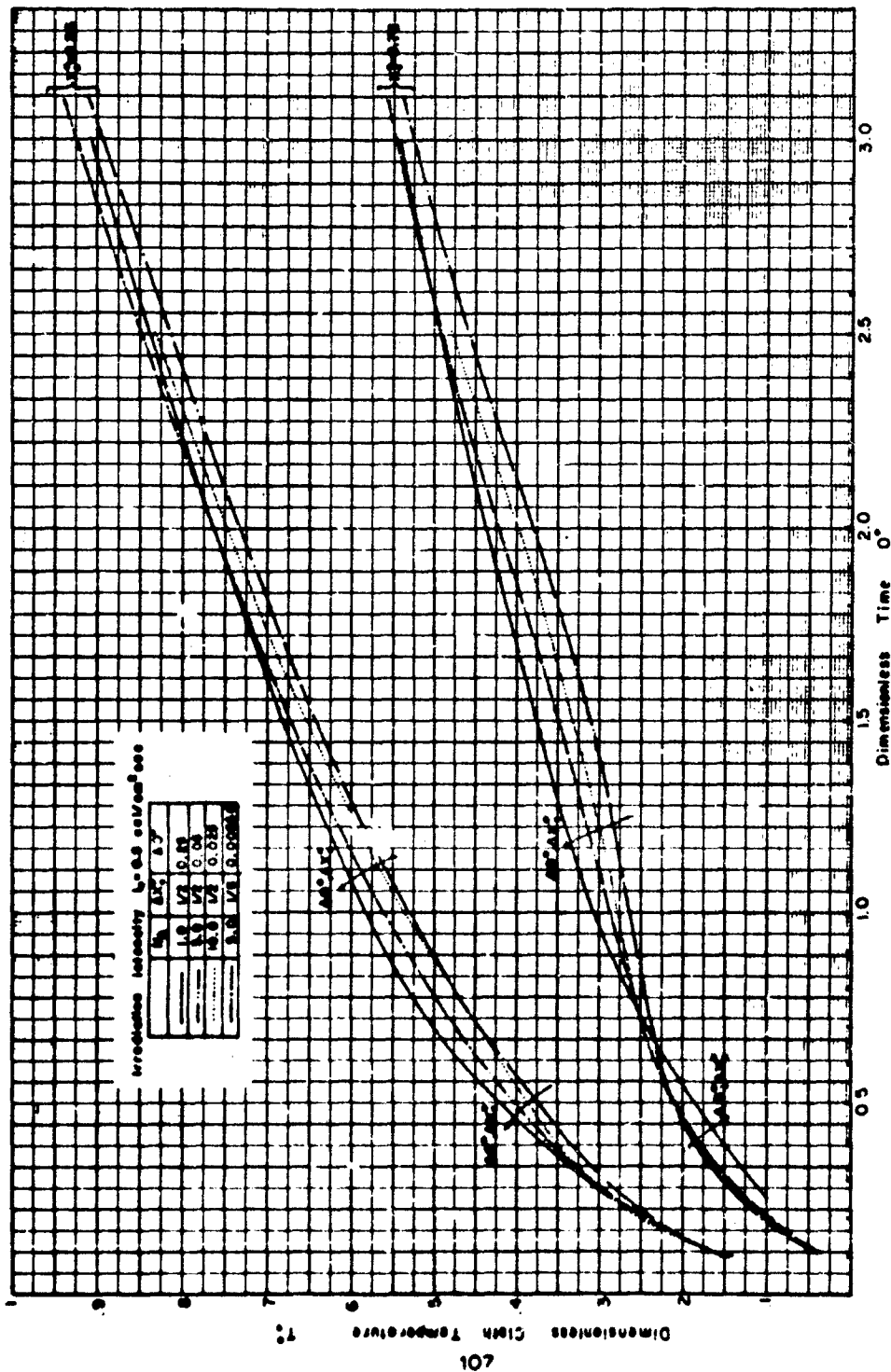


FIG. 24c CONVERGENCE OF THE DRETICAL SOLUTION.  
EFFECT OF  $Ma, \Delta x$ , AND  $\Delta \tau$  ON TEMPERATURE RESPONSE OF CLOTH.

**FIG. 2.5 TRIDIAGONAL EQUATION SYSTEM  
FOR SOLUTION OF EQUATION (2.14)**

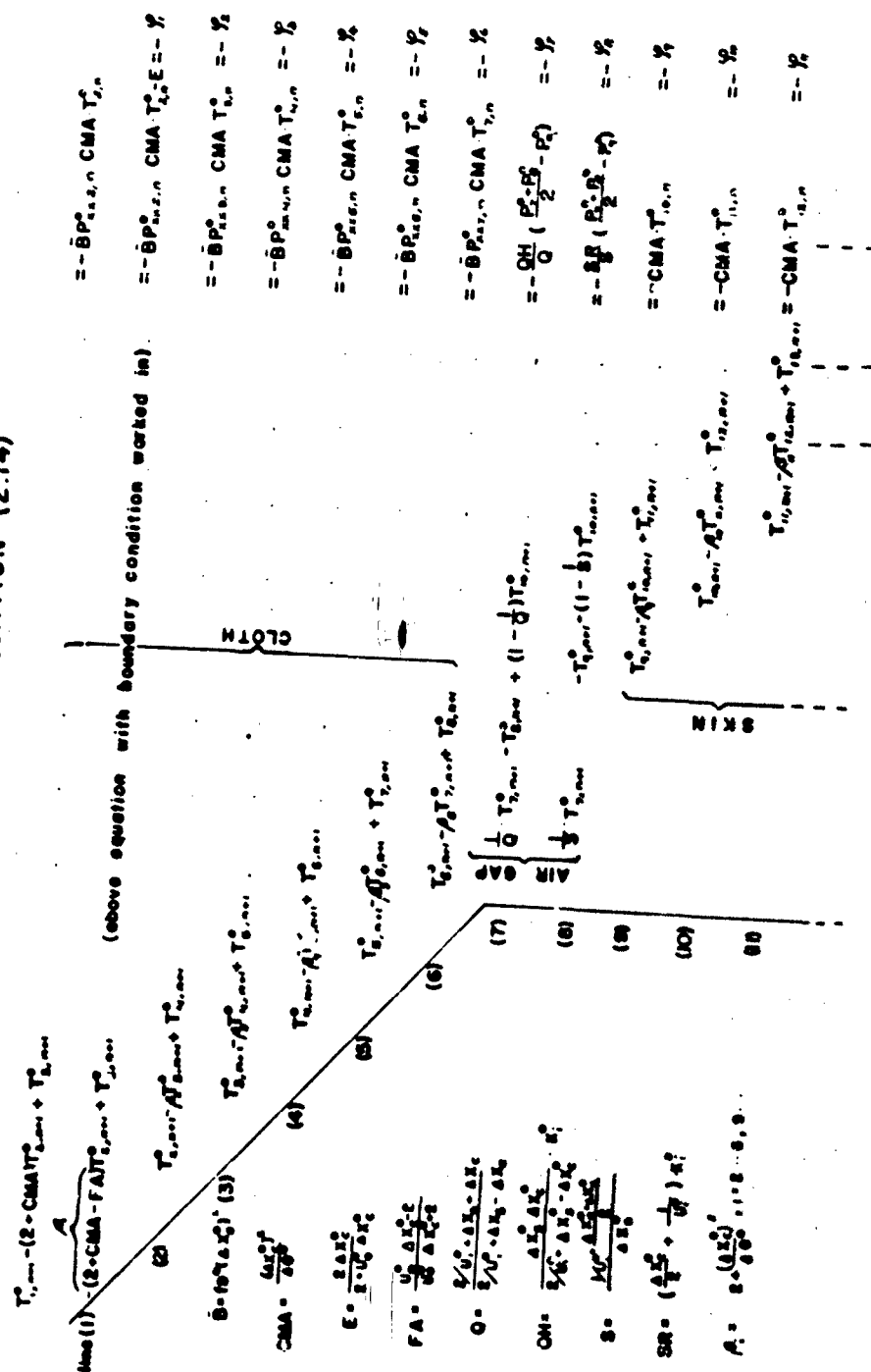


**FIG. 2.6 BIDIAGONAL EQUATION SYSTEM**

$$\begin{array}{ll}
 \text{line (1)} & -\nu_1 T_{1,n+1}^0 + T_{2,n+1}^0 \\
 (2) & -\nu_2 T_{2,n+1}^0 + T_{3,n+1}^0 \\
 (3) & -\nu_3 T_{3,n+1}^0 + T_{4,n+1}^0 \\
 (4) & -\nu_4 T_{4,n+1}^0 + T_{5,n+1}^0 \\
 (5) & -\nu_5 T_{5,n+1}^0 + T_{6,n+1}^0 \\
 (6) & -\nu_6 T_{6,n+1}^0 + T_{7,n+1}^0 \\
 (7) & -\nu_7 T_{7,n+1}^0 + T_{8,n+1}^0 \\
 (8) & -\nu_8 T_{8,n+1}^0 + T_{9,n+1}^0 \\
 (9) & -\nu_9 T_{9,n+1}^0 + T_{10,n+1}^0 \\
 (10) & -\nu_{10} T_{10,n+1}^0 + T_{11,n+1}^0 \\
 (11) & -\nu_{11} T_{11,n+1}^0 + T_{12,n+1}^0
 \end{array}$$

FIG. 2.7 FLOW-CHART OF MAIN PROGRAM  
MOIST CLOTH-SKIN SIMULANT SYSTEM

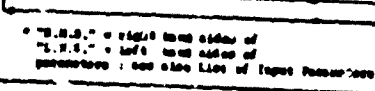


**FIG. 2.8 FLOW-CHART OF SUBROUTINE SUBP  
MOIST CLOTH-SKIN SIMULANT SYSTEM**



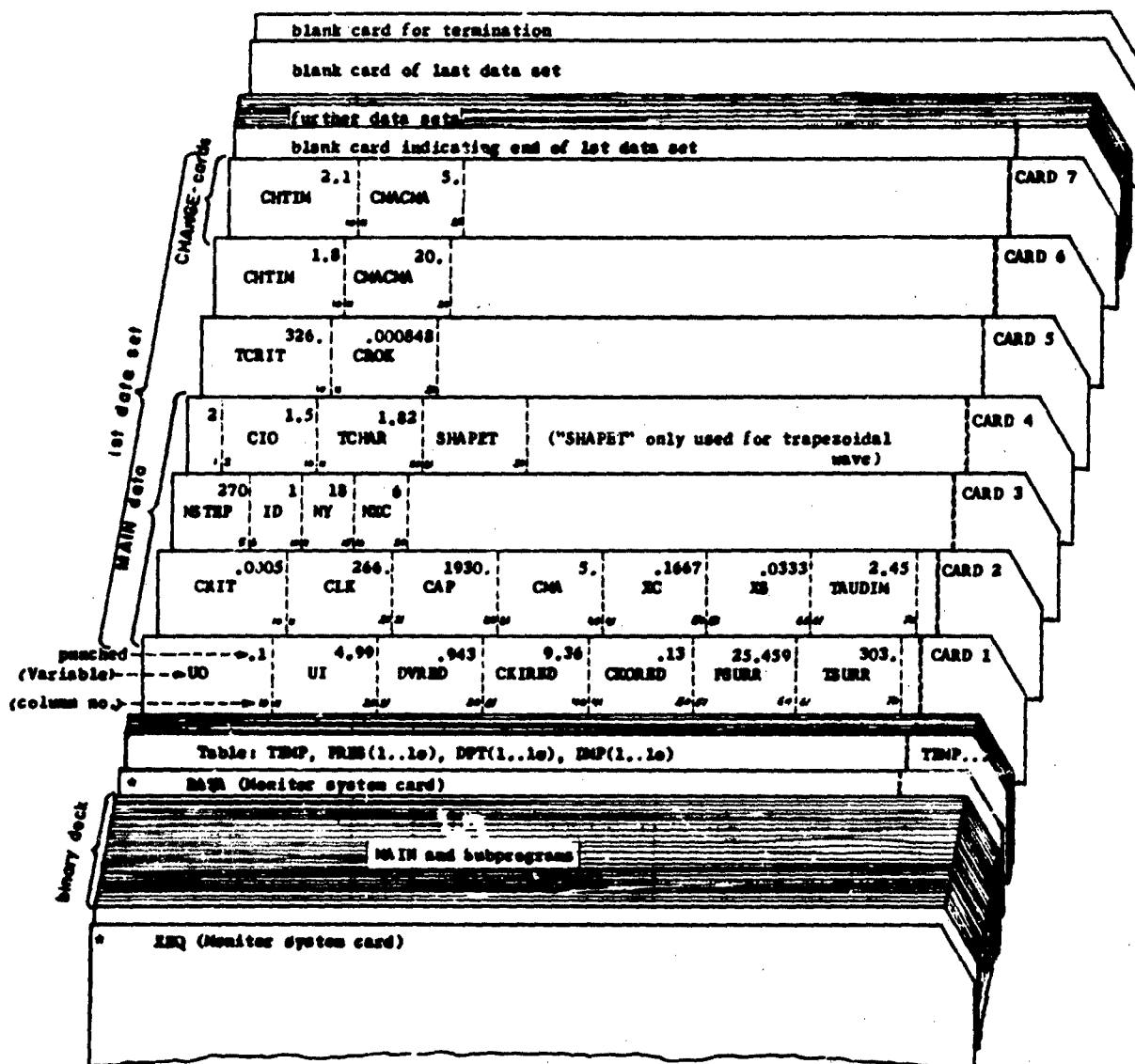


FIG 2.9 MAKE-UP OF RUN CARD DECK

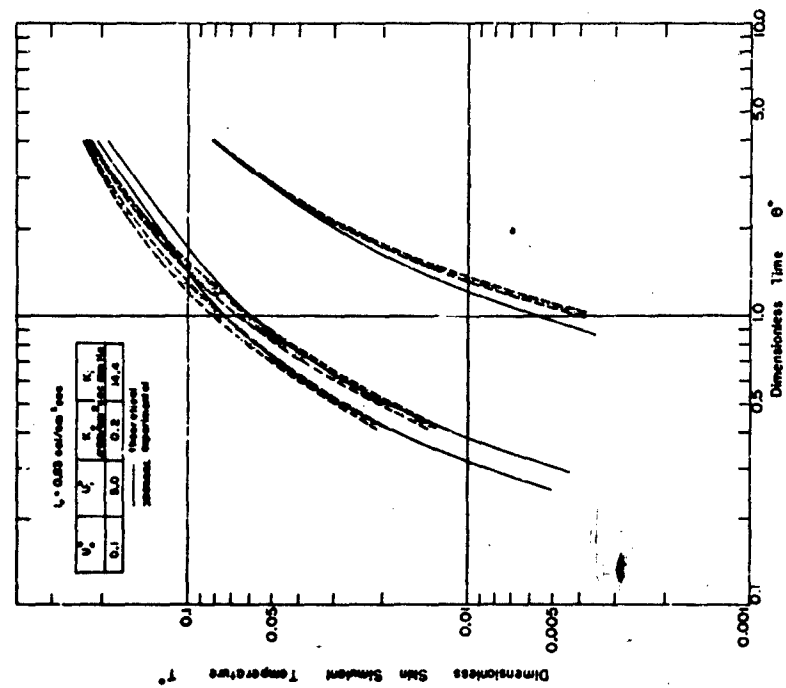


FIG. 2.11 TEMPERATURE RESPONSE OF MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS.

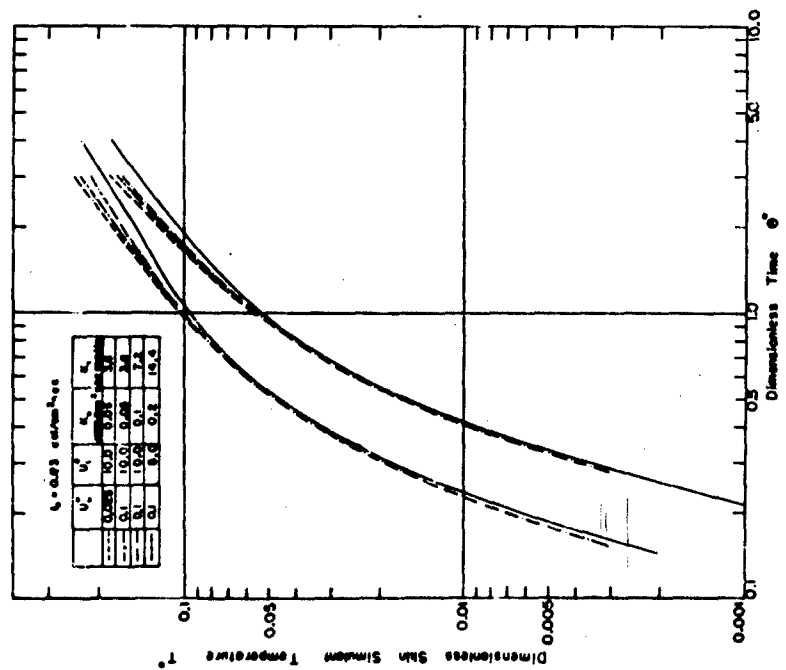


FIG. 2.10 THEORETICAL SOLUTION FOR MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). INFLUENCE OF HEAT AND MASS TRANSFER COEFFICIENTS.

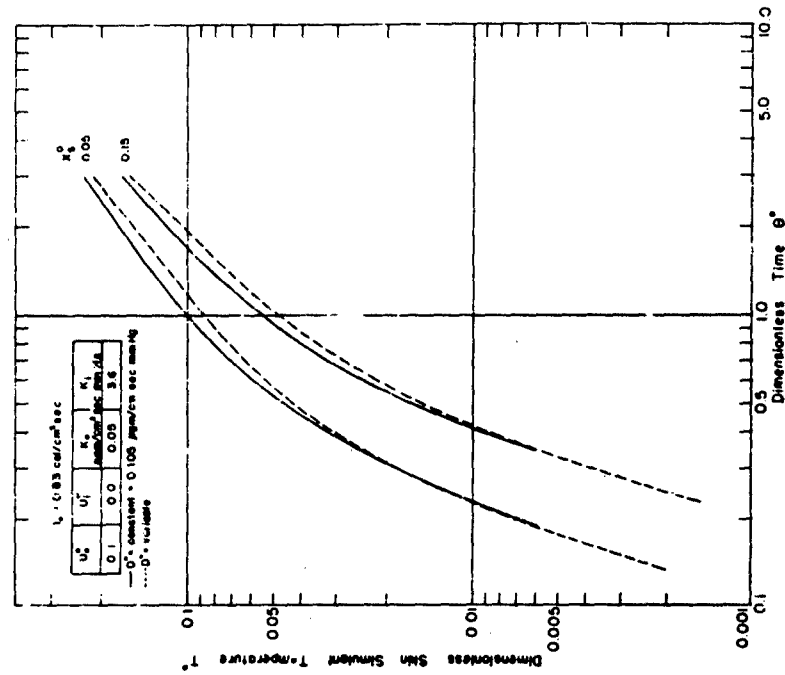


FIG. 2.13 THEORETICAL SOLUTION FOR MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). INFLUENCE OF FIXED OR VARIABLE DIFFUSIVITY.

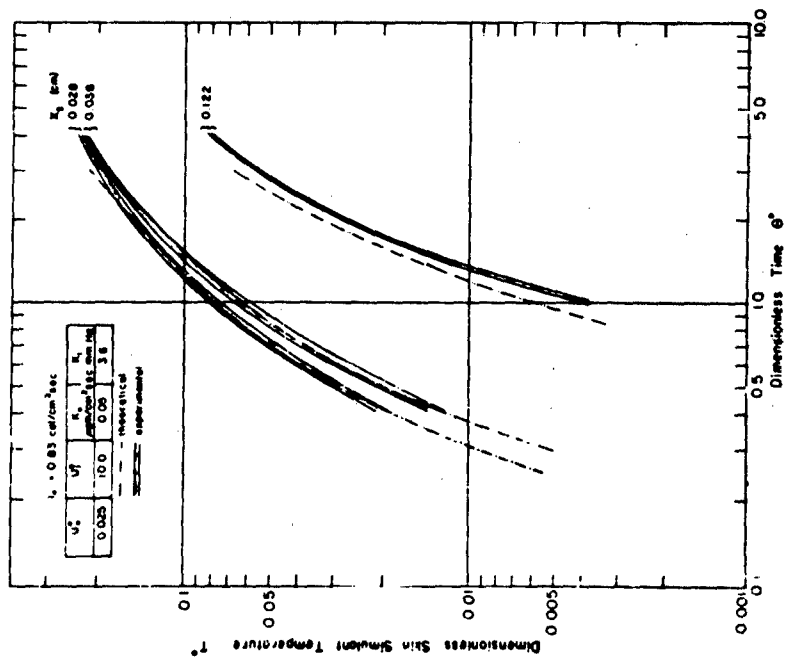


FIG. 2.12 TEMPERATURE RESPONSE OF MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS.

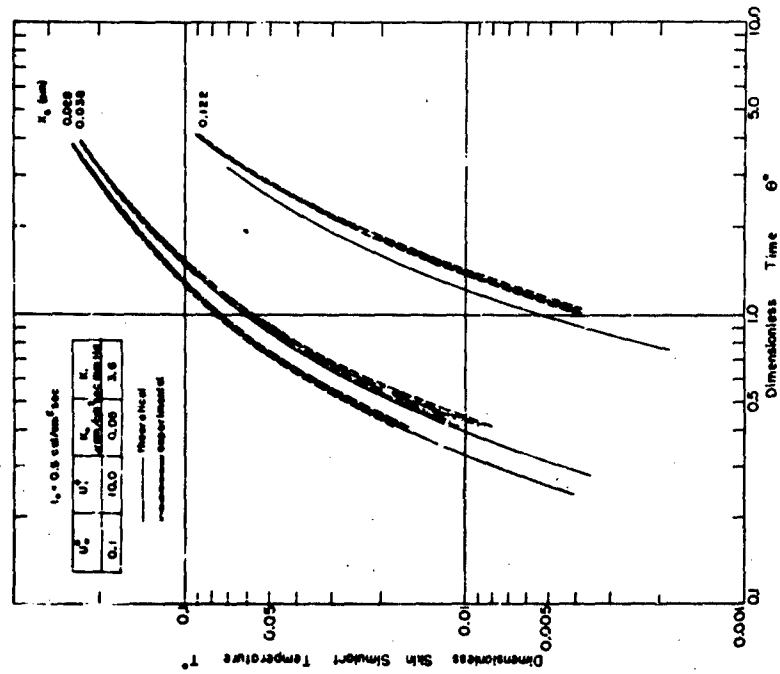


FIG. 2.14 THEORETICAL SOLUTION FOR MOIST CLOTH-SKIN SYSTEM (OPAQUE). INFLUENCE OF TRANSFER COEFFICIENTS.

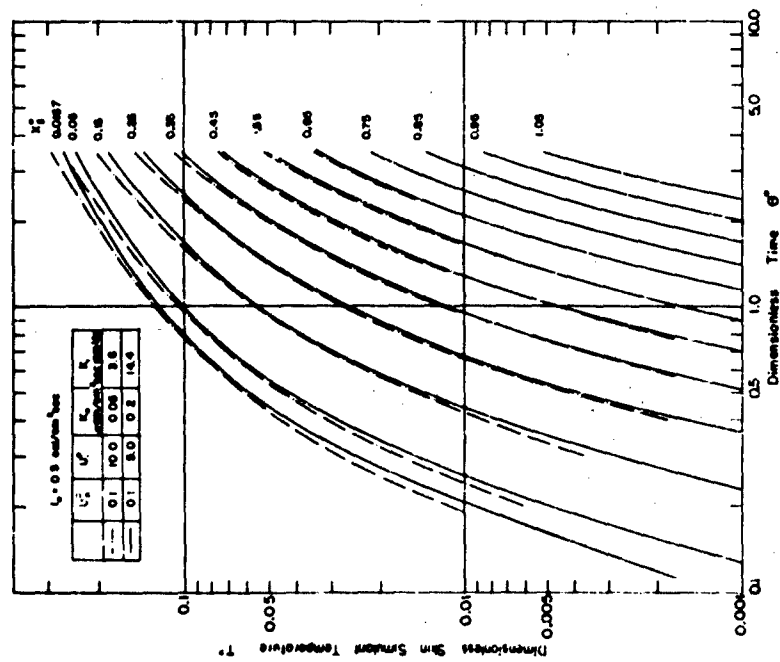


FIG. 2.15 TEMPERATURE RESPONSE OF MOIST CLOTH-SKIN SIMULATOR SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS.

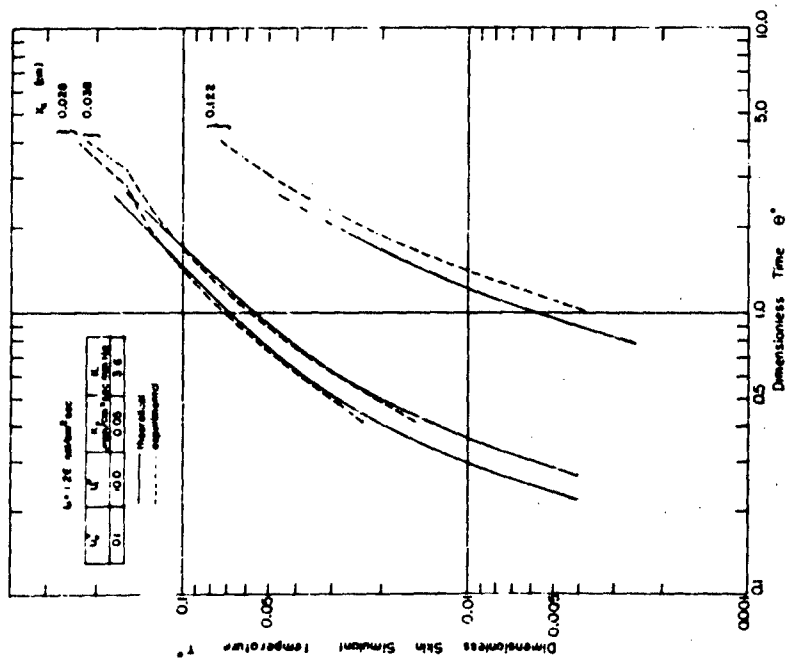


FIG 2.16 TEMPERATURE RESPONSE OF MOIST CLOTH-4-SKIN  
SIMULANT SYSTEM (OPAQUE). COMPARISON OF  
THEORETICAL AND EXPERIMENTAL RESULTS.

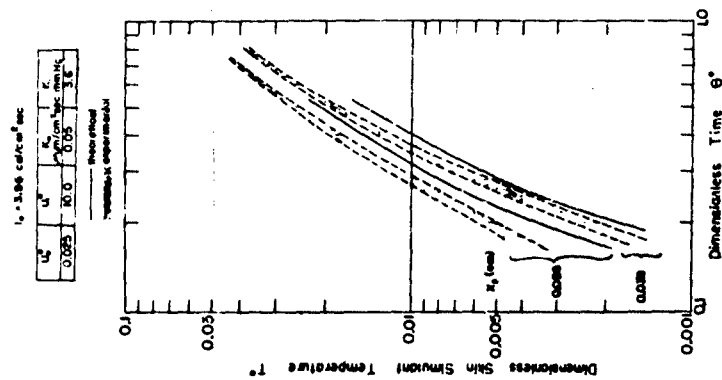


FIG 2.17 TEMPERATURE RESPONSE OF MOIST CLOTH-SKIN  
SIMULANT SYSTEM (OPAQUE). COMPARISON OF  
THEORETICAL AND EXPERIMENTAL RESULTS.

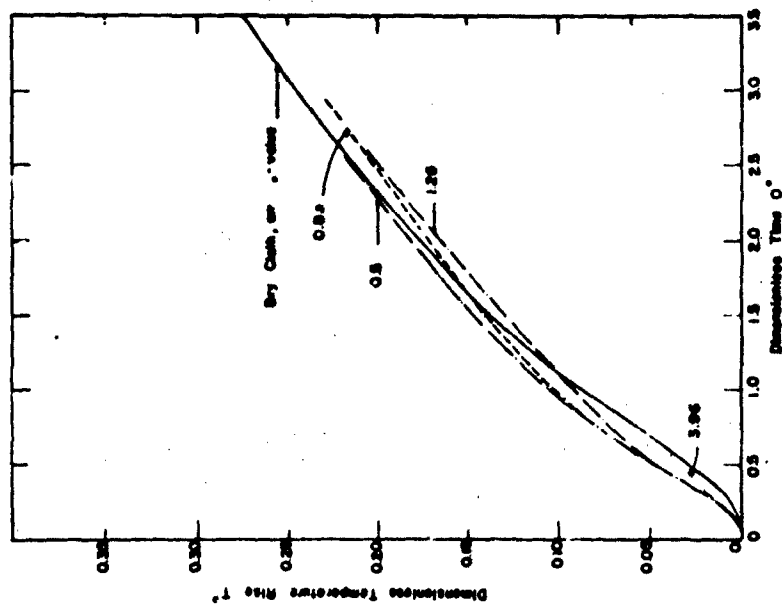


FIG 2.18 EFFECT OF INTENSITY ON THE TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (THEORETICAL SOLUTION) CLOTH - WHITE, W-4, 9.1% MOISTURE, 80% RELATIVE HUMIDITY,  $T_0 = 30^\circ\text{C}$  TEMPERATURE RESPONSE AT  $X_0 = 0.15$

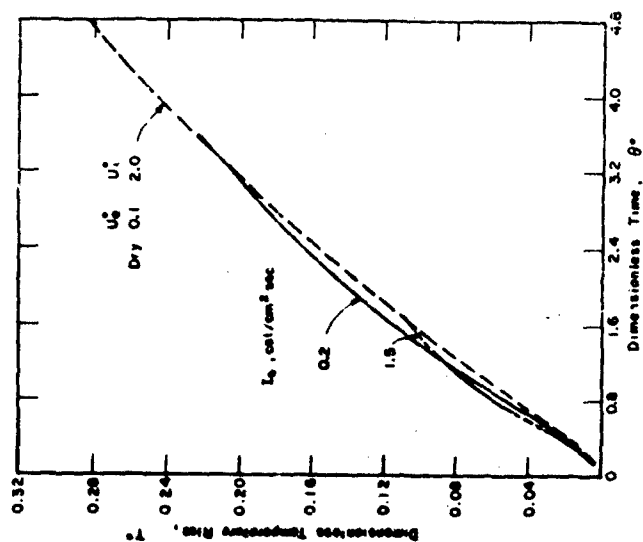


FIG 2.19 EFFECT OF INTENSITY ON THE TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (THEORETICAL SOLUTION) CLOTH - WHITE, W-4, 9.1% MOISTURE, 80% RELATIVE HUMIDITY,  $T_0 = 30^\circ\text{C}$  TEMPERATURE RESPONSE AT  $X_0 = 0.15$

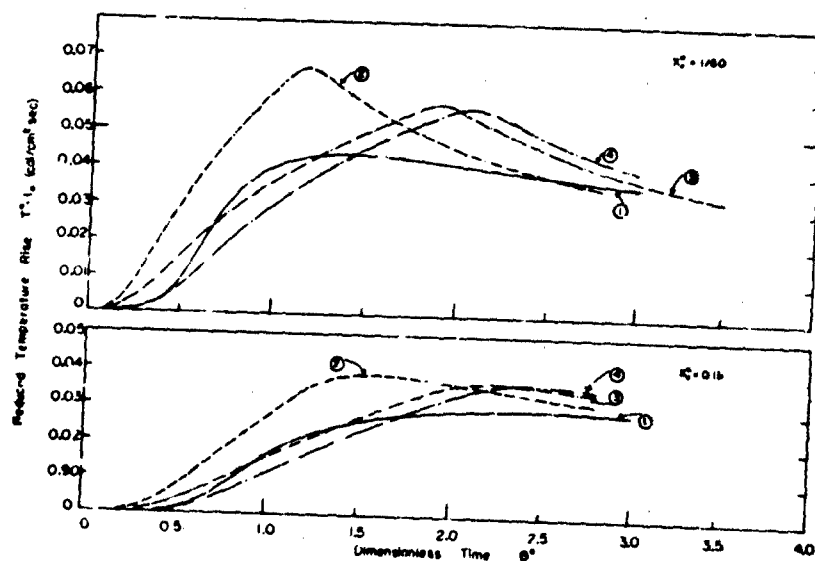
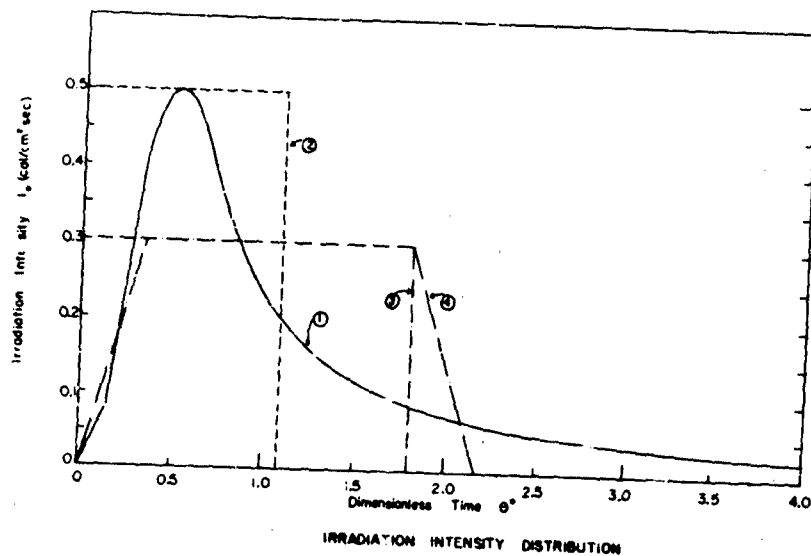


FIG 220 TEMPERATURE RESPONSE OF A MOIST OPAQUE CLOTH -  
SKIN SIMULANT SYSTEM INFLUENCE OF IRRADIATION PULSE  
SHAPE; PULSE AREA = 0.545 cal/cm<sup>2</sup>sec

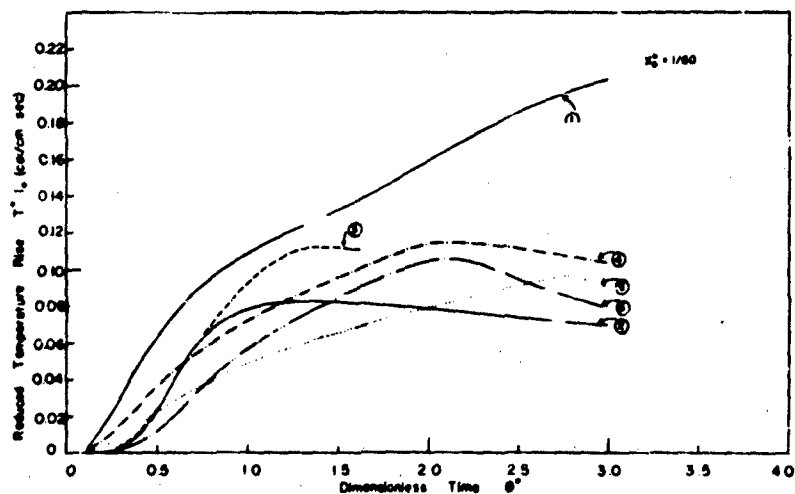
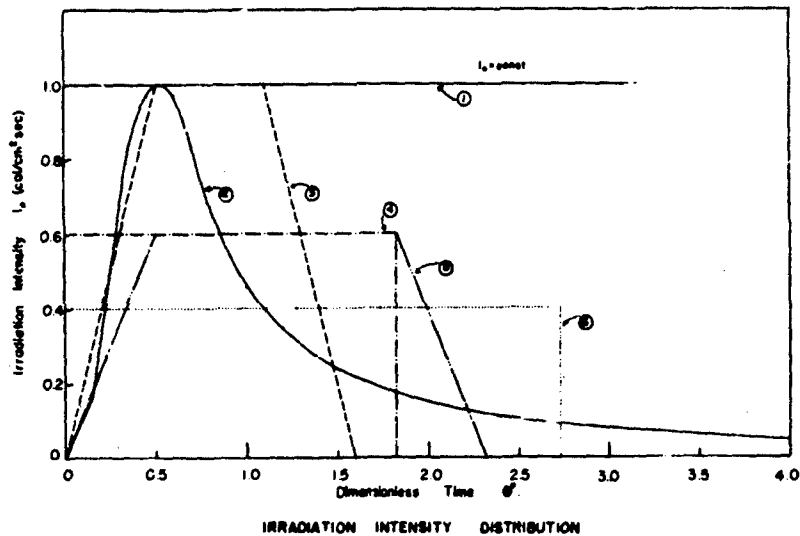


FIG. 2.21 TEMPERATURE RESPONSE OF A MOIST OPAQUE CLOTH - SKIN SIMULANT SYSTEM. INFLUENCE OF IRRADIATION PULSE SHAPE; PULSE AREA = 1.09 cal/cm<sup>2</sup> sec

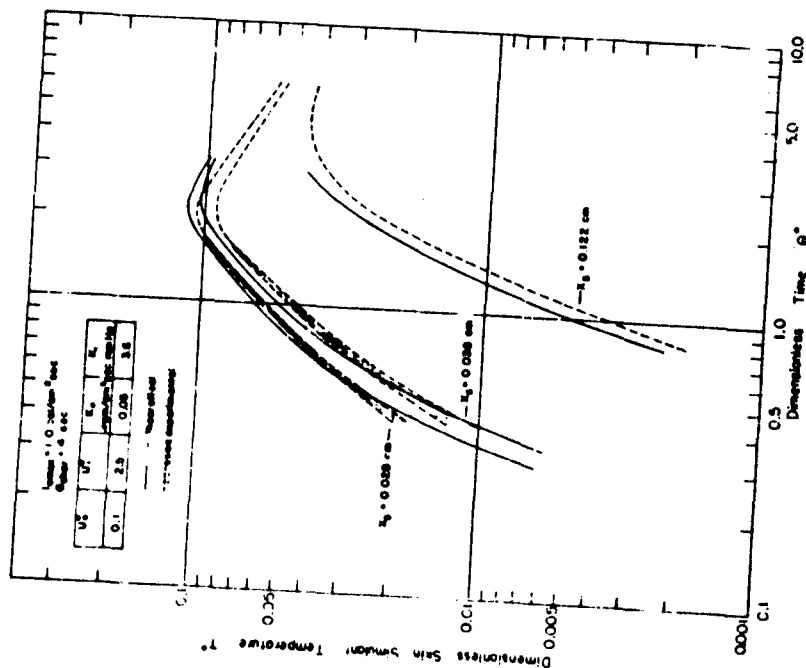


FIG 222 TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

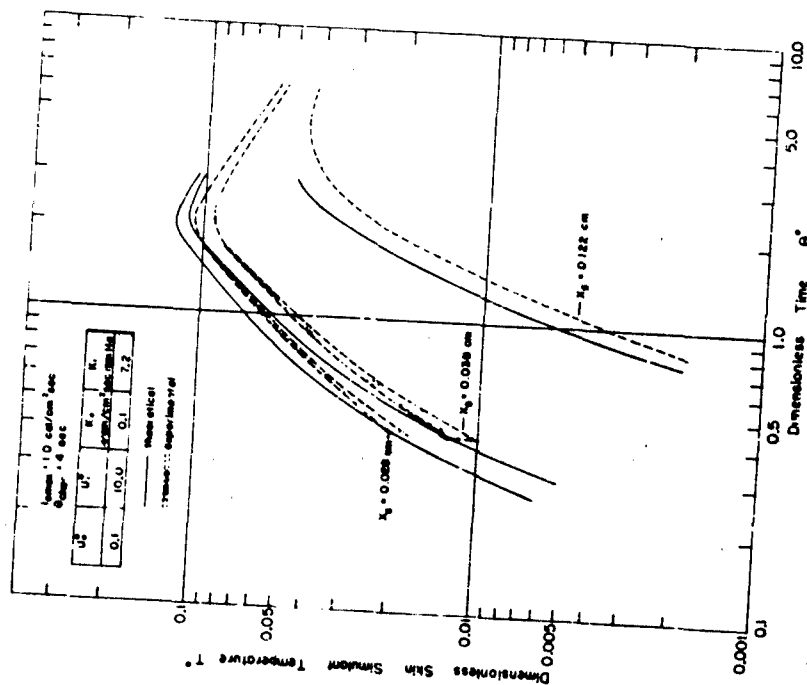


FIG 223 TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

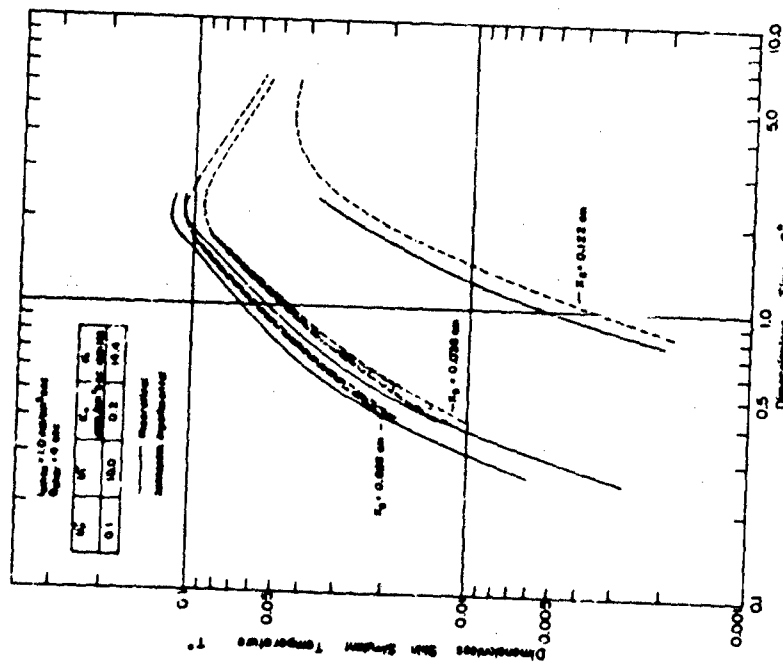


FIG 2.24 TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

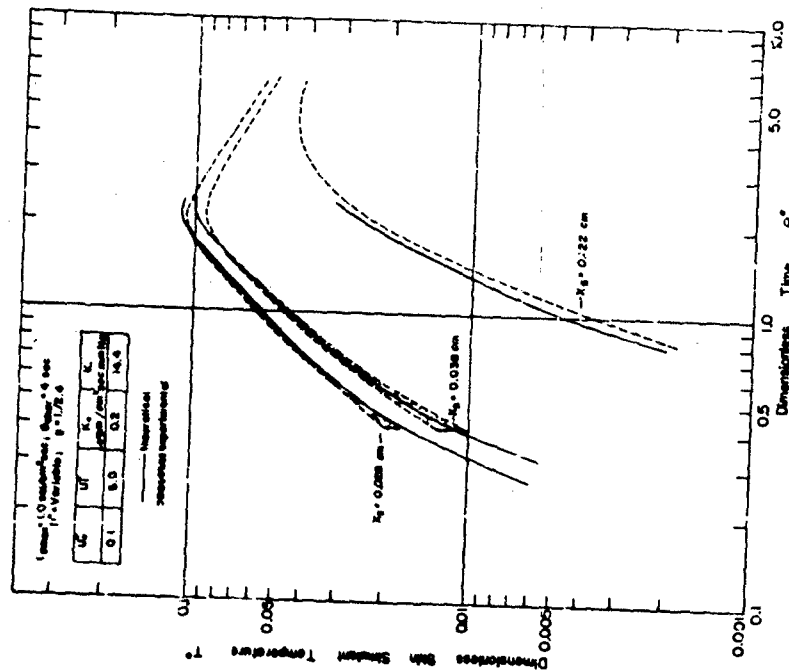


FIG 2.25 TEMPERATURE RESPONSE OF A MOIST CLOTH-SKIN SIMULANT SYSTEM (OPAQUE). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

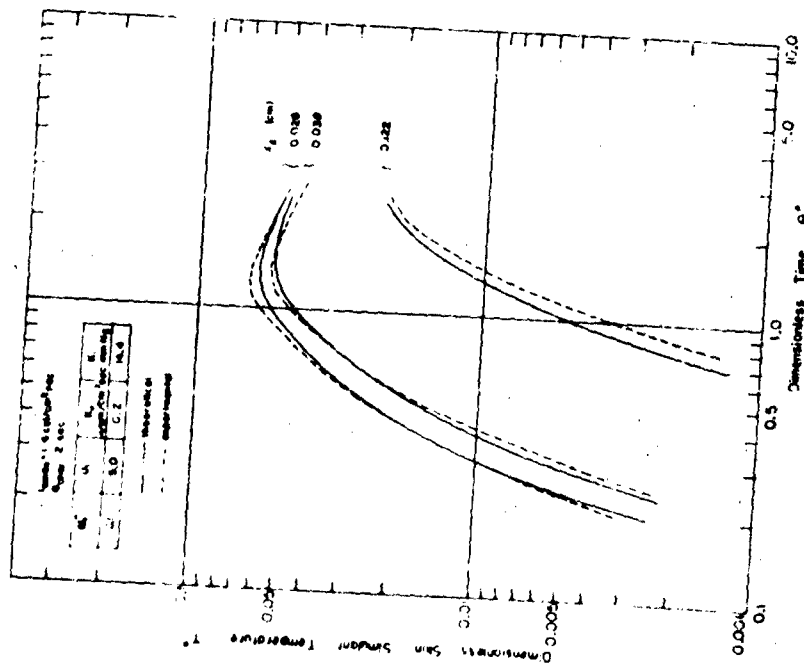


FIG 2.26 TEMPERATURE RESPONSE OF A MOIST CLOTH SKIN SIMULANT SYSTEM (OPAQ/E). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

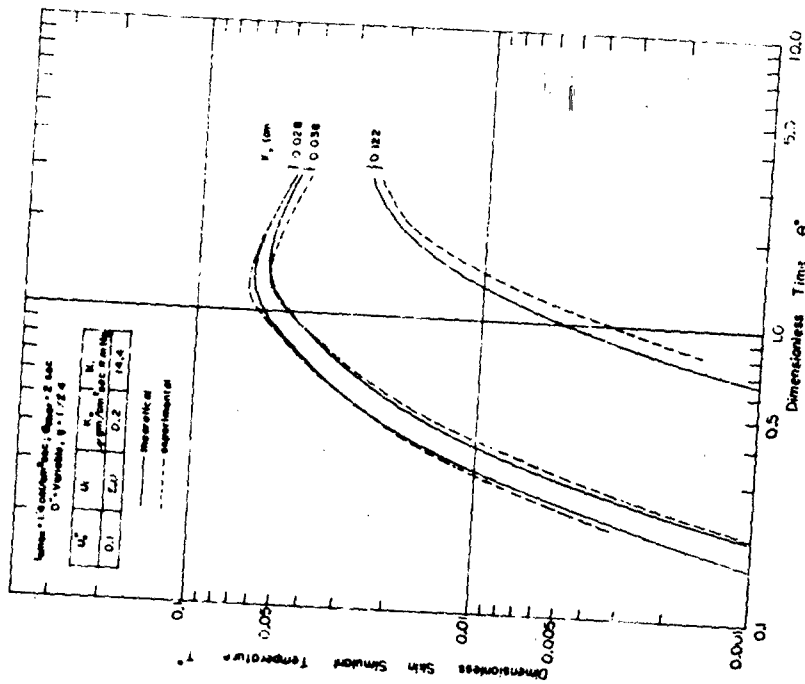


FIG 2.27 TEMPERATURE RESPONSE OF A MOIST CLOTH SKIN SIMULANT SYSTEM (OPAQ/E). COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR SQUARE WAVE IRRADIATION.

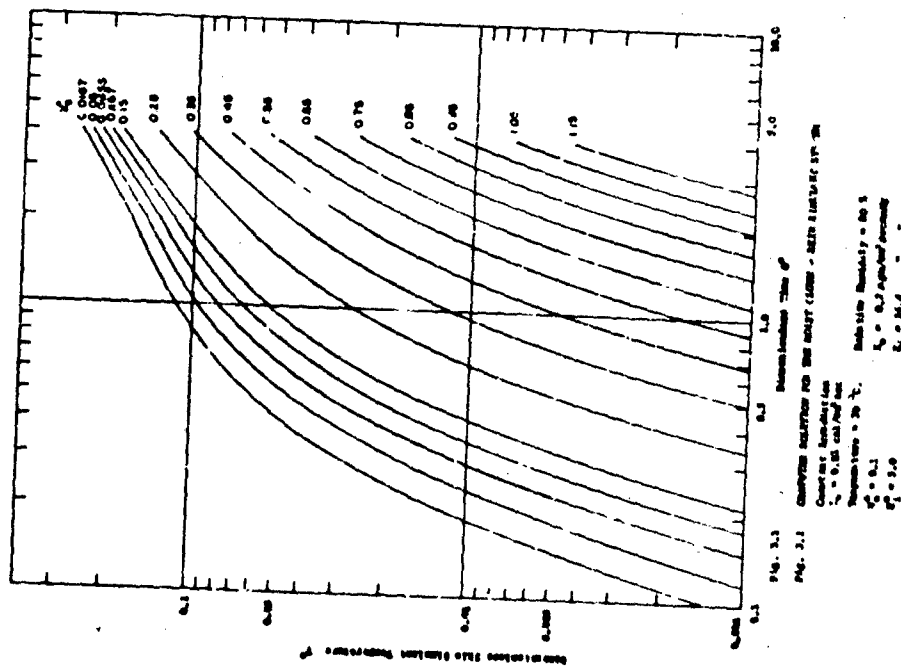


Fig. 3.1  
COMPOSITE SOLUTION FOR THE MOIST CLOUD - BEER SIMULANT SYSTEM

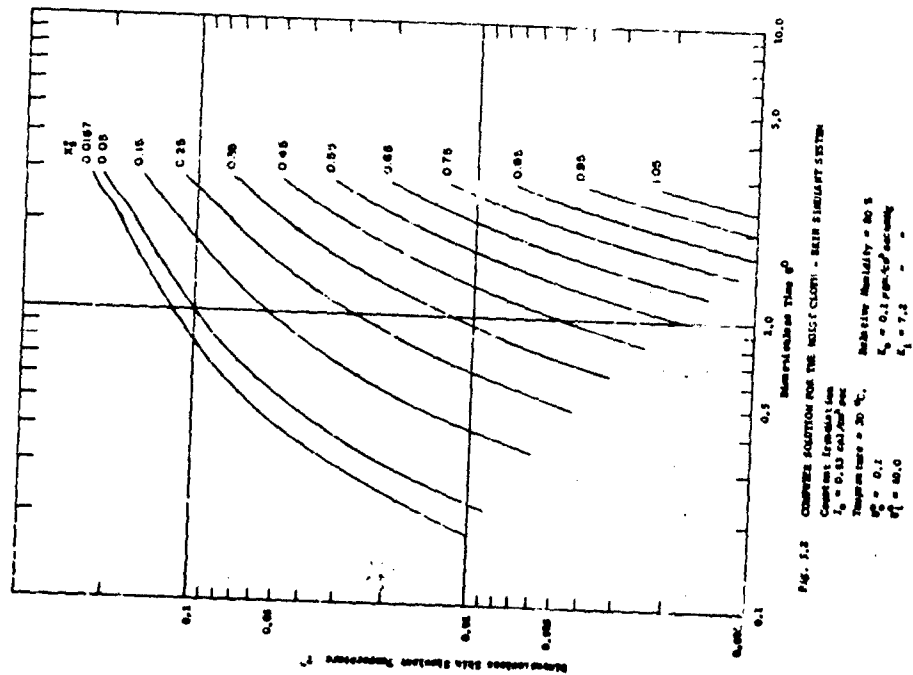


Fig. 3.2  
COMPOSITE SOLUTION FOR THE MOIST CLOUD - BEER SIMULANT SYSTEM

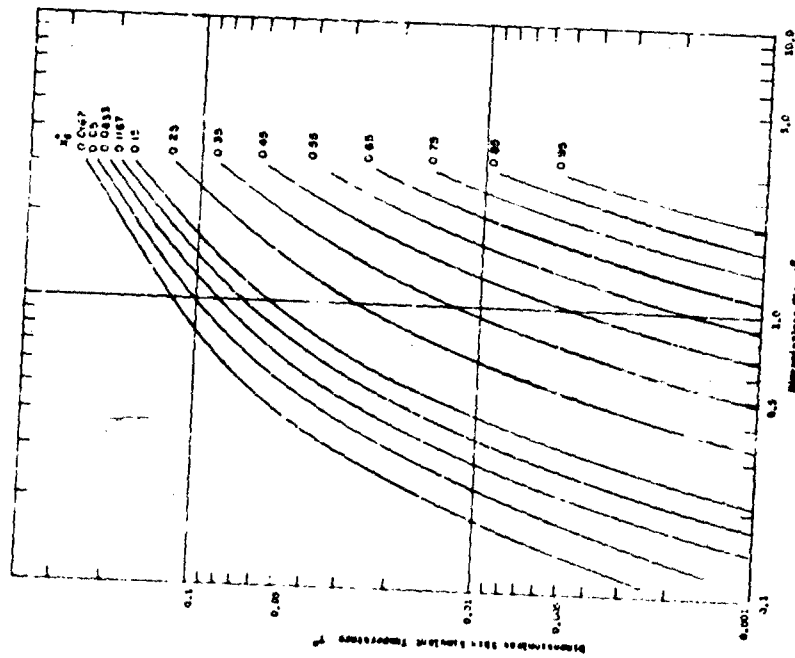


FIG. 3.1 CHART FOR DETERMINING THE RELATIONSHIP BETWEEN THE RATIO OF THE HEAT TRANSFER COEFFICIENT TO THE THERMAL CONDUCTIVITY OF THE MATERIAL,  $h/k$ , AND THE DIMENSIONLESS TIME,  $t/\tau$ .

Constant Irradiation  
 $I_0 = 0.83 \text{ cal/cm}^2 \text{ sec}$   
 Temperature =  $20^\circ \text{C}$   
 $\rho C_p = 0.4$   
 $\rho = 1.0$   
 Relative Humidity = 1.0  
 $h_0 = 0.05 \text{ gm/cm}^2 \text{ sec}$   
 $h_1 = 3.0$

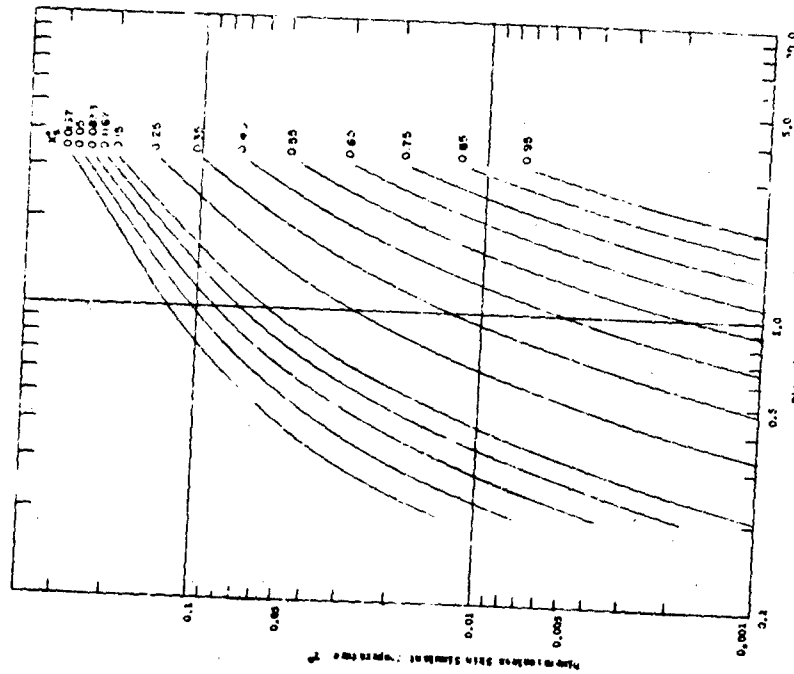


FIG. 3.2 CHART FOR DETERMINING THE RELATIONSHIP BETWEEN THE RATIO OF THE HEAT TRANSFER COEFFICIENT TO THE THERMAL CONDUCTIVITY OF THE MATERIAL,  $h/k$ , AND THE DIMENSIONLESS TIME,  $t/\tau$ .

Constant Irradiation  
 $I_0 = 0.83 \text{ cal/cm}^2 \text{ sec}$   
 Temperature =  $20^\circ \text{C}$   
 $\rho C_p = 0.4$   
 $\rho = 1.0$   
 Relative Humidity = 1.0  
 $h_0 = 0.05 \text{ gm/cm}^2 \text{ sec}$   
 $h_1 = 3.0$

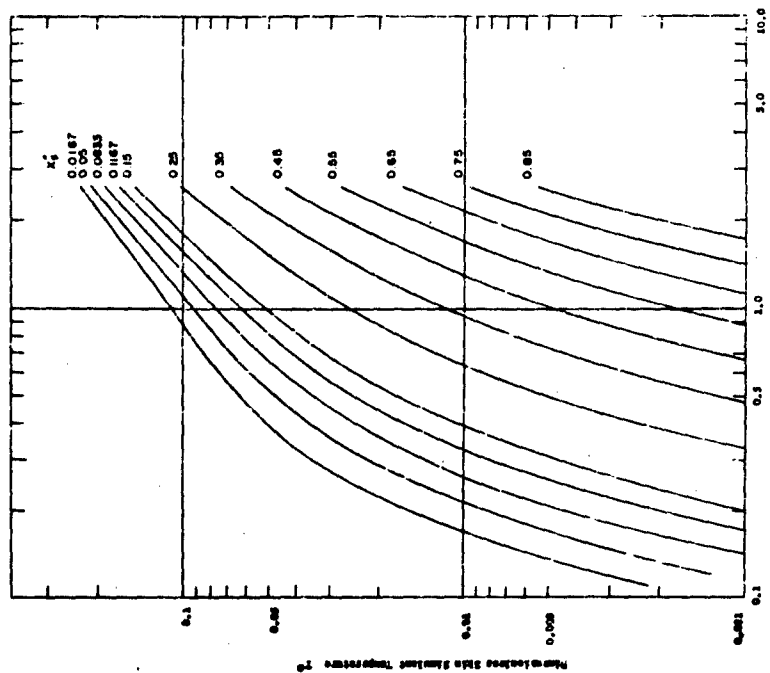


Fig. 3.4 COMPARISON SOLUTION FOR THE MOIST CLOTH - IN A SIMULANT SYSTEM

Constant Irradiation  
 $I_0 = 1.24 \text{ cal/cm}^2 \text{ sec}$   
 Temperature = 30 °C  
 $\rho_c = 0.1$   
 $\rho_f = 0.05 \text{ g/cm}^2 \text{ sec}$   
 $k_1 = 3.0$   
 $k_2 = 10.0$

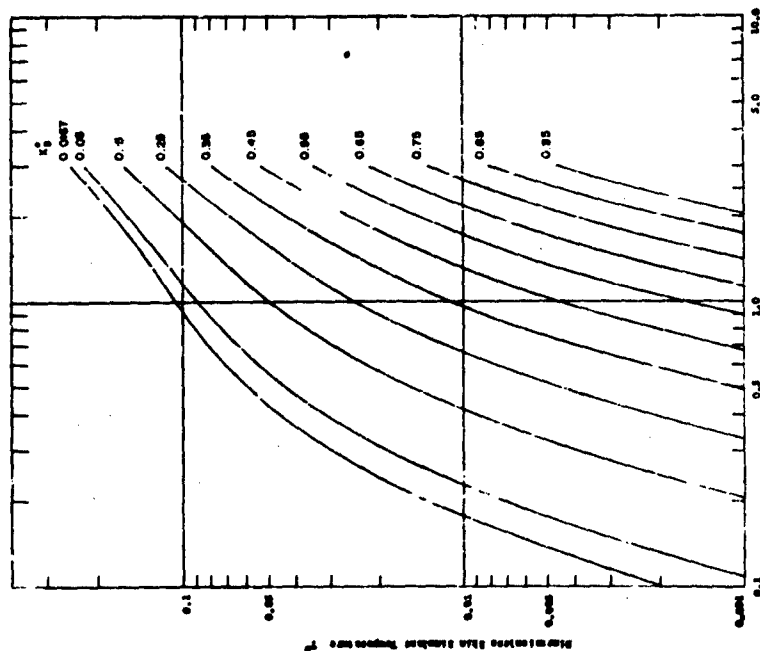


Fig. 3.5 COMPARISON SOLUTION FOR THE MOIST CLOTH - IN A SIMULANT SYSTEM

Constant Irradiation  
 $I_0 = 1.24 \text{ cal/cm}^2 \text{ sec}$   
 Temperature = 30 °C  
 $\rho_c = 0.1$   
 $\rho_f = 0.05 \text{ g/cm}^2 \text{ sec}$   
 $k_1 = 3.0$   
 $k_2 = 10.0$

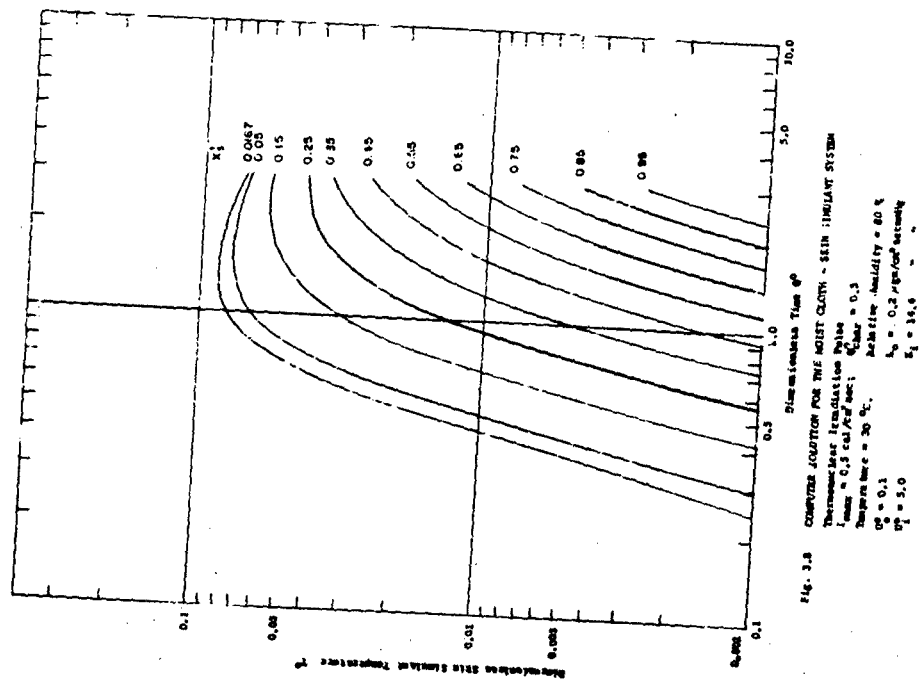


Fig. 3.7

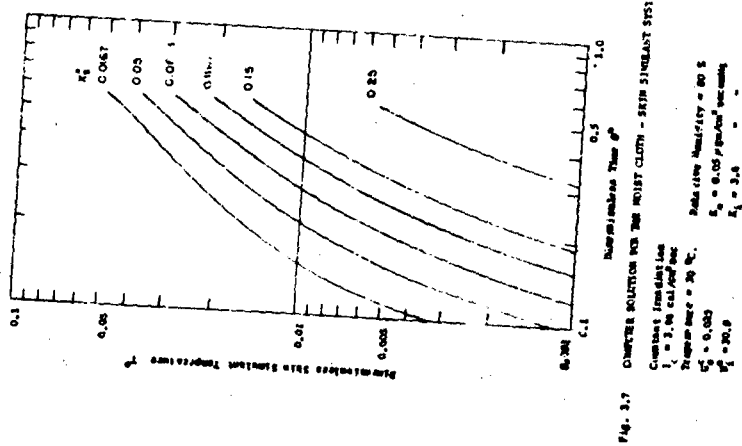


Fig. 3.8

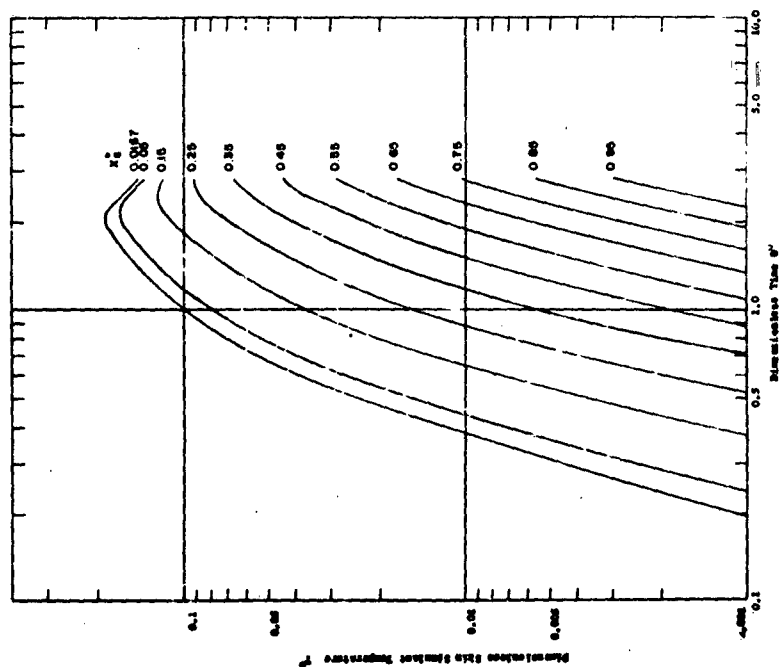


Fig. 3.10 COMPUTER SOLUTION FOR THE 517° CLOTH - 517° SIMULANT SYSTEM

Thermal Mass Iteration  
 $T_{s0} = 0.1$  cal/cm<sup>2</sup> sec<sup>2</sup>  $T_{s0} = 0.1$   $T_{s0} = 0.1$   
 Temperature = 30 °C. Relative Humidity = 10 %  
 $T_{s0} = 0.1$   $T_{s0} = 0.1$   $T_{s0} = 0.1$   
 $T_{s0} = 0.1$   $T_{s0} = 0.1$   $T_{s0} = 0.1$

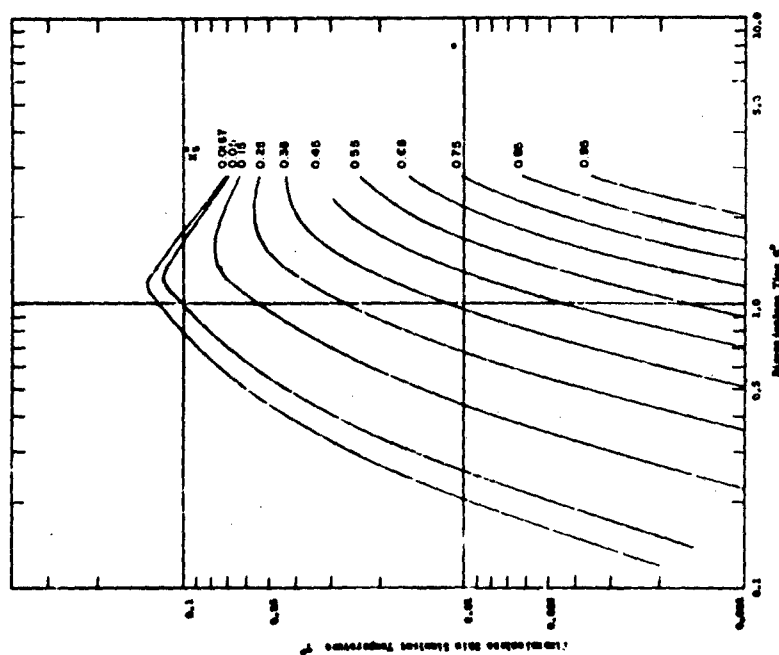


Fig. 3.10 COMPUTER SOLUTION FOR THE 517° CLOTH - 517° SIMULANT SYSTEM

Thermal Mass Iteration  
 $T_{s0} = 0.1$  cal/cm<sup>2</sup> sec<sup>2</sup>  $T_{s0} = 0.1$   $T_{s0} = 0.1$   
 Temperature = 30 °C. Relative Humidity = 10 %  
 $T_{s0} = 0.1$   $T_{s0} = 0.1$   $T_{s0} = 0.1$   
 $T_{s0} = 0.1$   $T_{s0} = 0.1$   $T_{s0} = 0.1$

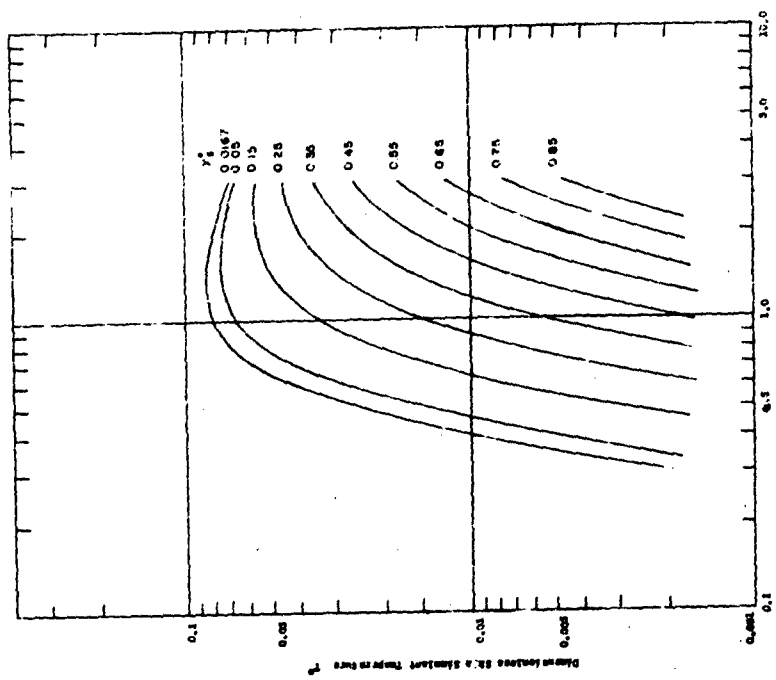


FIG. 3.12 COMPARISON SOLUTION FOR THE MOIST CLOTH - 8318 SIMULANT SYSTEM  
 Thermodynamic Properties:  $\rho_{\text{air}} = 1.0 \text{ g/cc}$ ;  $C_{\text{air}} = 0.5$   
 Temperature = 30 °C; Relative Humidity = 30 %  
 $\rho_0 = 0.1$   $\rho_1 = 0.2 \text{ g/cc}$   
 $\rho_2 = 5.0$   $\rho_3 = 14.5$

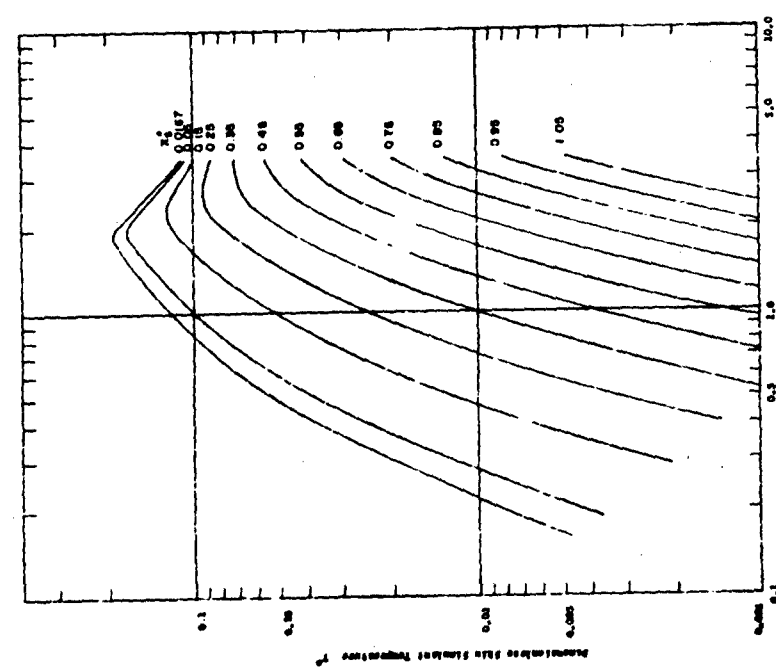


FIG. 3.11 COMPARISON SOLUTION FOR THE MOIST CLOTH - 8318 SIMULANT SYSTEM  
 Thermodynamic Properties:  $\rho_{\text{air}} = 1.0 \text{ g/cc}$ ;  $C_{\text{air}} = 0.5$   
 Temperature = 30 °C; Relative Humidity = 30 %  
 $\rho_0 = 0.1$   $\rho_1 = 0.2 \text{ g/cc}$   
 $\rho_2 = 5.0$   $\rho_3 = 14.5$

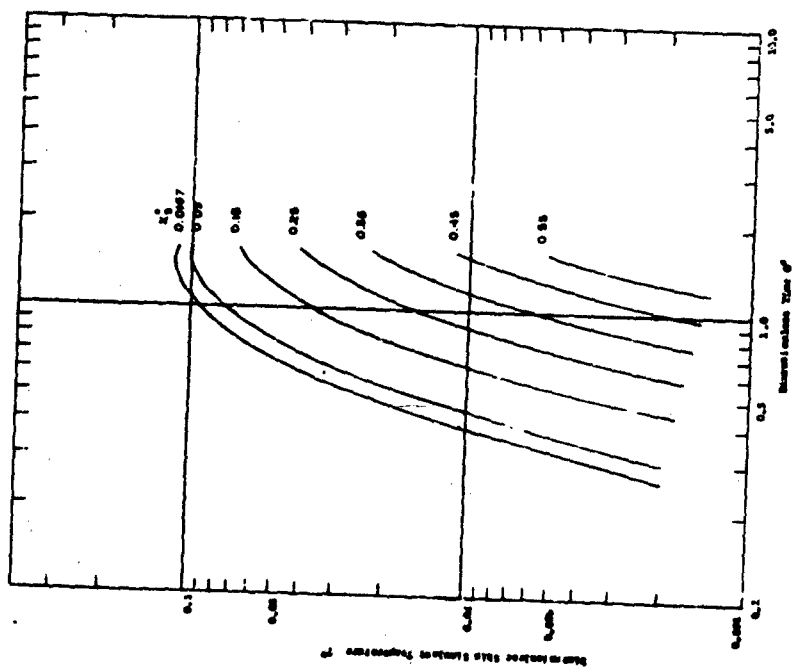


FIG. 3.13 CURVED SOLUTION FOR THE MOIST CLOTH - STEAM SIMULATION SYSTEM

Square wave irradiation  
 $\epsilon_{\text{cloth}} = 1.0$  cal/cm<sup>2</sup> sec  
 $\epsilon_{\text{steam}} = 1.0$   
 $\epsilon_{\text{water}} = 0.1$   
 $\epsilon_{\text{air}} = 0.2$  g/cm<sup>3</sup> sec

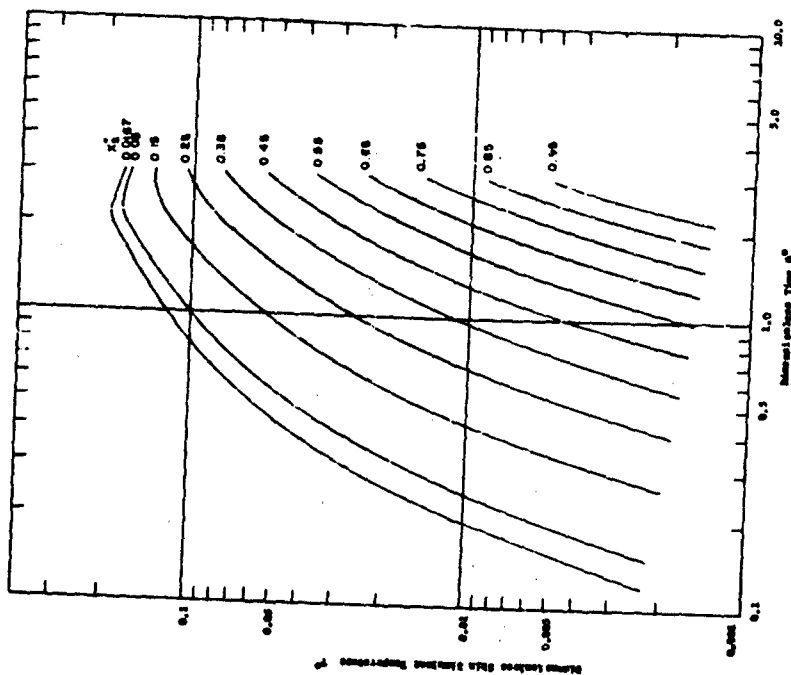
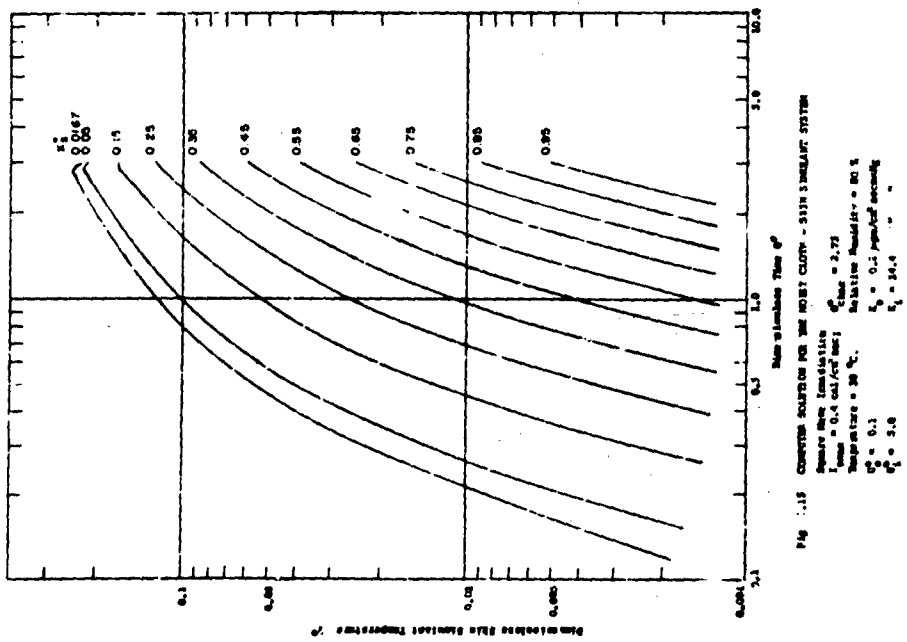
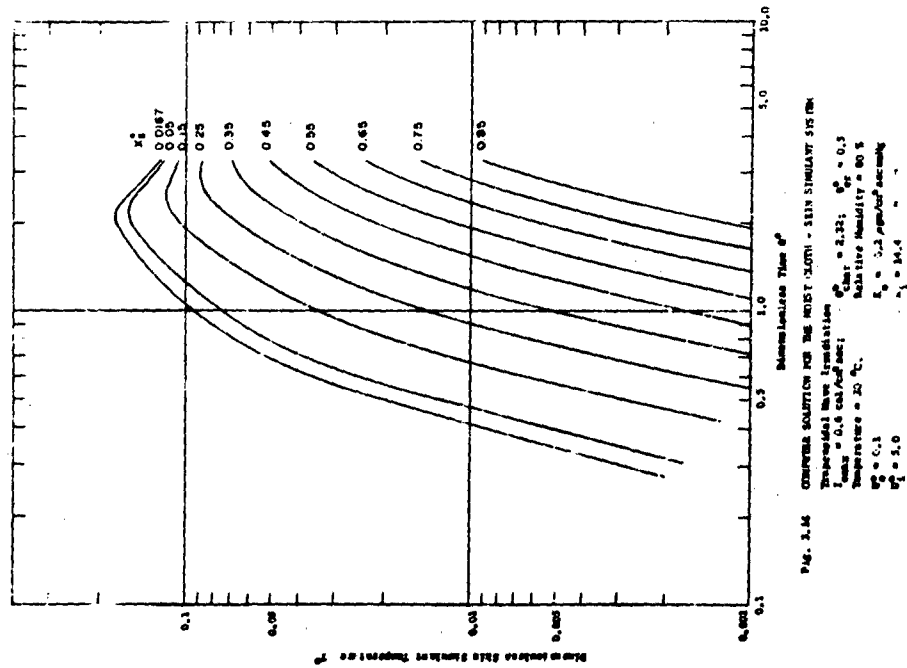


FIG. 3.14 CURVED SOLUTION FOR THE MOIST CLOTH - STEAM SIMULATION SYSTEM

Square wave irradiation  
 $\epsilon_{\text{cloth}} = 1.0$  cal/cm<sup>2</sup> sec  
 $\epsilon_{\text{steam}} = 1.0$   
 $\epsilon_{\text{water}} = 0.1$   
 $\epsilon_{\text{air}} = 0.2$  g/cm<sup>3</sup> sec



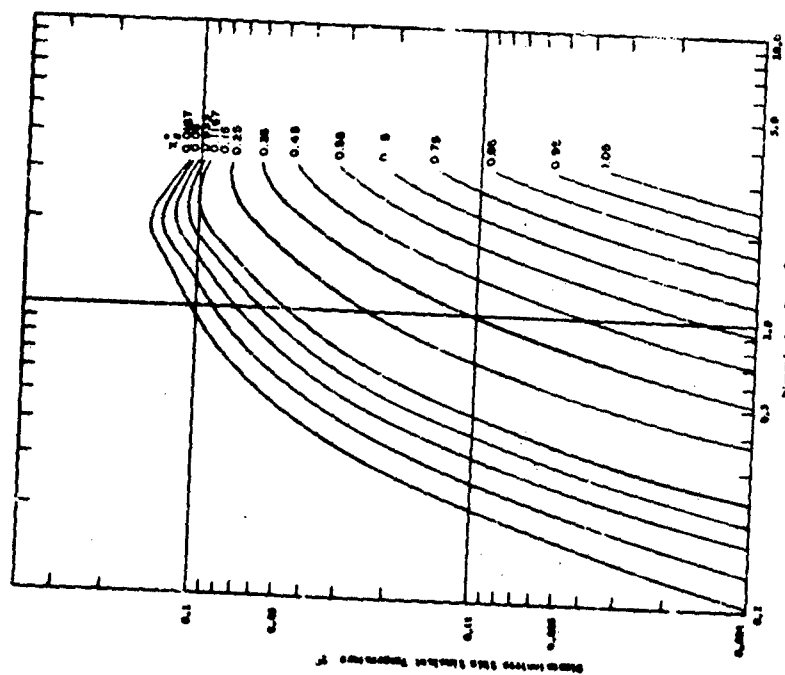


Fig. 2.27 COMPRESS SOLUTION FOR THE HERTZ CASE - 2024 SIMILARITY 5.0 200

Figure 2.27: Dimensionless Rate vs. Dimensionless Time for the Hertz Case. The graph shows a series of curves for different values of the dimensionless rate parameter  $\lambda$  (0.007 to 100.0). The curves generally decrease as time increases, with higher  $\lambda$  values resulting in higher rates. A vertical line is drawn at  $t' = 1.0$ .

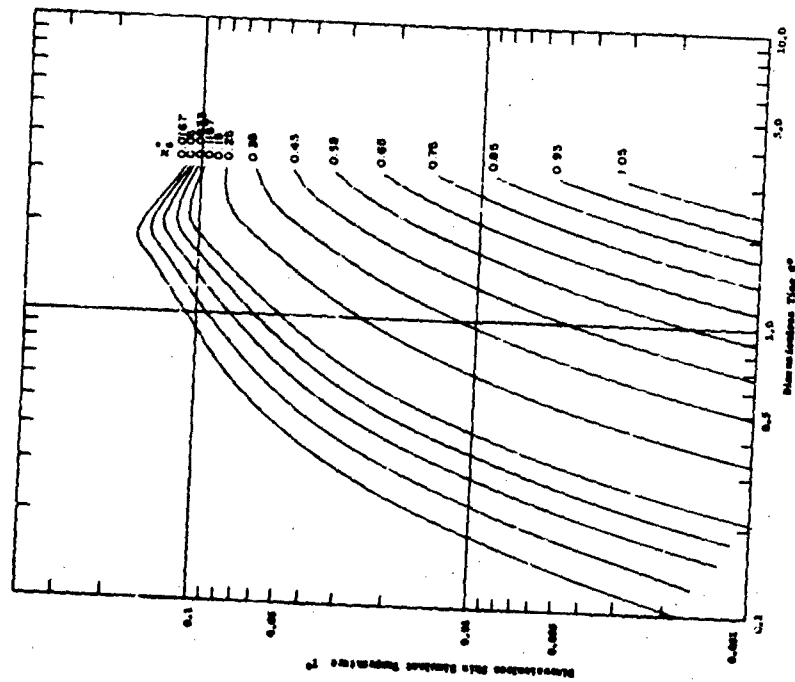
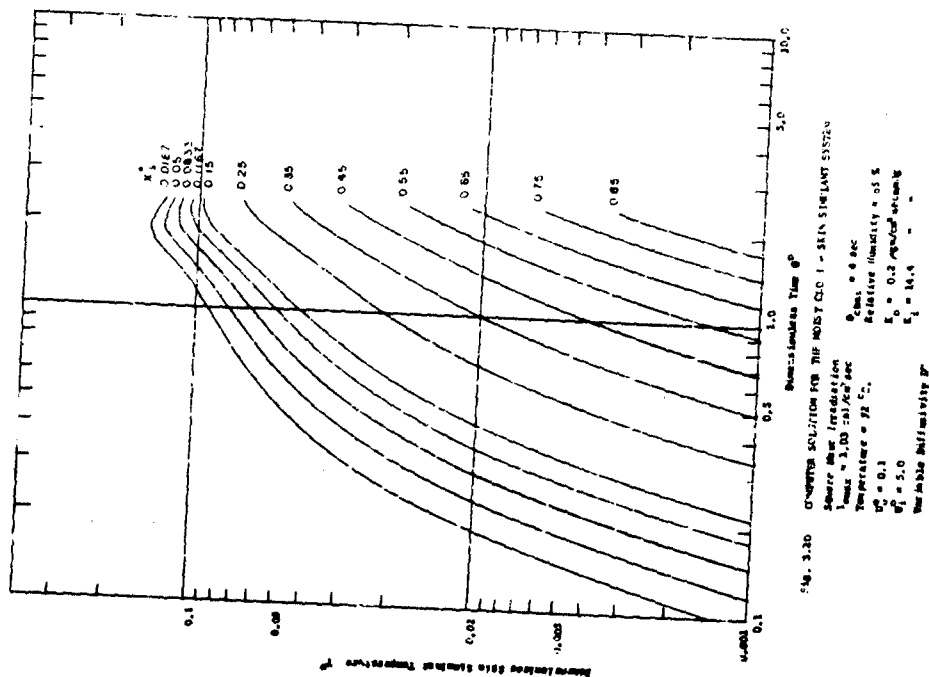
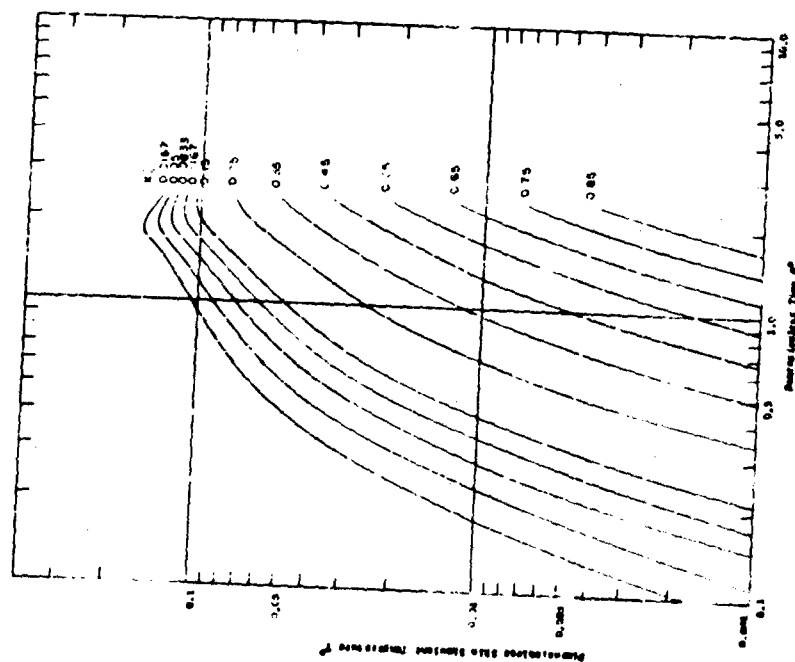


Fig. 2.28 COMPRESS SOLUTION FOR THE HERTZ CASE - 2024 SIMILARITY 5.0 200

Figure 2.28: Dimensionless Rate vs. Dimensionless Time for the Hertz Case. The graph shows a series of curves for different values of the dimensionless rate parameter  $\lambda$  (0.007 to 100.0). The curves generally decrease as time increases, with higher  $\lambda$  values resulting in higher rates. A vertical line is drawn at  $t' = 1.0$ .



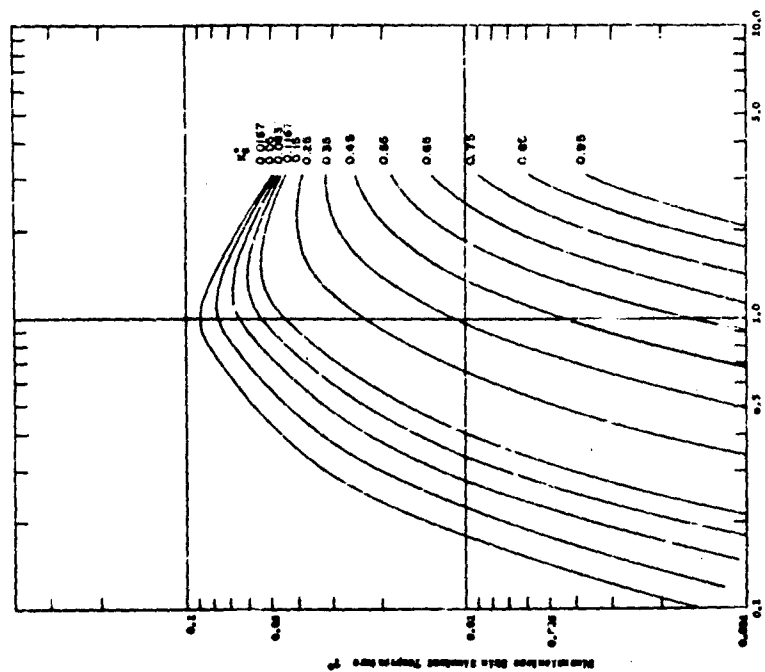
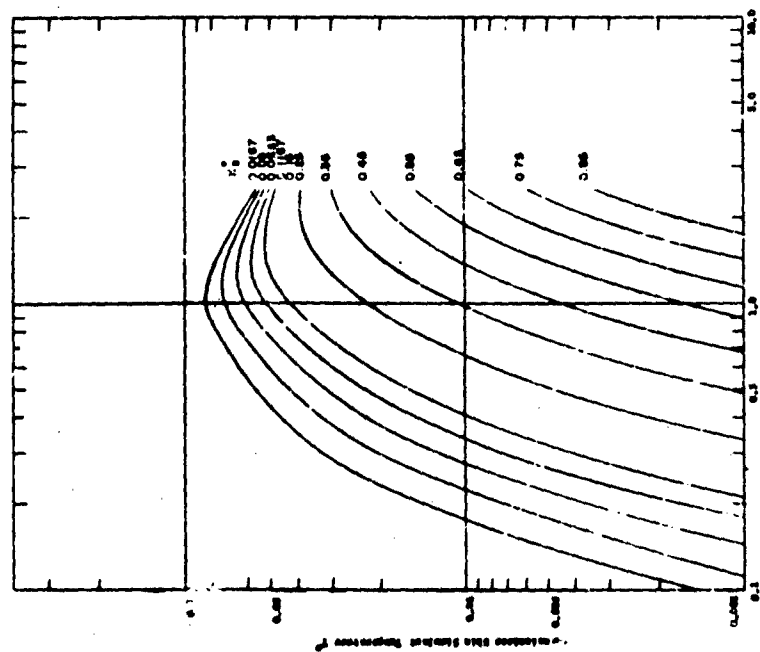


Fig. 3.22 COMPUTER SOLUTION FOR THE MOIST CURE - SEEN 5 INCH NOT SYSTEM

Exposure Time Irradiation  
 $t_{\text{exposure}} = 3.4 \text{ cal/cm}^2 \text{ sec.}$   
 Temperature =  $32^\circ \text{C.}$   
 $U_0^0 = 0.1$   
 $U_0^1 = 3.0$   
 Variable Diffusivity  $D^0$   
 $D^0_{\text{air}} = 2 \text{ sec.}$   
 Relative Humidity = 0.5  
 $K_2 = 6.2 \mu\text{g/cm}^2 \text{ sec.}$   
 $K_1 = 10.4$



Pgs. 1,23 COMPUTER CONTROL FOR THE INDUSTRY CLASH - SEE SUPPLEMENT 515 THE

Figure 1 shows the results of  
 $\gamma_{\text{max}} = 1.0 \text{ cal/deg}^2 \text{ sec}$ ;  
 Temperature =  $20^\circ \text{C}$ .  
 $\epsilon_0 = 0.1$   
 $\epsilon_1 = 3.0$   
 $\epsilon_{\text{max}} = 2 \text{ sec}$   
 Definition:  $\text{Mod} \text{ Mod} = 0.5$   
 $\epsilon_0 = 0.2 \text{ deg/deg}^2 \text{ sec/deg}$   
 $\epsilon_1 = 10.4$

APPENDIX G

EQUILIBRIUM DATA ON MOIST CLOTH

This data is used in the numerical solution of transient heat and moisture transfer through cloth.

TABLE G.1  
EQUILIBRIUM MOISTURE CONTENT OF CLOTH AS A FUNCTION  
OF TEMPERATURE AND RELATIVE HUMIDITY

| T, °C | RH, % |      |      |      |      |      |      |      |      |      |      |      |      |      |  |  |  |  |  |
|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|--|--|--|--|--|
|       | .05   | .1   | .2   | .3   | .4   | .5   | .6   | .65  | .7   | .75  | .8   | .85  | .9   | .95  |  |  |  |  |  |
| 20    | .015  | .021 | .030 | .038 | .047 | .055 | .065 | .070 | .077 | .085 | .095 | .109 | .128 | .156 |  |  |  |  |  |
| 30    | .013  | .018 | .027 | .035 | .044 | .052 | .061 | 0.67 | .073 | .081 | .091 | .103 | .121 | .147 |  |  |  |  |  |
| 40    | .011  | .016 | .025 | .033 | .041 | .049 | .058 | .064 | .070 | .077 | .086 | .099 | .115 | .142 |  |  |  |  |  |
| 50    | .010  | .015 | .023 | .031 | .039 | .047 | .056 | .061 | .067 | .075 | .084 | .096 | .113 | .139 |  |  |  |  |  |
| 60    | .009  | .013 | .021 | .029 | .037 | .045 | .054 | .059 | .065 | .072 | .081 | .094 | .110 | .143 |  |  |  |  |  |
| 70    | .008  | .012 | .020 | .027 | .035 | .043 | .052 | .057 | .062 | .069 | .079 | .092 | .111 | .151 |  |  |  |  |  |
| 80    | .007  | .011 | .018 | .026 | .033 | .041 | .050 | .054 | .060 | .067 | .077 | .092 | .114 | .157 |  |  |  |  |  |
| 90    | .006  | .010 | .018 | .025 | .032 | .039 | .047 | .051 | .057 | .065 | .077 | .095 | .118 | .164 |  |  |  |  |  |
| 100   | .006  | .009 | .017 | .024 | .030 | .037 | .045 | .049 | .054 | .062 | .073 | .092 | .122 | .169 |  |  |  |  |  |
| 110   | .005  | .009 | .016 | .022 | .029 | .035 | .042 | .046 | .051 | .058 | .068 | .097 | .119 | .166 |  |  |  |  |  |
| 120   | .004  | .009 | .015 | .021 | .028 | .034 | .040 | .044 | .043 | .055 | .064 | .083 | .112 | .160 |  |  |  |  |  |

Date of Urquhardt and Williams (22)

TABLE G.2

GRADIENTS OF EQUILIBRIUM MOISTURE CONTENT OF CLOTH  
AS FUNCTIONS OF TEMPERATURE AND PARTIAL WATER VAPOR PRESSURE

| AS FUNCTIONS OF TEMPERATURE AND PARTIAL WATER VAPOR PRESSURE |        |                                 |        |        |        |        |        |        |        |        |        |        |         |  |
|--------------------------------------------------------------|--------|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|--|
| T (°K)                                                       |        | HUMIDITY RATIO CONTENT OF CLOTH |        |        |        |        |        |        |        |        |        |        |         |  |
| 303.                                                         | 1.454  | 2.959                           | 7.320  | 10.32  | 12.36  | 15.96  | 19.28  | 22.17  | 24.86  | 26.29  | 27.17  | 27.96  | PRES 1  |  |
| 313.                                                         | 3.175  | 6.040                           | 13.91  | 19.43  | 23.24  | 29.78  | 35.33  | 40.20  | 44.65  | 46.96  | 48.30  | 49.48  | PRES 2  |  |
| 323.                                                         | 6.459  | 11.70                           | 25.48  | 35.06  | 41.63  | 52.60  | 61.52  | 69.40  | 76.44  | 80.09  | 82.11  | 85.86  | PRES 3  |  |
| 333.                                                         | 12.34  | 21.58                           | 44.94  | 60.70  | 71.29  | 86.54  | 102.4  | 114.7  | 125.4  | 131.0  | 134.1  | 136.7  | PRES 4  |  |
| 343.                                                         | 22.29  | 37.99                           | 76.24  | 100.9  | 117.1  | 142.8  | 163.5  | 182.2  | 193.1  | 206.6  | 211.2  | 215.2  | PRES 5  |  |
| 353.                                                         | 39.28  | 64.04                           | 124.4  | 161.4  | 184.9  | 221.7  | 251.6  | 279.3  | 302.5  | 315.2  | 322.0  | 328.1  | PRES 6  |  |
| 363.                                                         | 62.85  | 103.7                           | 195.6  | 248.9  | 281.9  | 332.7  | 374.5  | 414.8  | 448.1  | 466.7  | 476.8  | 486.1  | PRES 7  |  |
| 373.                                                         | 99.09  | 161.6                           | 296.5  | 370.7  | 415.6  | 484.4  | 541.0  | 598.5  | 645.9  | 672.8  | 687.6  | 701.5  | PRES 8  |  |
| 403.                                                         | 316.2  | 502.0                           | 845.6  | 1016.  | 1120.  | 1283.  | 1399.  | 1550.  | 1682.  | 1757.  | 1800.  | 1042.  | PRES 9  |  |
| 433.                                                         | 789.1  | 1216.                           | 1857.  | 2194.  | 2431.  | 2833.  | 3006.  | 3357.  | 3706.  | 3889.  | 3997.  | 4103.  | PRES 10 |  |
| j -                                                          |        |                                 |        |        |        |        |        |        |        |        |        |        |         |  |
| 303.                                                         | .1191  | .2191                           | .4821  | .6747  | .8115  | 1.043  | 1.221  | 1.378  | 1.521  | 1.592  | 1.629  | 1.661  | DPT 1   |  |
| 313.                                                         | .2363  | .4150                           | .8679  | 1.188  | 1.410  | 1.773  | 2.046  | 2.290  | 2.504  | 2.612  | 2.667  | 2.714  | DPT 2   |  |
| 323.                                                         | .4377  | .7445                           | 1.495  | 1.997  | 2.331  | 2.861  | 3.267  | 3.632  | 3.941  | 4.103  | 4.185  | 4.256  | DPT 3   |  |
| 333.                                                         | .7629  | 1.270                           | 2.463  | 3.207  | 3.682  | 4.413  | 4.993  | 5.526  | 5.963  | 6.201  | 6.324  | 6.434  | DPT 4   |  |
| 343.                                                         | 1.260  | 2.064                           | 3.882  | 4.933  | 5.574  | 6.542  | 7.339  | 8.098  | 8.710  | 9.056  | 9.239  | 9.408  | DPT 5   |  |
| 353.                                                         | 1.981  | 3.211                           | 5.860  | 7.281  | 8.116  | 9.361  | 10.41  | 11.48  | 12.33  | 12.83  | 13.10  | 13.35  | DPT 6   |  |
| 363.                                                         | 2.984  | 4.793                           | 8.488  | 10.34  | 11.40  | 12.98  | 14.32  | 15.78  | 16.97  | 17.67  | 18.07  | 18.45  | DPT 7   |  |
| 373.                                                         | 4.324  | 6.888                           | 11.82  | 14.15  | 15.48  | 17.51  | 19.14  | 21.13  | 22.78  | 23.76  | 24.32  | 24.87  | DPT 8   |  |
| 403.                                                         | 10.81  | 16.72                           | 25.61  | 29.81  | 32.63  | 37.39  | 39.58  | 44.13  | 48.56  | 50.94  | 52.38  | 53.80  | DPT 9   |  |
| 433.                                                         | 21.40  | 31.57                           | 41.62  | 48.86  | 55.46  | 67.77  | 68.93  | 78.15  | 89.00  | 94.06  | 97.07  | 100.0  | DPT 10  |  |
| j -                                                          |        |                                 |        |        |        |        |        |        |        |        |        |        |         |  |
| 303.                                                         | 5.205  | 4.267                           | 2.393  | 1.830  | 1.786  | 2.376  | 3.677  | 5.401  | 7.498  | 8.837  | 9.681  | 10.51  | DMP 1   |  |
| 313.                                                         | 3.062  | 2.427                           | 1.250  | .9198  | .9294  | 1.401  | 2.249  | 3.335  | 4.603  | 5.368  | 5.844  | 6.284  | DMP 2   |  |
| 323.                                                         | 1.849  | 1.417                           | .6747  | .9954  | .5324  | .8832  | 1.436  | 2.123  | 2.896  | 3.354  | 3.626  | 3.871  | DMP 3   |  |
| 333.                                                         | 1.147  | .8479                           | .3764  | .2880  | .3327  | .5845  | .9474  | 1.389  | 1.866  | 2.150  | 2.316  | 2.462  | DMP 4   |  |
| 343.                                                         | .7253  | .5178                           | .2196  | .1931  | .2254  | .4007  | .6381  | .9267  | 1.227  | 1.409  | 1.513  | 1.607  | DMP 5   |  |
| 353.                                                         | .4674  | .3228                           | .1357  | .1262  | .1617  | .2820  | .4379  | .6293  | .8237  | .9434  | 1.011  | 1.075  | DMP 6   |  |
| 363.                                                         | .3055  | .2050                           | .08964 | .09306 | .1211  | .2029  | .3054  | .4343  | .5628  | .6436  | .6899  | .7345  | DMP 7   |  |
| 373.                                                         | .2025  | .1331                           | .06336 | .07166 | .09276 | .1486  | .2159  | .3039  | .3914  | .4471  | .4796  | .5113  | DMP 8   |  |
| 403.                                                         | .06435 | .04287                          | .02995 | .03642 | .04458 | .06375 | .08216 | .1121  | .1437  | .1639  | .1763  | .1890  | DMP 9   |  |
| 433.                                                         | .02606 | .01916                          | .01657 | .01880 | .02185 | .02983 | .03436 | .04552 | .05933 | .06759 | .07283 | .07824 | DMP 10  |  |

APPENDIX H

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