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# AN ANALYTICAL STUDY OF THE APPLICATION OF PHASE-CHANGE MATERIALS TO CONTROL GUN TUBE TEMPERATURES

## TECHNICAL REPORT

**Dr. William J. Leech**

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An analytical study was conducted by the Research Directorate, Weapons Laboratory at Rock Island, to determine the feasibility of using layers of phase-change materials to control gun tube temperatures. A mathematical model of the process was developed and programmed for numerical evaluation. Results of a parametric study were used to determine the optimum characteristics of the phase-change layer.

A brief literature survey was made to determine the thermal property-values of materials in which phase-change occurs in the desired temperature range. Two materials were chosen for further numerical study. The results of this investigation show that gun-tube temperature control with a phase-change layer is thermally feasible. The major difficulty is that of finding a material with the desirable thermal properties by which structural soundness of the gun tubes will be provided. The barrel exterior is the best location for the phase-change layer. Thermal control is provided, and it is obvious that applying a thin layer of phase-change material to the outside surface of the barrel will not affect its structural strength.

# CONTENTS

## INTRODUCTION

A primary factor limiting the burst length and tube life of high rate of fire automatic weapons is the temperature rise that occurs when heat from the propellant gas is absorbed by the gun tube. The high temperatures attained during sustained bursts cause thermal expansion, which leads to seizure at the interface of moving parts. The barrel material has lower yield strength at higher temperatures and may become deformed or ruptured. The bore surface becomes quite hot and erosion of the surface seriously reduces tube life. A number of techniques for reducing the seriousness of the heating problem have been investigated.

Three basic approaches are available for reducing gun tube temperatures. One approach is to increase the heat loss at the tube exterior. This may be accomplished by an increase in convective heat transfer by directing a high-speed air stream over the tube or providing the tube with fins. Increased heat loss can also be brought about by an increase in the thermal emissivity of the tube surface because the heat loss by thermal radiation is increased. These techniques have practical limits and are not, by themselves, sufficient to cool high rate of fire guns. A second approach is to limit the heat input to the barrel. This can be done by use of a multilayer barrel having a layer of material which has high thermal resistance.[1] Ablative materials may be added to the round to absorb heat[2], and propellant additives may be used to reduce the effective gas temperature.[3] A third approach is to increase the thermal capacity of the barrel. This can be done by an increase in the weight or in the specific heat of the barrel. Barrel weights should be as small as possible. Thus, increasing the weight is limited as a practical solution. Little variation occurs in the specific heats of typical barrel materials, so that method is also severely limited. Another method of increasing the thermal capacity, which appears not to have been investigated previously, is to provide the barrel with a layer of material which changes phase.

In this report, the investigation of the feasibility of using a phase-change layer to control barrel temperatures will be discussed; this will be investigated from a thermal point of view only, even though structural and fabrication considerations are equally important. The belief is that the thermal feasibility, or lack of it, should first be established.

Relatively large amounts of heat are absorbed when a material changes phase. The phase change occurs at an essentially isothermal condition, so that heat is absorbed with little temperature increase. The method is completely passive, and the thermal capacity is increased by the phase change layer with little or no increase in weight. A reduction in weight is conceivable. Types of phase changes for solids include solid-solid, solid-liquid, and solid-gas. A solid-to-gas phase change would be undesirable for a barrel layer. A solid-solid phase change is more desirable from a structural point of view, but these phase changes usually have small latent heats. A solid-liquid phase change usually has a larger latent heat associated with it, but structural soundness and fabrication techniques become a problem.

In the analysis which follows, the temperature distribution will be determined for a slab which contains a layer that may change phase. The governing equations are given in the following section. Additional sections describe the numerical algorithm, and give the results of a parametric study. A discussion of the results and their application to gun tubes and conclusions and recommendations are also given.

## THEORETICAL ANALYSIS

In this section, the theoretical analysis of the heat conduction problem in a gun tube which contains a phase change layer is outlined. A physical model was proposed and is used to obtain a mathematical formulation of the problem. The governing equations are then recast in dimensionless form to determine the significant physical parameters. Two criteria are given for comparing a barrel having a phase change layer, with a conventional barrel.

### Physical Model

A simplified physical model was used in this analysis. The model was chosen so that the significant physical mechanisms could be isolated and examined without causing unnecessary mathematical complexity. The physical model which was isolated for detailed analysis is illustrated in FIGURE 1.

A section of the gun barrel wall that contains a layer which may change phase is shown in FIGURE 1. The tube wall is approximated by a slab. Heat flow is one dimensional; and the materials constituting the slab are each assumed to be homogeneous and isotropic, and behave in accordance with the Fourier Biot Law. Physical properties are constant.

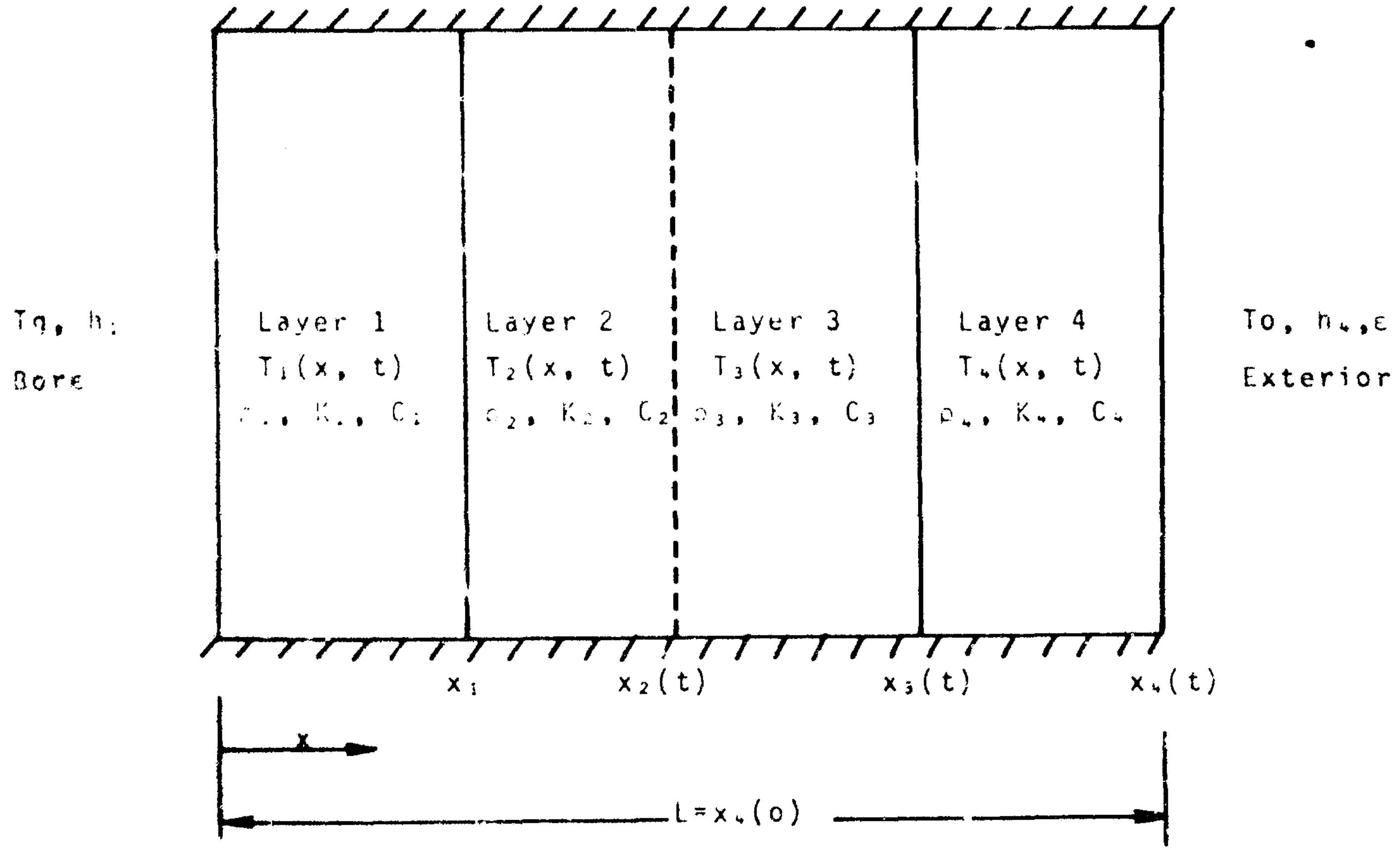


FIGURE 1 Physical Model of a Gun Tube Wall Containing a Phase-Change Layer

but may be different for each layer. Layers 1 and 4 represent conventional gun barrel materials. Layers 2 and 3 represent the phase-change material, with layer 2 being the transformed phase and layer 3 the original phase. The interface between layers 2 and 3 is one-dimensional and the phase change between the two layers takes place at a known, fixed value of temperature. A hot, nonradiating gas, at temperature $T_g$, flows through the bore. A constant convection coefficient, $h_1$, is present at the bore surface. The temperature of the exterior surroundings is at a constant temperature $T_o$. Heat exchange between the exterior surface and the surroundings takes place by both convection and thermal radiation. A constant convection coefficient, $h_4$, and constant surface emissivity, $\varepsilon$, are prescribed at the exterior surface. The mathematical equations by which the model is described are given in the following subsection:

Mathematical Model

The governing equations for the model described in the preceding subsection are given by:

1. Energy Equations:

A. Layer 1:
$$\frac{\partial T_1}{\partial t} = \alpha_1 \frac{\partial^2 T_1}{\partial x^2} \tag{1}$$

B. Layer 2:
$$\frac{\partial T_2}{\partial t} = \alpha_2 \frac{\partial^2 T_2}{\partial x^2} \tag{2}$$

C. Layer 3:
$$\frac{\partial T_3}{\partial t} = \alpha_3 \frac{\partial^2 T_3}{\partial x^2} - U_3 \frac{\partial T_3}{\partial x} \tag{3}$$

D. Layer 4:
$$\frac{\partial T_4}{\partial t} = \alpha_4 \frac{\partial^2 T_4}{\partial x^2} - U_4 \frac{\partial T_4}{\partial x} \tag{4}$$

2. Boundary Conditions:

A. $x = 0$;
$$-K_1 \frac{\partial T_1}{\partial x}(0,t) = h_1[T_g - T_1(0,t)] \tag{5}$$

B. $x = x_1$;
$$T_1(x_1,t) = T_2(x_1,t) \tag{6}$$

$$K_1 \frac{\partial T_1}{\partial x}(x_1,t) = K_2 \frac{\partial T_2}{\partial x}(x_1,t) \tag{7}$$

C. $x=x_2(t);\ T_2(x_2,t)=T_3(x_2,t)=T_m$ (8)

$$\frac{dx_2}{dt}=\frac{-K_2}{\rho_2\lambda}\frac{\partial T_2}{\partial x}(x_2,t)+\frac{K_3}{\rho_2\lambda}\frac{\partial T_3}{\partial x}(x_2,t) \qquad (9)$$

$$U_3=\frac{dx_2}{dt}\left(1-\frac{\rho_2}{\rho_3}\right) \qquad (10)$$

D. $x=x_3(t);\ T_3(x_3,t)=T_4(x_3,t)$ (11)

$$K_3\frac{\partial T_3}{\partial x}(x_3,t)=K_4\frac{\partial T_4}{\partial x}(x_3,t) \qquad (12)$$

$$U_4=U_3 \qquad (13)$$

E. $x=x_4(t);\ -K_4\frac{\partial T_4}{\partial x}(x_4,t)=h_4[T_4(x_4,t)-T_0]$ (14)

$$+\varepsilon\sigma[T_4^4(x_4,t)-T_0^4]$$

3. Initial Conditions:

A. $T_1(x,o)=T_{1o}(x)$ (15)

B. $T_2(x,o)=T_{2o}(x)$ (16)

C. $T_3(x,o)=T_{3o}(x)$ (17)

D. $T_4(x,o)=T_{4o}(x)$ (18)

The equations listed above are all of familiar form with the possible exceptions of Equations (9) and (10). Equation (9) gives the velocity of the interface between the two layers of phase-change material. The equation is an expression of the conservation of energy at the interface. According to this equation, the net difference between the heat conducted to and away from the interface is absorbed by a change in the phase of the material. Equation (10) represents conservation of mass at the interface and shows that a relative velocity will be present between the phases if their densities differ and phase change occurs.

Recasting the governing equations into dimensionless form is desirable before determination of a solution. A better understanding of the relationship among the physical parameters may be obtained from the dimensionless representation. The following variables are introduced:

$$\theta=\frac{T-T_o}{T_g-T_o} \qquad (19)$$

$$y=\frac{x}{L} \qquad (20)$$

$$s=\frac{x_2(t)}{L} \qquad (21)$$

$$\tau=\frac{\alpha_1 t}{L^2} \qquad (22)$$

Substitution of the dimensionless variables into the governing equations results in the following:

1. Energy Equations:

A. Layer 1; $\frac{\partial\theta_1}{\partial\tau}=\frac{\partial^2\theta_1}{\partial y^2}$ (23)

B. Layer 2; $\frac{\partial\theta_2}{\partial\tau}=\frac{\alpha_2}{\alpha_1}\frac{\partial^2\theta_2}{\partial y^2}$ (24)

C. Layer 3; $\frac{\partial\theta_3}{\partial\tau}=\frac{\alpha_3}{\alpha_1}\frac{\partial^2\theta_3}{\partial y^2} - \frac{ds}{d\tau}(1 - \frac{\rho_2}{\rho_3})\frac{\partial\theta_3}{\partial y}$ (25)

D. Layer 4; $\frac{\partial\theta_4}{\partial\tau}=\frac{\alpha_4}{\alpha_1}\frac{\partial^2\theta_4}{\partial y^2} - \frac{ds}{d\tau}(1 - \frac{\rho_2}{\rho_3})\frac{\partial\theta_4}{\partial y}$ (26)

2. Boundary Conditions.

A. $x=o,\ y=o;\ \frac{\partial\theta_1}{\partial y}(o,\tau)=\frac{-h_1K_1}{L}[1-\theta(o,\tau)]$ (27)

B. $x=x_1,\ y=y_1;\ \theta_1(y_1,\tau)=\theta_2(y_1,\tau)$ (28)

$$\frac{\partial\theta_1}{\partial y}(y_1,\tau)=(\frac{K_2}{K_1})\frac{\partial\theta_2}{\partial y}(y_1,\tau) \qquad (29)$$

C. $x=x_2(t),\ y=s(\tau);\ \theta_2(x,\tau)=\theta_3(s,\tau)=\theta_m$ (30)

$$\frac{ds}{d\tau}=[C_1\frac{(T_g-T_o)}{\lambda}](\frac{\rho_1}{\rho_2})[-(\frac{K_2}{K_1})\frac{\partial\theta_2}{\partial y}(s,\tau)+$$

$$(\frac{K_3}{K_1})\frac{\partial\theta_3}{\partial y}(s,\tau)] \qquad (31)$$

D. $x=x_3(t),\ y=y_3(\tau);\ \theta_3(y_3,\tau)=\theta_4(y_3,\tau)$ (32)

$$\frac{\partial\theta_3}{\partial y}(y_3,\tau)=\frac{K_4}{K_3}\frac{\partial\theta_4}{\partial y}(y_3,\tau) \qquad (33)$$

E. $x=x_4(t),\ y=y_4(\tau);$

$$\frac{\partial\theta_4}{\partial y}(y_4,\tau)=-\left[\frac{h_4L}{K_4}+\frac{\varepsilon\sigma}{K_4}(4T_o{}^3+(T_g-T_o)^3\theta_4^3(y_4,\tau)\right. \qquad (34)$$

$$\left.+T_o(T_g-T_o)^2\theta_4^2(y_4,\tau)+T_o^2(T_g-T_o)\theta_4(y_4,\tau)\right]\theta_4(y_4,\tau)$$

3. Initial Conditions:

$\theta_1(y,o)=\theta_{1o}(y)$ (35)

$\theta_2(y,o)=\theta_{2o}(y)$ (36)

$\theta_3(y,o)=\theta_{3o}(y)$ (37)

$\theta_4(y,o)=\theta_{4o}(y)$ (38)

A good preliminary estimate of the relative importance of each parameter is obtained from the dimensionless form of the governing equations. The ratios $\alpha_2/\alpha_1$, $\alpha_3/\alpha_1$, and $\alpha_4/\alpha_1$ in Equations (24), (25) and (26) should be less than unity to reduce the rate of temperature change in those layers. The advantage of $\rho_2$ being greater than or equal to $\rho_3$ is illustrated by Equations (25) and (26). A lower rate of temperature increase in layers 3 and 4 results from this condition. From a structural point of view, $\rho_2$ should equal $\rho_3$ so that no dimensional changes occur as a result of a phase change. The phase-change temperature must be less than the maximum allowable operating temperature of the gun tube to provide useful temperature control. The expression $C_1(T_g-T_o)/\lambda$ in Equation (31) represents a ratio of sensible to latent heat. This parameter should be small to provide lower phase-change rates. The specific heat, $C_1$, should be large so that the maximum amount of sensible heat can be absorbed for a given temperature rise. Therefore, the latent heat, $\lambda$, should also be large. The ratios $\rho_1/\rho_2$ and $K_2/K_1$ in Equation (31) should be less than unity and the ratio $K_3/K_1$ greater than unity to reduce the phase-change rate. This completes the formulation and discussion of the mathematical model.

## Comparison Criteria

In this section, two criteria are offered for judging whether a barrel containing a layer of phase-change material is more effective, from a thermal point of view, than a homogeneous barrel. The two criteria discussed are constant wall volume and constant weight. If the barrel wall is constrained to be of a specific thickness, then some of the original barrel material must be eliminated to provide space for the phase-change material. The proper criterion for judging the thermal effectiveness of the phase-change barrel would be to compare its time-temperature history with that of a homogeneous barrel when both barrels are of equivalent thickness and subjected to the same thermal boundary conditions. The constraint of constant weight requires that the total weight of the barrel with the phase-change layer be equal to that of the original barrel. The barrel wall cross-sections are illustrated in FIGURE 2 for consideration.

A homogeneous barrel of thickness $L_1$ with a density $\rho_h$ and a composite barrel, of thickness $L_2$, containing a layer of phase-change material of thickness d, which has a density $\rho_p$ are illustrated in FIGURE 2. The other two layers of the composite barrel contain the same material as that of the homogeneous barrel. The weight, per unit area, of the homogeneous barrel is:

$$W_h = \rho_h L_1 \tag{39}$$

and the weight of the composite barrel is:

$$W_c = \rho_h (L_2 - d) + \rho_p\, d \tag{40}$$

Equating the two weights gives the following relation between the two barrel thicknesses:

$$L_2 = L_1 \left[1 + \frac{d}{L_1} \left(1 - \frac{\rho_p}{\rho_h}\right)\right] \tag{41}$$

Thus, the criterion of comparison is to compare the time-temperature distribution history of a homogeneous barrel of thickness $L_1$ to that of a composite barrel whose total thickness, $L_2$, is given by Equation (41) where both barrels are subjected to the same thermal boundary conditions.

## NUMERICAL ALGORITHM

The governing equations comprise a set of nonlinear, coupled partial differential equations and can be solved only by numerical or approximate methods. The solution is

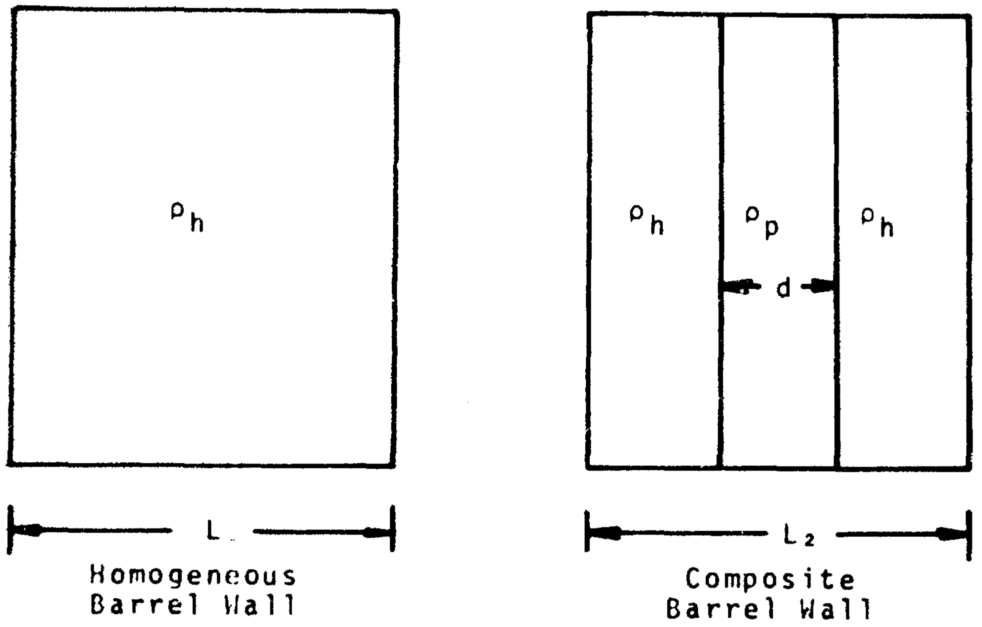


FIGURE 2 Cross-Sectional Representations of A Homogeneous and A Composite Barrel Wall Section

complicated by the presence of the moving interface between layers 2 and 3. The moving interface causes difficulty in establishing a spatial grid net for solution by finite difference techniques. Elimination of the time-dependent thickness of layers 2 and 3 is possible provided a transformation of coordinates is performed. The following set of coordinates are introduced:

$$Z_1(y) = \frac{y}{y_1}, \quad 0 \leq y \leq y \tag{42}$$

$$Z_2(y,\tau) = \frac{y-y_1}{s(\tau)-y_1}, \quad y_1 \leq y \leq s(\tau) \tag{43}$$

$$Z_3(y,\tau) = \frac{y-s(\tau)}{y_3(\tau)-s(\tau)}, \quad s(\tau) \leq y \leq y_3(\tau) \tag{44}$$

$$Z_4(y,\tau) = \frac{y-y_3(\tau)}{y_3(\tau)-y_4(\tau)}, \quad y_3(\tau) \leq y \leq y_4(\tau) \tag{45}$$

The transformed set of governing equations takes the following form:

1. Governing Equations:

A. Layer 1;
$$\frac{\partial\theta_1}{\partial\tau} = \frac{1}{y_1^2}\frac{\partial^2\theta_1}{\partial Z_1^2} \tag{46}$$

B. Layer 2,
$$\frac{\partial\theta_2}{\partial\tau} = \frac{1}{(s-y_1)^2}\frac{\alpha_2}{\alpha_1}\frac{\partial^2\theta_2}{\partial Z_2^2} + \frac{Z_2}{(s-y_1)}\frac{ds}{dt}\frac{\partial\theta_2}{\partial Z_2} \tag{47}$$

C. Layer 3;
$$\frac{\partial\theta_3}{\partial\tau} = \frac{1}{(y_3-s)^2}\frac{\alpha_3}{\alpha_1}\frac{\partial^2\theta_3}{\partial Z_3^2} + \frac{(Z_3-1)}{(y_3-s)}\frac{ds}{d\tau} X \left(1-\frac{\rho_2}{\rho_3}\right)\frac{\partial\theta_3}{\partial Z_3} \tag{48}$$

D. Layer 4,
$$\frac{\partial\theta_4}{\partial\tau} = \frac{1}{(y_4-y_3)^2}\frac{\alpha_4}{\alpha_1}\frac{\partial^2\theta_4}{\partial Z_4^2} + \frac{(Z_4-1)}{(y_4-y_3)}\frac{ds}{d\tau} X \left(1-\frac{\rho_2}{\rho_3}\right)\frac{\partial\theta_3}{\partial Z_3} \tag{49}$$

2. Boundary Conditions.

A. $y=0$, $Z_1=0$;
$$\frac{\partial\theta_1}{\partial Z_1} = -\frac{y_1 h_1 L}{K_1}[1-\theta_1(0,\tau)] \tag{50}$$

B. $y=y_1,\ Z_1=1,\ Z_2=o$

$$\theta_1(1,\tau)=\theta_2(o,\tau) \tag{51}$$

$$\frac{\partial\theta_1}{\partial Z_1}(1,\tau)=\frac{K_2}{K_1}\frac{\partial\theta_2}{\partial Z_2}(o,\tau) \tag{52}$$

C. $y=y_2,\ Z_2=1,\ Z_3=o$

$$\theta_2(1,\tau)=\theta_3(o,\tau)=\theta_m \tag{53}$$

$$\frac{ds}{d\tau}=[C_1\frac{(T_g-T_o)}{\lambda}](\frac{\rho_1}{\rho_2})[-(\frac{K_2}{K_1})(\frac{1}{s-y_1})\frac{\partial\theta_2}{\partial Z_2}(1,\tau)+ (\frac{K_3}{K_1})(\frac{1}{y_3-s})\frac{\partial\theta_3}{\partial Z_3}(o,\tau)] \tag{54}$$

D. $y=y_3,\ Z_3=1,\ Z_4=o$

$$\theta_3(1,\tau)=\theta_4(o,\tau) \tag{55}$$

$$\frac{\partial\theta_3}{\partial Z_3}(1,\tau)=\frac{K_4}{K_1}\frac{\partial\theta_4}{\partial Z_4}(o,\tau) \tag{56}$$

E. $y=y_4,\ Z_4=1$

$$\frac{\partial\theta_4}{\partial Z_4}(1,\tau)=-(y_4-y_3)[\frac{h_4L}{K_4}+\frac{\varepsilon\sigma}{K_4}(4T_o^3+(T_g-T_o)^3\theta_4^3(1,\tau) +T_o(T_g-T_o)^2\theta_4^2(1,\tau)+T_o^2(T_g-T_o)\theta_4(1,\tau)]\theta_4(1,\tau) \tag{57}$$

3. Initial Conditions:

A. $\theta_1(Z_1,o)=\theta_{10}(Z_1)$ (58)

B. $\theta_2(Z_2,\ o)=\theta_{20}(Z_2)$ (59)

C. $\theta_3(Z_3,\ o)=\theta_{30}(Z_3)$ (60)

$$D.\quad \theta_4(\bar{Z}_4,\ o)=\theta_{40}(Z_4) \qquad (61)$$

This set of equations represents coupled heat conduction and phase change in four layers whose boundaries are fixed. The equations were programmed for solution by the method of explicit finite differences. The only modification to the standard method came about as a result of the time-stability criteria. In order for the explicit finite difference algorithm for the one-dimensional linear diffusion equation to be stable, the maximum time increment must be.[4]

$$\Delta t \leq \frac{\Delta x^2}{2\alpha} \qquad (62)$$

where $\Delta t$ is the maximum allowable time step and $\Delta x$ is the spatial increment between finite difference nodes. Other authors[5,6] have found that the time-stability criteria are more restrictive when phase change takes place, and the maximum allowable time interval is about half that given by Equation (62). When phase change begins, layer 2 is of zero thickness and remains thin for some finite time interval. During this period, the stability criteria requirement is that the time interval be extremely small and, therefore, computing time becomes excessive. The same situation is encountered when phase change nears completion and the thickness of layer 3 approaches zero. This problem was avoided because the sensible heat change was neglected in layers 2 and 3 whenever they were quite small. The interface velocity for small thicknesses of layer 2 was approximated by

$$\frac{ds}{d\tau}=\left[C\,\frac{(T_g-T_o)}{\lambda}\right]\left(\frac{\rho}{\rho_2}\right)\left[-\frac{1}{y}\,\frac{\partial\theta}{\partial Z}(1,\tau)+\left(\frac{K}{K}\right)\left(\frac{1}{y-s}\right)\times\right.$$

$$\left.\frac{\partial\theta_3}{\partial Z_3}(o,\tau)\right] \qquad (63)$$

As the phase change approaches completion, the interfacial velocity is approximated by

$$\frac{ds}{d\tau}=\left[C\,\frac{(T_g-T_o)}{\lambda}\right]\left(\frac{\rho}{\rho_2}\right)\left[-\left(\frac{K}{K}\right)\left(\frac{1}{s-y}\right)\frac{\partial\theta_2}{\partial Z_2}(1,\tau)+\left(\frac{K}{K}\right)\times\right.$$

$$\left.\left(\frac{1}{y_4-y_3}\right)\frac{\partial\theta}{\partial Z}(o,\tau)\right] \qquad (64)$$

The computer program was written so that the following situations could be handled: heat conduction in four layers with phase change between the two center layers, in three layers with no phase change, and in a homogeneous, single-layered barrel. The results of numerical evaluation are given in the following section.

## ANALYTICAL RESULTS

The mathematical equations were evaluated with the use of the numerical algorithm described in the previous section. A parametric analysis was conducted by the varying of one parameter while all others were held constant. A slab with a phase-change layer having a dimensionless thickness of 0.2 and centered in the slab was analytically investigated. The slab was subjected to thermal convection from a hot propellant gas at one side and thermal convection to the surroundings at the other side. The properties of layers 1 and 4 were assumed equal and the properties of layers 2 and 3 were also taken to be equal. The parameters varied were $K_2/K_1$, $C_2/C_1$, $\rho_2/\rho_1$, $C_1(T_g-T_o)/\lambda$, and $\theta_m$. Nominal values of unity were chosen for the fractional parameters and a nominal value of 0.6 was chosen for $\theta_m$. The typical values of 0.2 and 0.02 were assigned to $B_1$ and $B_4$, respectively. Radiation was neglected in the parametric study. The results of the parametric analysis are shown graphically in FIGURES 3, 4, 5, 6 and 7, where dimensionless boundary temperatures are plotted versus dimensionless time. The effects of varying the thermal conductivity are illustrated in FIGURE 3. The boundary temperatures are held lower for a greater time period if the phase-change material has a lower thermal conductivity than that of the conventional barrel material. The effect of phase change on the boundary temperatures can be observed by a comparison of the solid-line curves with the dash-line curves, which indicate the boundary temperatures of a homogeneous barrel subjected to the same boundary conditions. The phase change causes the barrel to remain at an essentially isothermal condition while phase change takes place. At the time phase change is completed, the rises in boundary temperatures are about 25 per cent less than for a homogeneous barrel. Lower thermal conductivity will also result in an increase in the time needed for phase change to be completed. Specific heat effects are illustrated in FIGURE 4. A high specific heat in the phase-change layer is desirable so that more sensible heat will be absorbed. The time required for the phase change to be completed was not significantly dependent on the value of specific heat of the phase-change layer. The effects of density variations are shown in FIGURE 5. A higher density of the phase-change layer

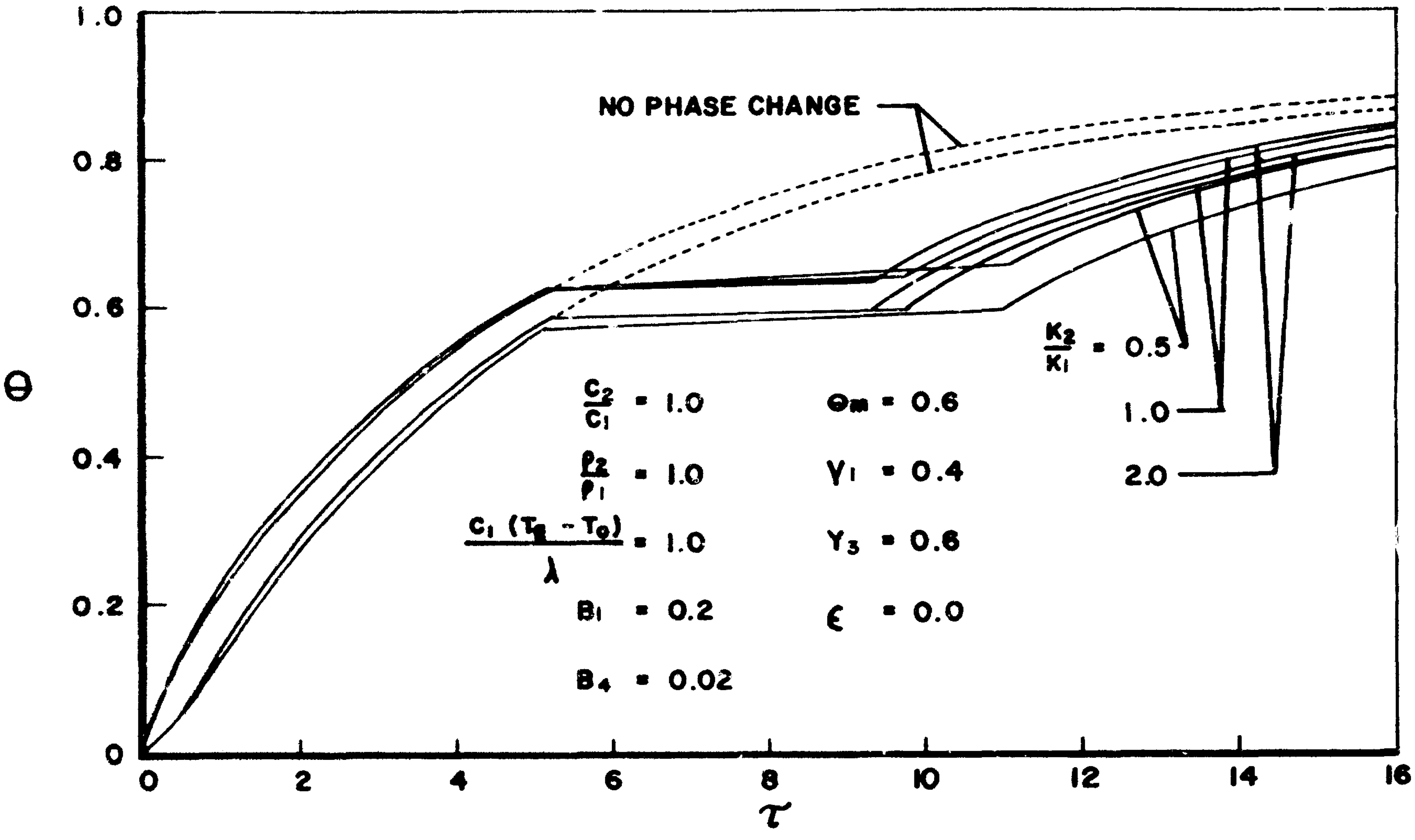


FIGURE 3. EFFECTS OF THERMAL CONDUCTIVITY OF PHASE CHANGE LAYER.

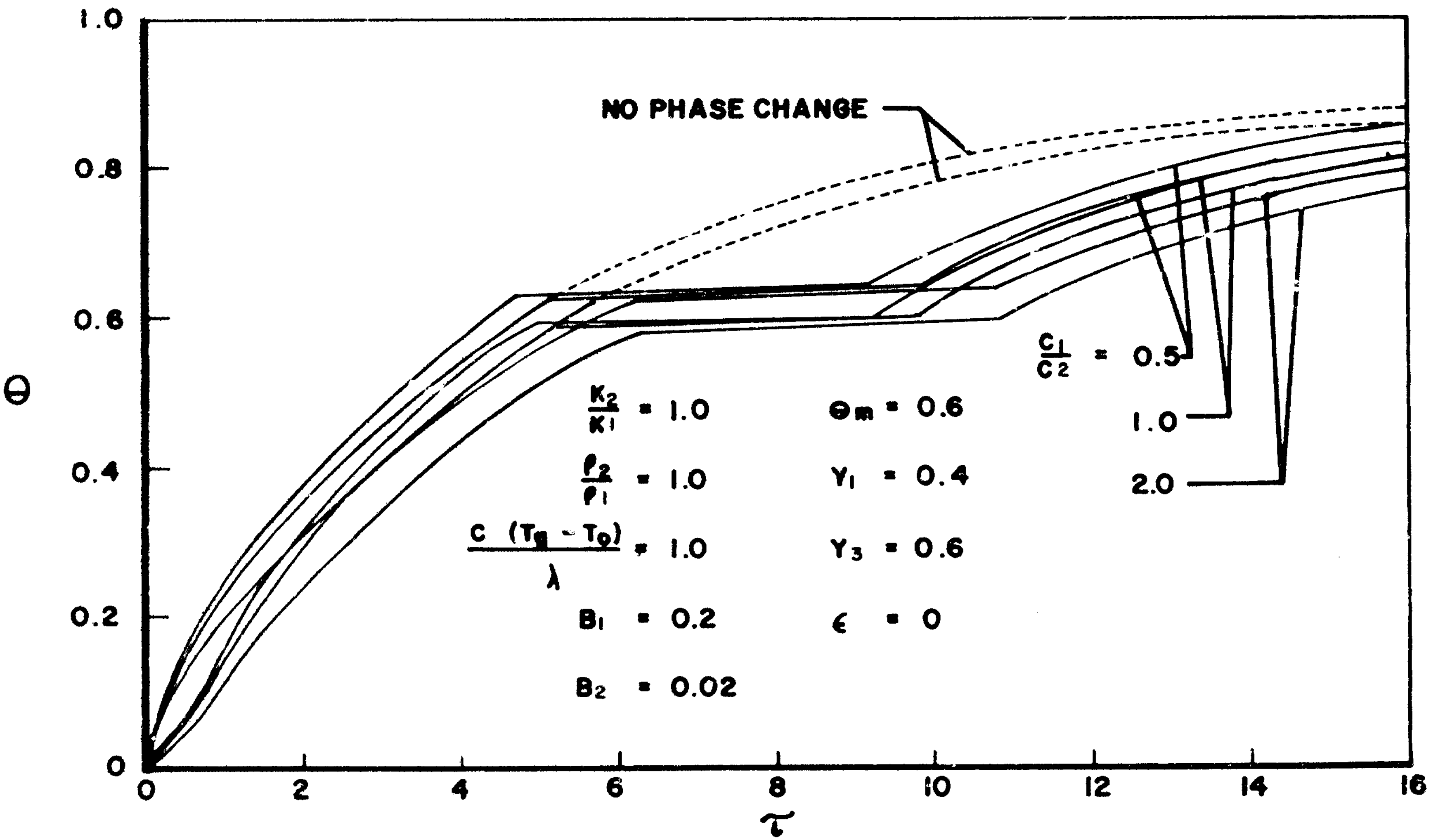


FIGURE 4. EFFECTS OF SPECIFIC HEAT OF PHASE CHANGE LAYER.

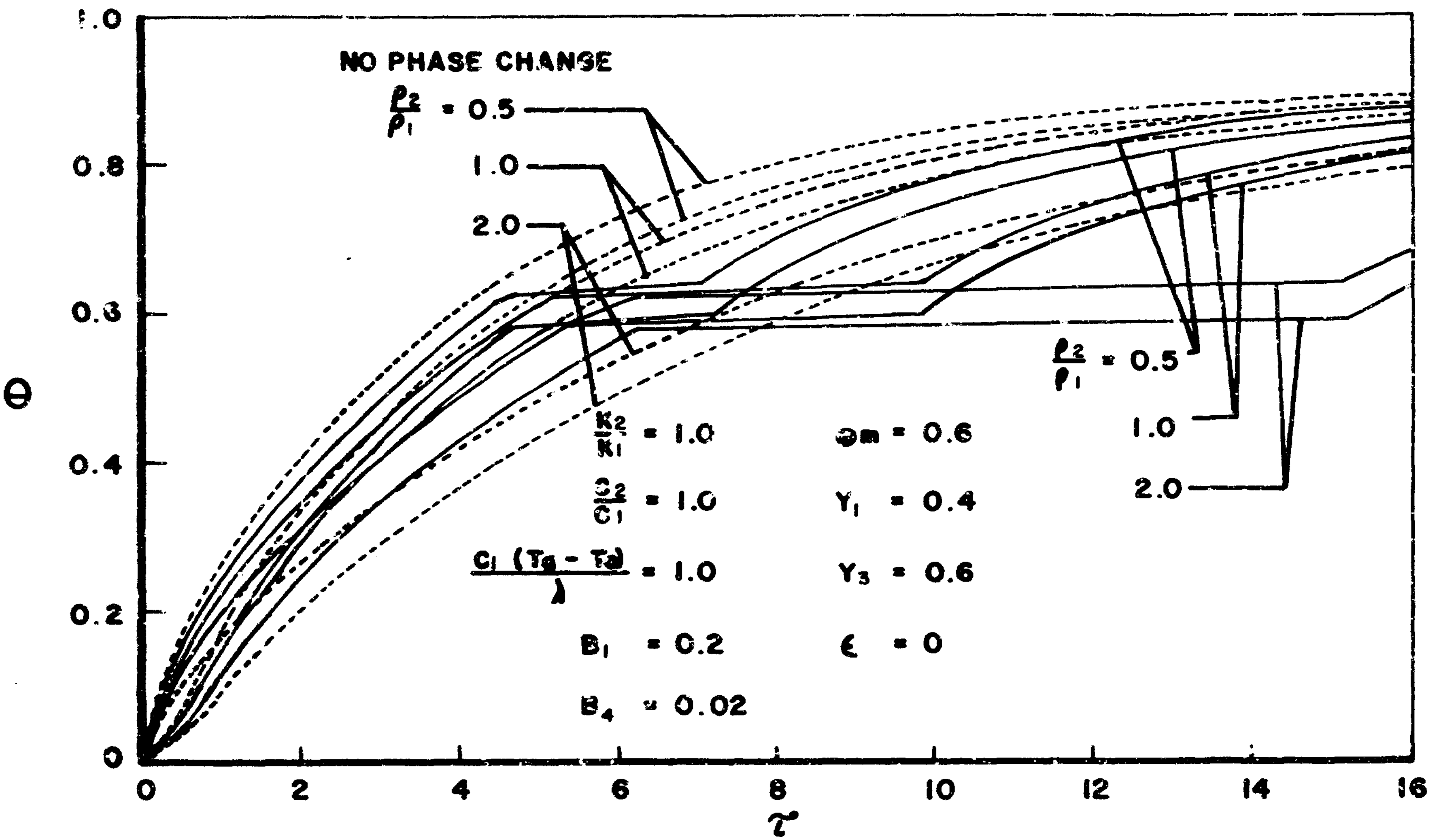


FIGURE 5. EFFECTS OF DENSITY OF PHASE CHANGE LAYER.

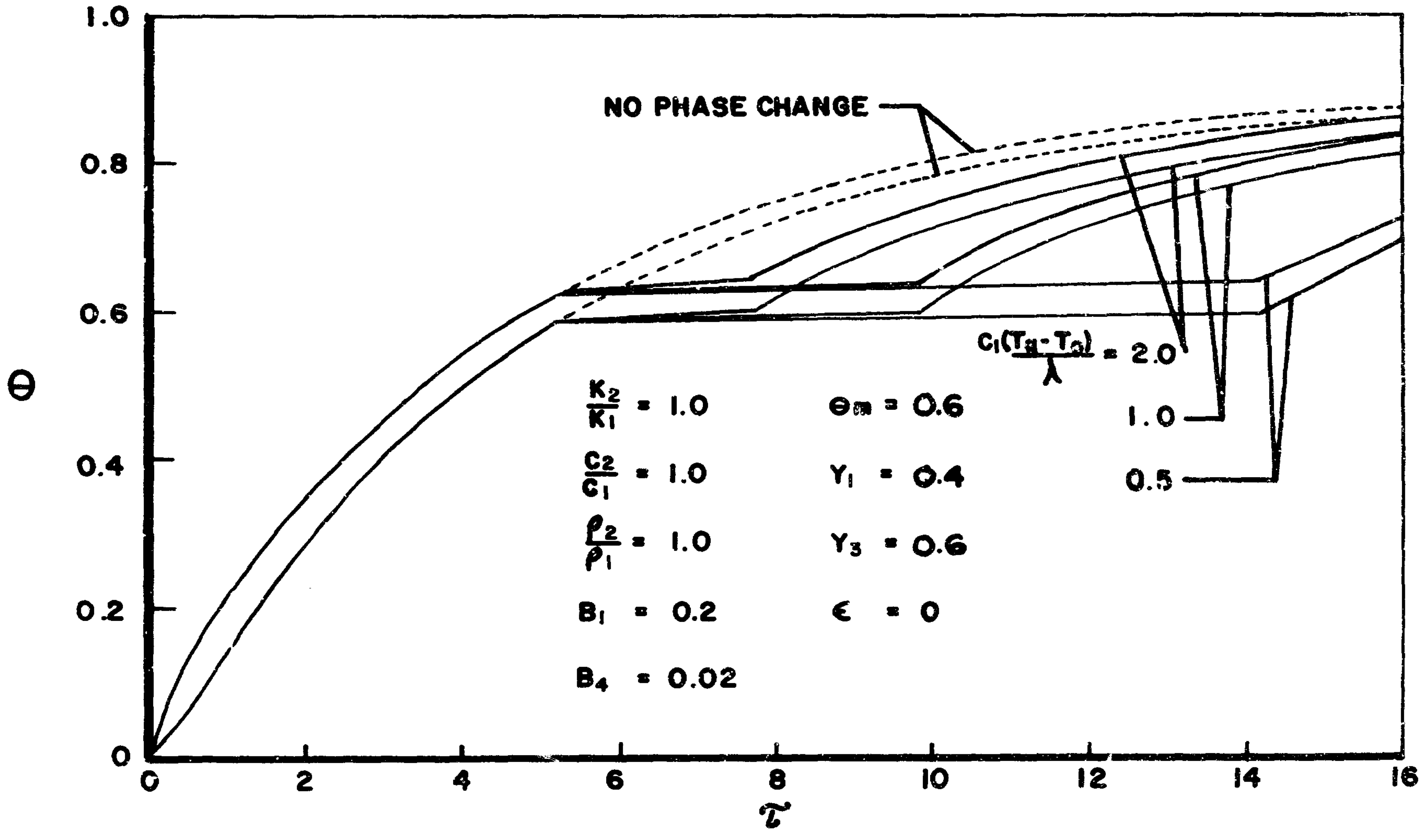


FIGURE 6. EFFECTS OF LATENT HEAT OF PHASE CHANGE LAYER.

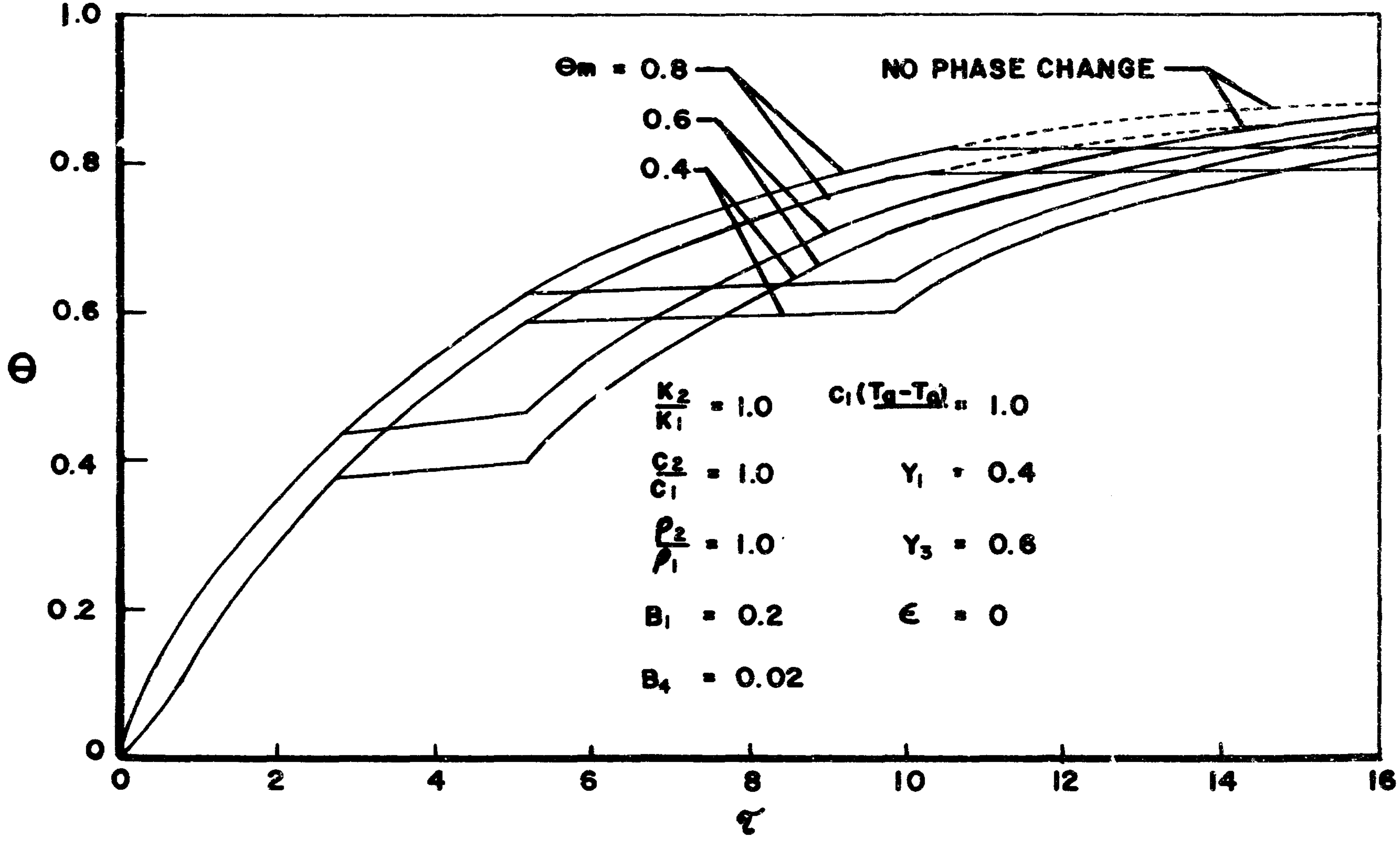


FIGURE 7. EFFECTS OF MELTING TEMPERATURE OF PHASE CHANGE LAYER.

results in greater absorption of both sensible and latent heat. The time necessary for phase change completion is almost directly proportional to the density. The effect of an increase in the sensible thermal capacity can be observed by a comparison of the three sets of dash-line curves, which indicate the boundary temperatures when a layer of a different density is present and no phase change occurs. Latent heat effects are illustrated in FIGURE 6. The required time for phase-change is proportional to the value of the latent heat. The effect of phase transition temperature is illustrated in FIGURE 7. The transition temperature should have the highest possible value that is less than the maximum allowable operating temperature. With a material having a lower transition temperature, the phase change occurs while the flux to the barrel is still relatively high. Thus, phase change takes place more rapidly and the barrel temperature begins to rise again. Changes in layer location were made and no significant effect in this particular example was noted. For larger values of $B_1$, the effect might be significant. The phase-change time was also found to be directly proportional to the layer thickness. In summary, for this specific application of controlling gun barrel temperature, the phase-change layer should have low thermal conductivity, high density, high specific heat, high latent heat, and high transition temperature. Also, the phase-change layer should be as thick as possible. Finally, the layer location does not have a strong effect on the boundary temperatures. A further discussion is given in the following section.

## DISCUSSION OF RESULTS

The results of the parametric study indicate that significant increases in burst time are possible if a phase-change layer is used. It is illustrated in FIGURE 7 that a phase change layer having the identical thermal properties as the homogeneous barrel and a value of $C_1(T_g-T_o)/\lambda' = 1$, increases the time necessary for the bore to reach 70 per cent of the effective gas temperature by 63 per cent. If the maximum allowable temperature is 70 per cent of the effective gas temperature, the burst time could be increased by 63 per cent. The values of the dimensionless variables given in FIGURE 7 are reasonable for an automatic weapon. For example, if $C_1 = 0.1$, $T_m = 1530$, $T_g = 2500$, $T_o = 70°F$ and $\lambda = 200$, the ratio $C_1(T_g-T_o)/\lambda$ is 1.22. If the maximum allowable bore temperature is 1600°F, a significant increase in burst length would be obtained. The effect would be even more appreciable if the thickness of the phase-change layer could be increased.

A literature survey was undertaken to determine some of the properties of material that change phase in the temperature range of interest. The primary references were Selected Values of Chemical Thermodynamic Properties[7] and Metals Handbook, Vol I.[8] Some of the materials are listed in Tables I and II. These materials were chosen from the references solely on the basis that their transition and fusion temperatures were in the desired temperature range. No attempt was made to determine such properties as corrosiveness or the possibility of violent chemical reactions. Cost and availability were not considered. The purpose of the listing is not to recommend these materials, but only to show the relative range of phase-change temperatures and latent heats of formation. A list of materials in which solid-solid phase changes occur is given in Table I, and a list of materials in which solid-liquid phase changes occur is given in Table II.

An examination of Table I reveals that very few solid-solid phase changes occur that would be useful for controlling gun barrel temperatures because the latent heats are relatively low. Several materials listed in Table II offer possibilities for gun barrel temperature control. These solid-liquid phase changes have relatively high latent heats of fusion. A further numerical evaluation was made with the use of germanium and aluminum as phase-change materials. These materials were chosen for further evaluation because of their high latent heats and because of the fact that their thermal properties are well documented. Neither material meets the criteria for an optimum material as determined in the previous section. Also, the use of germanium might not be economically feasible. However, sufficient thermal property data were unavailable to determine the optimum material for the numerical example. Both aluminum and germanium undergo solid-liquid phase changes; this condition is undesirable from a structural point of view. The possibility of using a solid-liquid layer while maintaining structural soundness will be discussed later.

The results of the numerical example are shown in FIGURES 8 and 9 where the boundary temperatures are plotted versus time for a slab of homogeneous steel, a slab of steel with an aluminum layer present, and a steel slab containing a layer of germanium. The results of an equivalent volume analysis are shown in FIGURE 8, and the results of an equivalent weight analysis are shown in FIGURE 9. Typical data for gun tubes were used for the examples and are shown in the figures. Neither aluminum nor gernamium has as high a sensible heat capacity per unit volume, $\rho c$, as steel. Therefore, for the constant volume case, the temperatures of the slabs containing

# TABLE I

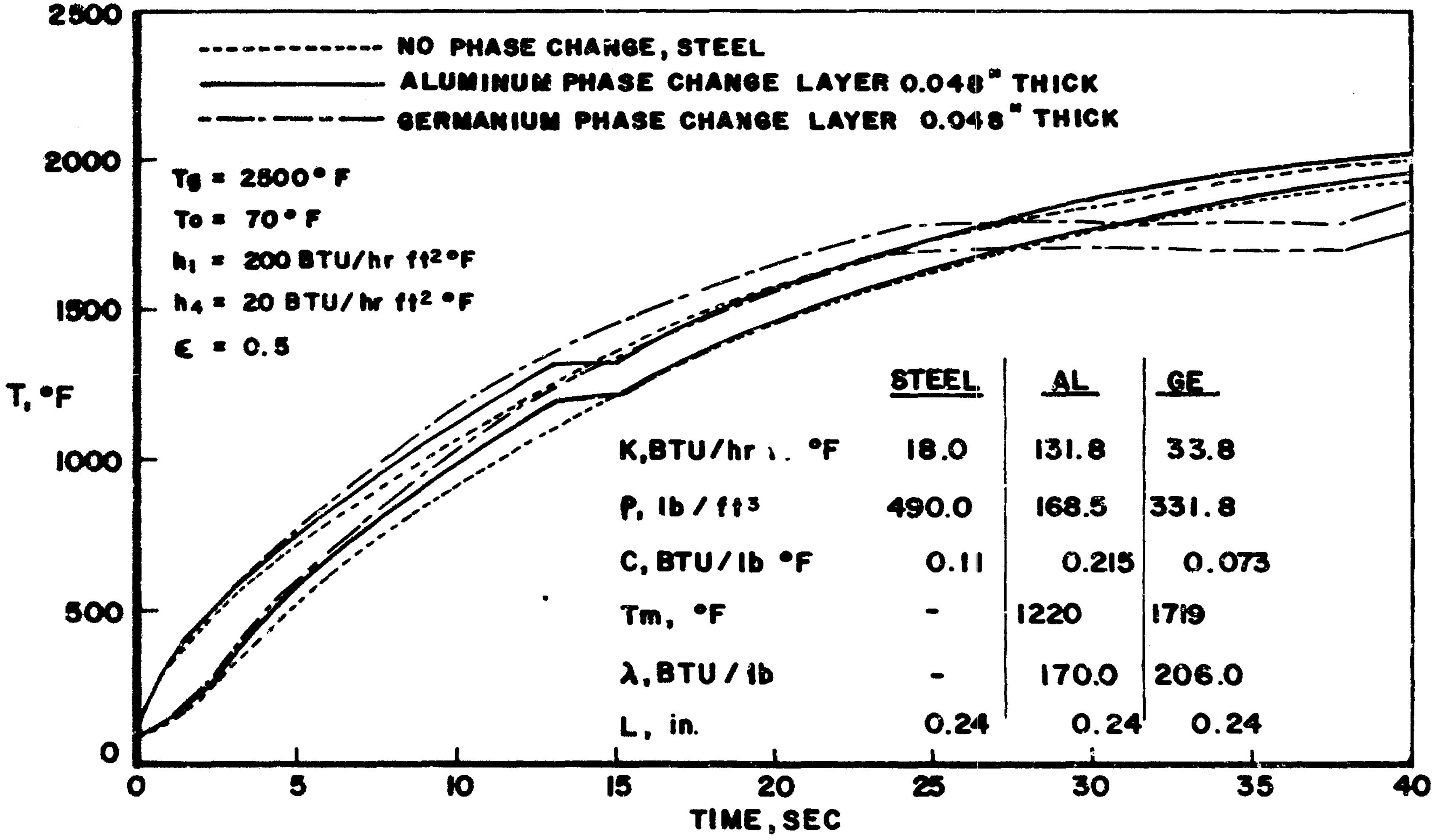
Transition Temperatures and Correspon g Latent Heats for Some Materials in Wh Solid-Solid Phase Changes Oc

| Element or Compound | Transition Temp. °F | Latent Heat BTU/lb |
|---|---|---|
| $AgSO_4$ | 770 | 17.65 |
| $Pd_3SO_4$ | 1740 | 17.4 |
| Mn | 1340 | 17.7 |
| $TiO$ | 1812 | 23.1 |
| $LiSO_4$ | 1116 | 119.0 |
| $Na_2MoO_4$ | 825 | 129.5 |
| $K_2SO_4$ | 1080 | 20.1 |
| $KcCrO_4$ | 1230 | 28.4 |
| CsCl | 332 | 18.5 |

## TABLE II

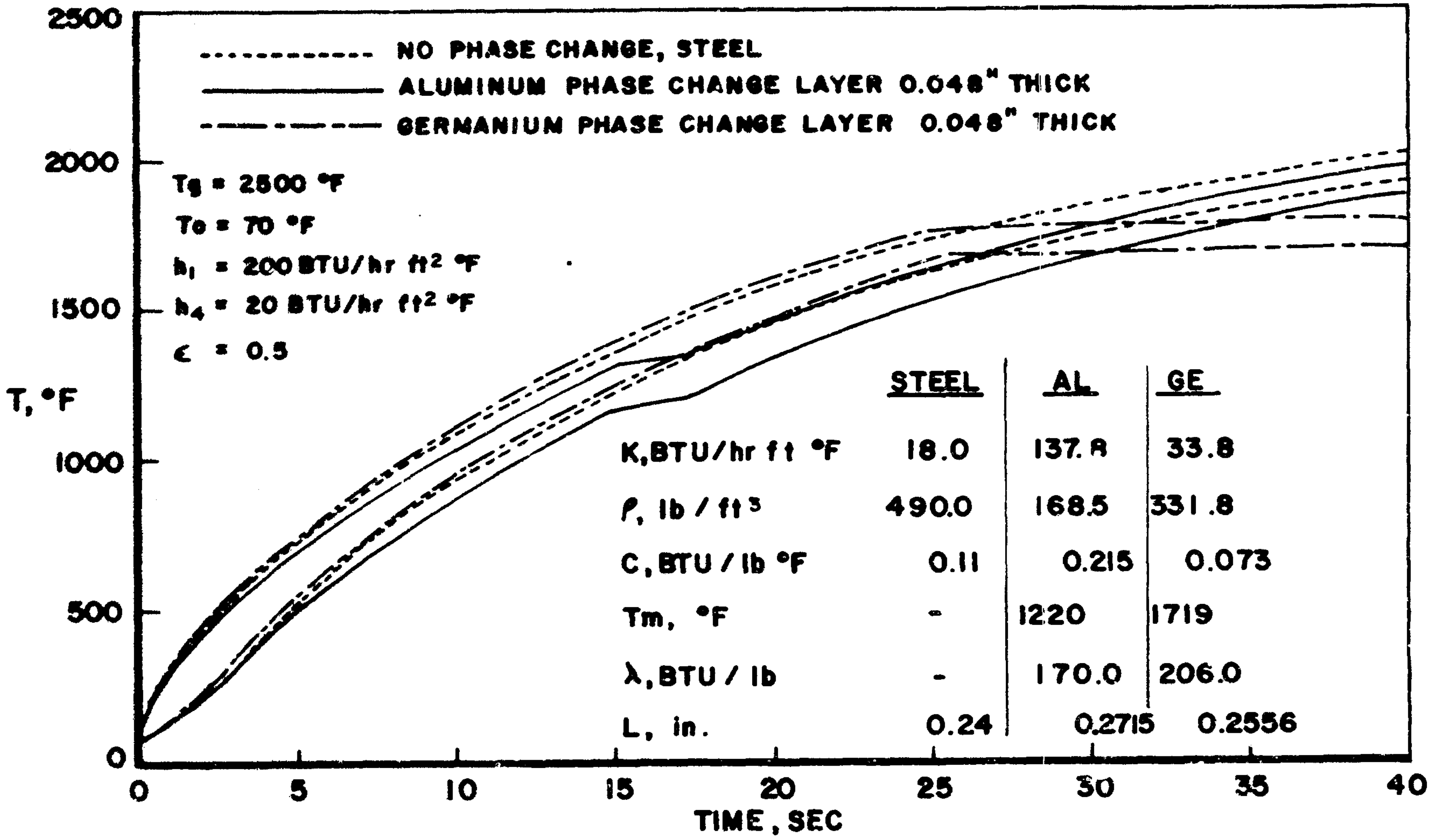
### Transition Temperatures and Corresponding Latent Heats For Some Materials in Which Solid-Liquid Phase Changes Occur

| Element or Compound | Transition Temp. °F | Latent Heat BTU/lb |
|---|---|---|
| Sb | 1167 | 68.9 |
| $SbO_6$ | 1210 | 75.6 |
| $G_e$ | 1719 | 206 |
| Zn | 787 | 43.36 |
| $ZnSb_2$ | 1050 | 57.6 |
| $Cu_2Cd_3$ | 1533 | 56.5 |
| $Ni_2S$ | 1293 | 59.3 |
| $FeCl_2$ | 1250 | 146.8 |
| $MnCl_2$ | 1200 | 126.6 |
| $CrCl_2$ | 1495 | 112.7 |
| $B_2O_3$ | 840 | 137.5 |
| Al | 1220 | 170 |



| | STEEL | AL | GE |
|---|---|---|---|
| K, BTU/hr . °F | 18.0 | 131.8 | 33.8 |
| ρ, lb / ft³ | 490.0 | 168.5 | 331.8 |
| C, BTU/lb °F | 0.11 | 0.215 | 0.073 |
| Tm, °F | - | 1220 | 1719 |
| λ, BTU / lb | - | 170.0 | 206.0 |
| L, in. | 0.24 | 0.24 | 0.24 |

FIGURE 8. BOUNDARY TEMPERATURES VERSUS TIME, CONSTANT VOLUME.



|  | STEEL | AL | GE |
|---|---|---|---|
| K, BTU/hr ft °F | 18.0 | 137.8 | 33.8 |
| ρ, lb / ft³ | 490.0 | 168.5 | 331.8 |
| C, BTU / lb °F | 0.11 | 0.215 | 0.073 |
| Tm, °F | - | 1220 | 1719 |
| λ, BTU / lb | - | 170.0 | 206.0 |
| L, in. | 0.24 | 0.2715 | 0.2556 |

FIGURE 9. BOUNDARY TEMPERATURES VERSUS TIME, CONSTANT WEIGHT.

aluminum and germanium rise more rapidly until phase change begins. Melting of the aluminum layer occurs at 1220°F, while the heat flux to the slab is still relatively high and dissipation to the surroundings is relatively low. Also, the latent heat capacity $\rho\lambda$, is low. After 25 seconds, the homogeneous steel barrel is actually cooler. Aluminum is a poor material in this example. However, if the effective gas temperature were lower, the aluminum layer would hold the slab near the melting temperature for a longer period of time. The germanium layer has a greater effect on slowing the temperature rise. As in the case of aluminum, the sensible heat capacity per unit volume is low, but the melting temperature, latent heat, and density are higher. As a result, the slab remains at a constant temperature, near the fusion temperature, for a much longer time period. The hot boundary of the homogeneous slab exceeds a temperature of 1800°F after 27.5 seconds, whereas the slab with the germanium layer does not exceed 1800°F for 37.9 seconds. If the maximum allowable bore temperature were 1800°F, an increase in burst time of 10.4 seconds, or 38 per cent, would result. The thickness of the fusible layer in this example was 0.048 inch. A thicker layer would result in a constant temperature condition for a proportionately longer time.

The comparison of the constant weight slabs is shown in FIGURE 9. The phase-change layer again has a thickness of 0.048 inch; but, because the densities of aluminum and germanium are less than that of steel, the thicknesses of the slabs are greater when those layers are present. A net increase will occur in sensible thermal capacity in comparison to that given in the previous example. In the case of aluminum, the sensible thermal capacity is increased because the specific heat of aluminum is greater than that of steel. A decrease in sensible thermal capacity still exists when a germanium layer is present. The aluminum layer is more effective than that cited in the previous example, but no significant improvement occurs because of its low melting temperature and low latent heat capacity. The germanium layer is more effective than that of the previous example because the higher sensible thermal capacity extends the time before the start of phase change. As a result, the temperatures of the hot boundary do not exceed 1800°F until 39.9 seconds, an improvement of 44 per cent over the homogeneous slab.

Neither of the materials used in the numerical examples was optimum. Both aluminum and germanium have high thermal conductivities, which was shown in Section 4 to be a disadvantage. The situation could be improved if alloys of these materials were used since a small amount of alloying significantly reduces thermal conductivity while other thermal properties remain nearly unchanged. The numerical examples showed the strong effect of melting temperatures on the thermal effectiveness of the phase-change layer. Melting temperature should be as high as possible to be advantageous. Therefore, no single material is optimum for all cases since the effective gas temperature and the maximum allowable operating temperature are variables.

The feasibility of using phase change for the thermal control of gun barrels is dependent upon finding a suitable material. Further investigation should be made in this area, since a suitable material would provide good possibilities for controlling gun barrel temperatures. A material in which a solid-solid phase change occurs with a high latent heat and in which good compressive strength exists would be most desirable. As indicated in TABLE II, solid-liquid phase changes generally have higher latent heats. Numerous structural problems associated with these materials exist. While some liquids will support a high compressive load, no liquid will support a tensile stress or a shear stress. Therefore, they cannot be used as an integral part of the gun barrel structure. Use of a honeycomb or a foamed metal material to provide structural soundness with a fusible material used to fill the voids might be possible. The basic honeycomb or foam metal layer could be filled with a material having the desirable melting temperature for a given situation, thus wide flexibility is provided. An interesting result of the study was that the location of the phase-change layer had little effect on the boundary temperatures. This indicates the possibility of locating the phase-change material on the outside of the barrel. Structural soundness would not be disturbed and the only problems would be to maintain close thermal contact between the barrel and fusible layer and to prevent the fusible material from escaping to the surroundings. Neither of these problems appears to be insurmountable.

## CONCLUSIONS AND RECOMMENDATIONS

The feasibility of using phase-change materials to control gun tube temperatures was analytically investigated. A mathematical model was formulated and programmed for numerical evaluation. The results of a parametric study were used to determine the optimum properties of the phase-change layer. A brief survey of property values was conducted to determine whether any materials had the desirable properties. Two materials were chosen as subjects for further numerical evaluations. Structural problems associated with phase-change materials were briefly discussed. Based on this study, the following conclusions were reached.

1. From a thermal point of view, control of gun tube temperatures is feasible with the use of a phase-change layer. The major obstacle appears to be finding a material with the proper thermal characteristics that is also suitable from a structural point of view.

2. The phase-change layer should have low thermal conductivity, high specific heat, high density, and large latent heat. Also, the phase transition temperature should be slightly less than the maximum allowable operating temperature of the gun tube

3. The location of the phase-change layer has little effect on gun tube temperatures. This indicates that the placement of material on the barrel exterior is possible. As a result, thermal control is provided without causing additional structural problems.

Since a phase-change layer is a potentially useful tool for controlling gun tube temperatures, the following recommendations for further study are made.

1. Particularly, further study should be conducted on the application of a phase change layer to the barrel exterior. Potential materials and application techniques should be identified by this study. Consideration should be given not only to future gun tube designs, but also to current operational weapons. Control of the tube temperatures of current weapons might prove possible by application of a phase-change material to the tube exterior while the rest of the weapon remains essentially unchanged.

2. A thorough investigation of the property values of existing materials should be made to determine whether any material is currently available which fulfills the requirements for a phase-change layer located within the barrel wall.

3. The feasibility of developing a honeycombed or foamed metal layer with a fusible substance for filling the voids should be studied. This would provide a highly flexible material for the thermal control of gun tubes as well as for other thermal control applications.

# LIST OF SYMBOLS

| Symbols | |
|---|---|
| $B$ | Biot number = $hL/K$ |
| $C$ | Specific heat |
| $d$ | Thickness of phase change layer |
| $h$ | Heat transfer coefficient |
| $K$ | Thermal conductivity |
| $L$ | Thickness of barrel wall |
| $S$ | Dimensionless interface position |
| $T$ | Temperature |
| $t$ | Time |
| $U$ | Velocity |
| $W$ | Weight |
| $x$ | Spatial coordinate |
| $y$ | Dimensionless spatial coordinate |
| $Z$ | Transformation coordinate |
| $\alpha$ | Thermal diffusivity |
| $\epsilon$ | Emissivity |
| $\theta$ | Dimensionless temperature |
| $\lambda$ | Latent heat of formation |
| $\rho$ | Density |
| $\tau$ | Dimensionless time |

# SUBSCRIPTS

| | |
|---|---|
| C | Composite |
| h | Homogeneous |
| m | Value at transition temperature |
| p | Phase change |
| o | Initial value |
| 1 | Phase 1, Interface 1 |
| 2 | Phase 2, Interface 2 |
| 3 | Phase 3, Interface 3 |
| 4 | Phase 4, Interface 4 |

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