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**SIMPLIFIED ANALYSIS OF THE BORE SURFACE HEAT TRANSFER
REDUCTION IN GUN BARRELS AS ACHIEVED BY USING WEAR-
REDUCING ADDITIVES**

L. H. Russell

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Dahlgren Laboratory, Virginia**

October 1975

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based upon a solution to an inverse conduction problem in which the convective heat flux at the barrel inside surface was estimated by utilizing a measured history at the bore surface.

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PREFACE

This report was prepared as an outgrowth of the barrel wear evaluation conducted for the EX 73 MOD 0 charge assembly. The work was funded by the Improved 5"/54 Projectile Program under ORDASK 5520420904 of September 1971. This investigation was performed during the period from 16 September 1973 to 19 January 1974.

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This report has been reviewed and approved by Dr. John A. Copley and Mr. L. M. Williams, III of the Mechanics Division.

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INTRODUCTION

During the firing of a gun, high-velocity, high-temperature, propellant combustion gases wash over the bore surface of the gun barrel. These severe in-bore conditions cause an extremely high convective heat transfer to the barrel and, consequently, enhance the rate of wear at the bore surface. This cause and effect relationship exists because most of the complex, interdependent processes which induce gun barrel erosion are themselves thermally driven phenomena (see references 1 and 2 for information in support of this contention). In an attempt to retard the surface erosion in medium- to major-caliber guns, various materials, generally in the form of liners about the propellant bed, have been introduced into the propelling charge assembly. Of the many solid substances which have been used as additives in these "wear-reducing liners," titanium dioxide and hydrated magnesium silicate, or talc, have proven to be most successful in slowing down the rate of bore surface erosion in medium- to major-caliber guns.^{3,4,5*} One liquid substance, a highly viscous silicone oil, has also shown promise in reducing bore surface wear when placed in a container which fits within the cartridge case closure plug.⁶

It has been experimentally observed during a gun firing that the use of these additives causes the bore surface temperature to be reduced below that which normally would occur when no additive is used. Thus, along with a reduction of bore surface erosion, use of these materials causes a reduction in the heat input to the gun barrel. There are several mechanisms which may be important in reducing propellant gas convective heat transfer to the bore surface. Some of the more important of these mechanisms are as follows:

1. The additive may cause endothermic chemical reactions to occur within the boundary layer on the bore surface.
2. The additive may be deposited upon and then ablated from the bore surface.
3. The additive may cause a residue to be deposited on the bore surface which inhibits the catalytic recombination of dissociated atomic species.
4. The additive (if in solid particulate form) may reduce the turbulence level near the bore surface.

*Raised numerals refer to identically numbered items in the list of references at the end of the main text.

5. A residue comprised of the additive material may coat the bore surface and act as a passive thermal barrier, or thermal resistance to heat flow.

Other less beneficial heat transfer reducing mechanisms, no doubt, also occur during the interior ballistic time frame. At the present time, the exact mechanisms or even the relative importance of the mechanisms of heat transfer reduction in gun barrels are unknown. This state of affairs should not be surprising since the problem of predicting the interaction of bore surface wear and bore surface heat transfer is extremely complicated. For example, to fully investigate the relative importance of one or all of the first four mechanisms identified above, one would have to utilize solutions of the nonsteady, chemically-reacting, turbulent boundary layer equations. Only mechanism number five can be investigated by a relatively simple theoretical analysis. Moreover, since a very thin residue has been visually observed on the bore surface of a gun barrel after a wear-reducing additive has been utilized (see references 5 and 6 for example), the heat transfer attenuating capability associated with mechanism number five becomes an obvious subject for further research.

In view of the above motivating facts, the objective of this work can now be stated. The objective was to show by a theoretical analysis whether or not certain very thin bore surface coatings, acting only as passive thermal barriers, can significantly reduce the bore surface temperature generated during a 5"/54 gun firing in which a high-energy, high-flame temperature propellant is utilized. By so restricting the investigation, the core of the analysis reduces to consideration of unsteady heat conduction through a multi-layered hollow cylinder with time-varying convective boundary conditions.

MATHEMATICAL MODEL

Consider now the mathematical model which was used in determining, for a given axial location, the time-varying convective heat transfer coefficient applicable to the inside surface of a gun barrel. Assume that the gun barrel is comprised of a single, circular cylindrical tube and that only radial heat conduction is significant. The governing equation is:

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial T}{\partial r} \right] \quad (1)$$

The boundary conditions, with heat flow in the outward radial direction defined as positive, are as follows:

$$\text{at } r = r_i, \quad -k \frac{\partial T}{\partial r} = h_i (T_g - T_{bs}) \quad (2)$$

$$\text{at } r = r_o, \quad -k \frac{\partial T}{\partial r} = h_o (T_w - T_{amb}) \quad (3)$$

The initial condition is:

$$\text{at } t = 0, \quad T = T_{init} \quad (4)$$

In the manner of reference 7, an alternative boundary condition can be written for the bore surface. This alternative expression is:

$$\text{at } r = r_i, \quad -k \frac{\partial T}{\partial r} = A_o e^{-ct} \quad (5)$$

By combining equations (2) and (5), the convective heat transfer coefficient relevant to the bore surface can be written as:

$$h_i = \frac{A_o e^{-ct}}{(T_g - T_{bs})} \quad (6)$$

If the constants A_o and c and the time-dependent parameters T_g and T_{bs} were explicitly known, then h_i could readily be found as a function of time.

PROCEDURES

A discussion will now be given of the computational steps involved in utilizing equation (6) to find that time dependent h_i which is relevant to a given charge assembly as it functions in a particular gun. Experimental bore surface temperature data were available for a 5"/54 gun firing using an M26 propelling charge assembly without a wear-reducing liner. This information was for a single-shot firing and pertained to an axial location 43.5 in. from the breech face. The thermocouple construction is detailed in references 8 and 9. The solid curve in Figure 1 represents the experimental temperature history of the bore surface thermocouple. In this and the subsequent figures, the zero time

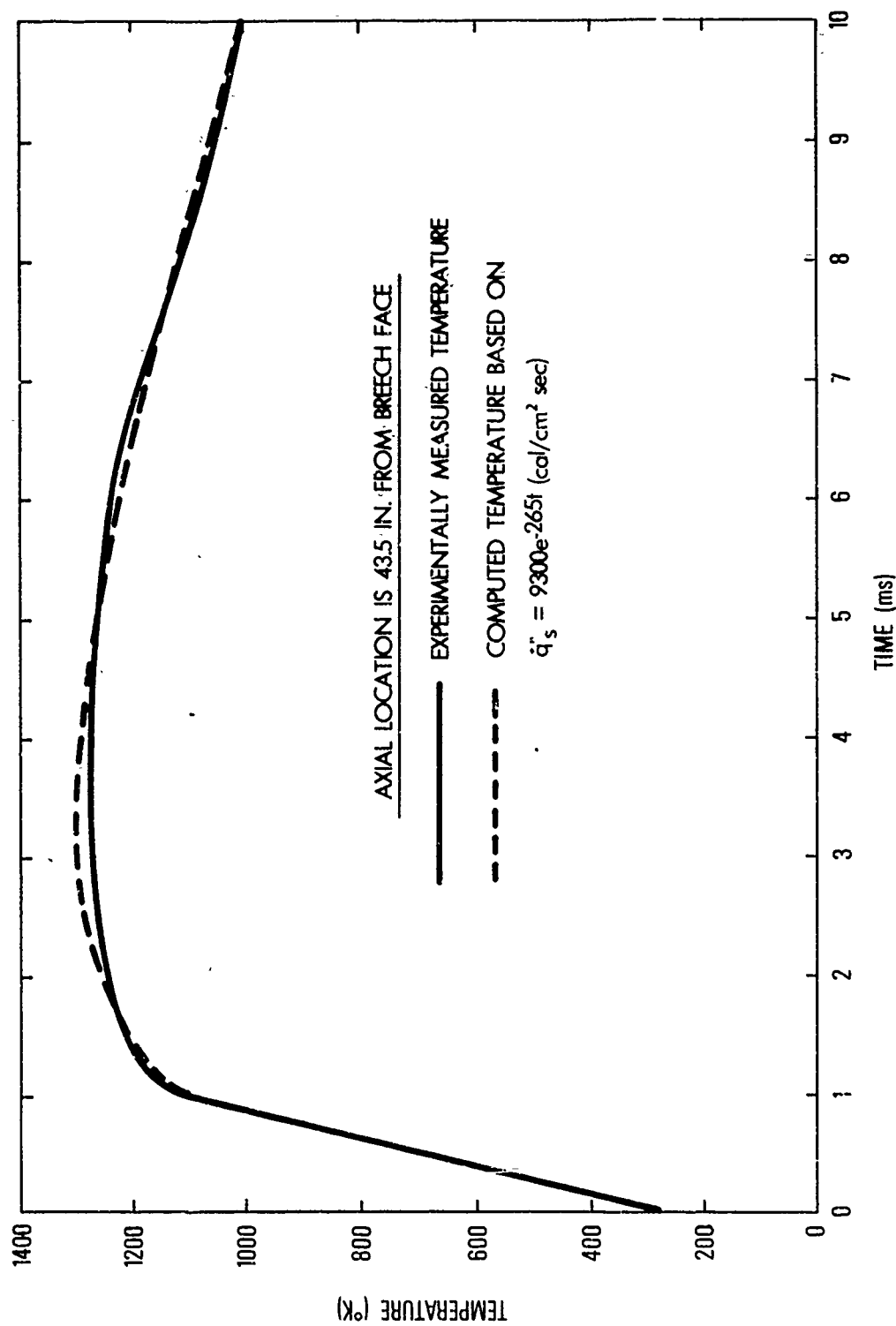


Figure 1. 5"/54 Bore Surface Temperatures Relevant to an M26 Propelling Charge Not Incorporating a Wear-Reducing Liner

is taken to be the time at which the projectile movement has exposed the thermocouple. The end points of the curves in Figure 1 and of curves in all remaining figures correspond to the ejection time of the projectile. The dashed curve in Figure 1 represents the temperature at the bore surface as caused by a surface heat flux of $9300e^{-265t}$ (cal/cm² sec). This heat flux function was the result of a solution to an inverse conduction problem. In this problem, it was required to minimize the degree of disparity between a mathematically predicted surface temperature and the experimentally measured bore surface temperature. The mathematical model used in this optimization process was an explicit finite difference scheme cast in radial coordinates. For a given gun barrel geometry and for fixed values of k , α , h_o , T_{init} , and T_{amb} , the degree of temperature disparity was a function only of A_o and c . Shown in Table 1 is the set of parameters, excluding A_o and c , which was used in generating the dashed curve of Figure 1.

Table 1. Parameters Used in Generating the Dashed Curve in Figure 1

<u>Parameter</u>	<u>Value</u>
k	0.0784 cal/cm sec °K
ρ	7.350 g/cm ³
c_p	0.1800 cal/g °K
α	0.0555 cm ² /sec
h_o	0.0005 cal/cm ² sec °K
T_{init}	273 °K
T_{amb}	273 °K
r_o	16.19 cm
r_i	6.35 cm

The thermophysical properties shown in Table 1 were chosen to be representative of gun steel (SAE 4335) when at a temperature of 900°K (see references 10 through 12). It should be noted that with the optimized, exponentially decaying heat flux function, 93 percent of the total accumulative heat transfer to the bore surface occurs in the 10-ms time interval between shot ejection and the time when the projectile passes the 43.5-in. axial location.

Solution of the inverse conduction problem yields the heat flux function and thus specifies the values of A_o and c needed in evaluating

h_i as per equation (6). The value of the bore surface temperature, T_{bs} , is given by the solid curve in Figure 1. The final piece of information needed to evaluate the inside surface heat transfer coefficient is T_g , the temperature at the edge of the thermal boundary layer on the bore surface. Shown in Figure 2 is the time-dependent temperature assumed to be equal to T_g . This gas temperature was generated from a transient, one-dimensional, compressible, two-phase flow interior ballistic solution for the particular 5"/54 single-shot firing under investigation. The computer model yielding this solution was an improved version of the one described in reference 13. The temperature history shown in Figure 2 represents the gas temperature of the entire inviscid core at the axial location 43.5 in. from the breech end. It is assumed that this temperature is nearly the same as the gas temperature actually present at the edge of the thermal boundary layer at this axial location.

Enough information is now available for the determination of h_i via equation (5). Shown in Figure 3 is the result of calculations for the convective heat transfer coefficient associated with the gun barrel bore surface at 43.5 in. from the breech end. This coefficient is pertinent to a single-shot, 5"/54 gun firing wherein an M26 propelling charge without a wear-reducing liner was utilized. Thus, this coefficient was derived for a clean bore surface; that is, a bore surface not having an insulative coating.

A key assumption for the subsequent analysis is that the convection coefficient just derived remains unchanged when the bore surface is coated with a thin insulative layer. For the particular situation under investigation, h_i is primarily a function of the thermophysical fluid properties in the boundary layer on the bore surface. An insulative coating will affect the temperature distribution in this thermal boundary layer, thus causing some change in the temperature-dependent thermophysical fluid properties. However, this effect should be minimal, and it was thus assumed that the value of h_i found from a no-layer situation applies equally well to the case when a thin insulative layer coats the bore surface.

With the knowledge of the time-dependent bore surface heat transfer coefficient and the time-dependent inviscid core gas temperature, the effect of a thin insulative layer on the bore surface can now be quantitatively evaluated. Note that these parameters are also spatially dependent. However, for the purpose of illustrating the method, the present discussion will be restricted to the axial station located 43.5 in. from the breech end of the 5"/54 gun. This station is located 1/2 in. downstream of the origin-of-bore on a new 5"/54 gun and, thus, is at a location particularly susceptible to gun barrel erosion.

Now that the appropriate time-varying convective boundary condition has been identified for the bore surface, the analysis reduces to consideration of unsteady, radial heat conduction through a two-layer hollow

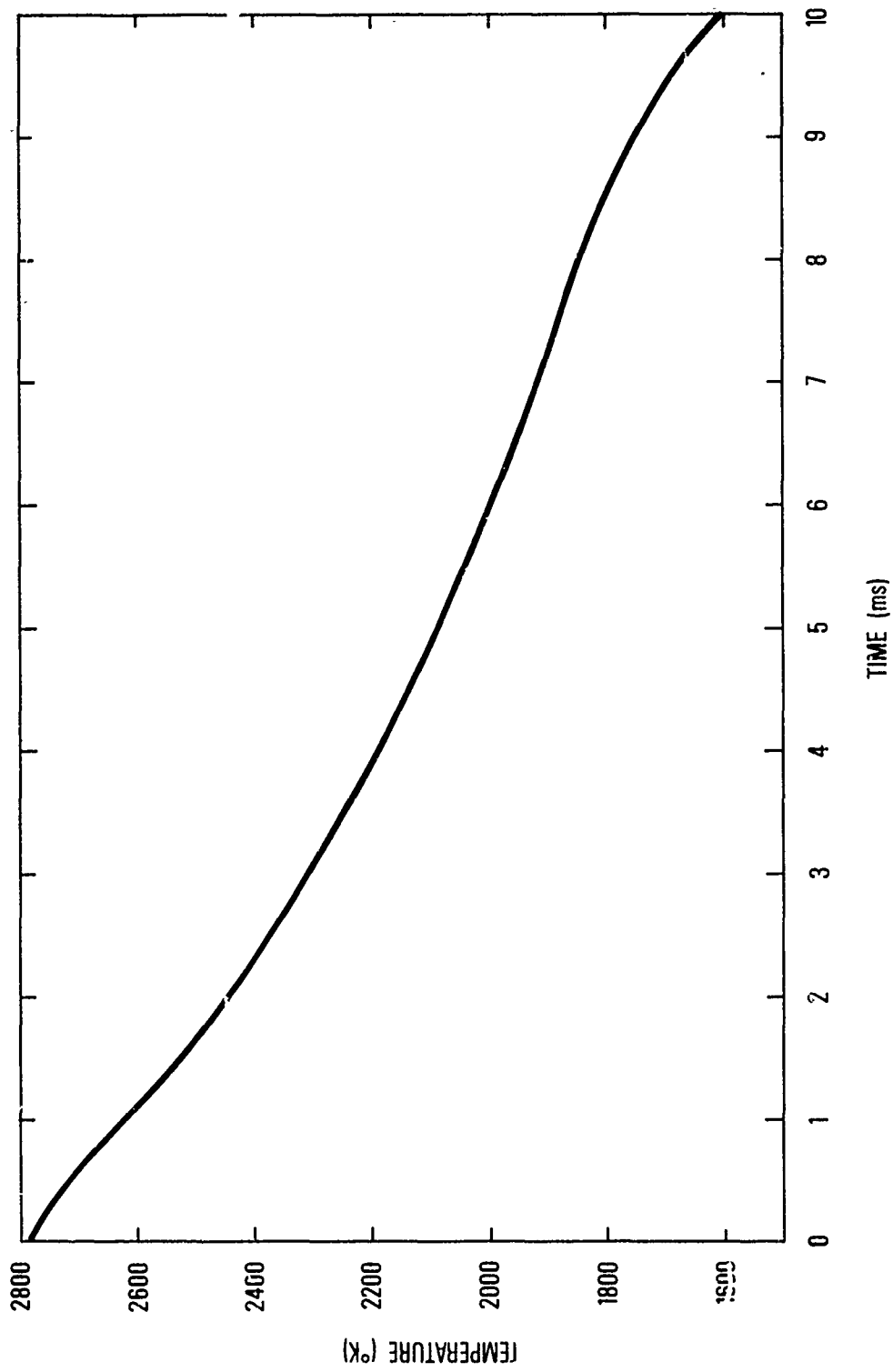


Figure 2. Calculated Inviscid Core Gas Temperature

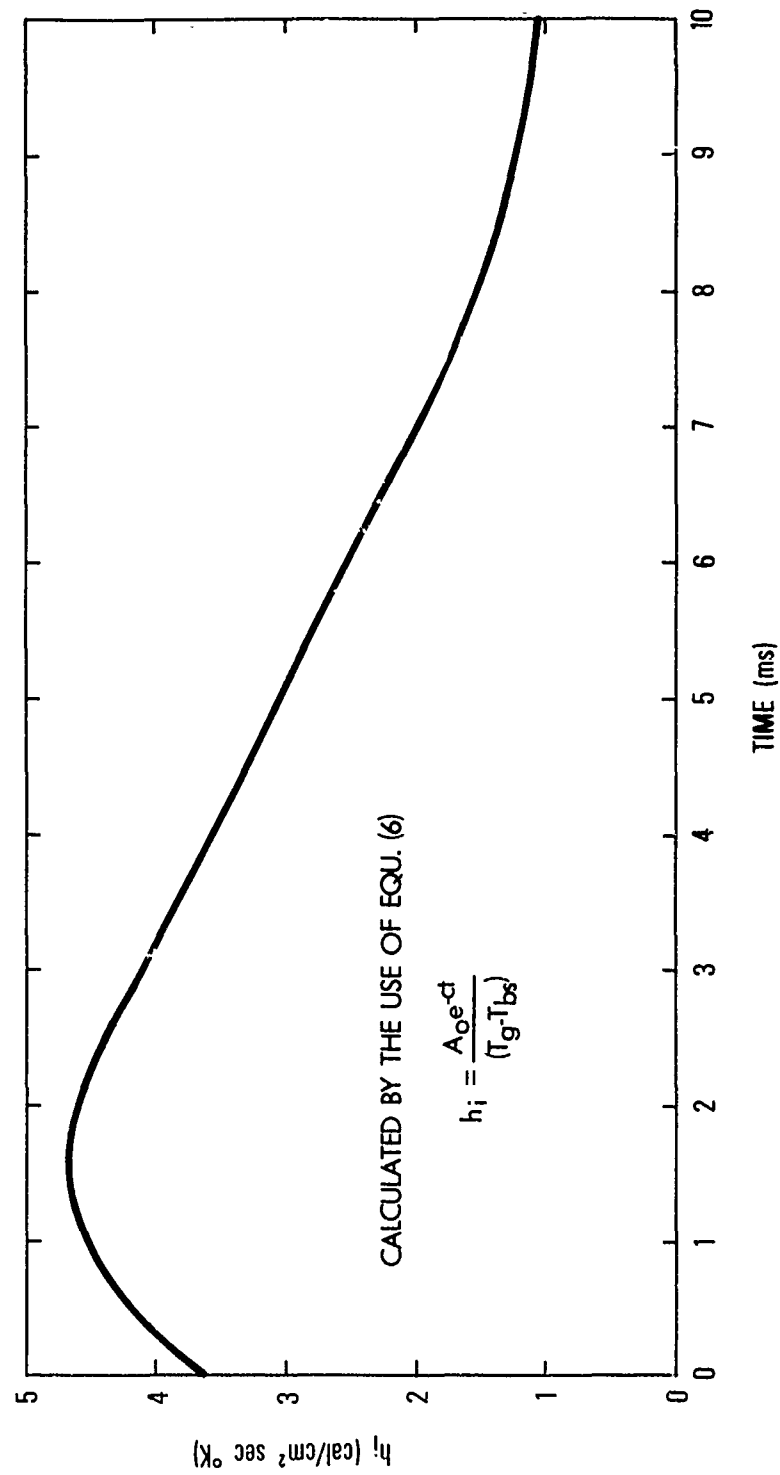


Figure 3. Convective Heat Transfer Coefficient Associated With the Bore Surface of the Gun Barrel

circular cylinder. An explicit, finite difference computer program was utilized in this analysis. In the calculations, it was assumed that perfect thermal contact existed between the insulative layer and the gun steel. Although the computer code can easily treat temperature-dependent thermophysical properties, constant values of thermal conductivity, specific heat, and density were used for both the insulative layer and the gun steel. The reasons for this action were as follows:

1. A complete set of thermophysical property values could not be found from the literature over the full temperature range of interest.
2. It was believed that the use of a set of thermophysical properties evaluated at one carefully selected temperature (900°K was the representative temperature chosen for use in the analysis) would not seriously compromise the quantitative predictions and would certainly not affect the qualitative trends of the analysis.

The past success of two wear-reducing liners, namely titanium dioxide (TiO_2) in a wax binder and hydrated magnesium silicate [$\text{Mg}_3(\text{Si}_4\text{O}_{10}(\text{OH})_2$] in a wax binder, guided the choice of material assumed to compromise the insulative layers. Three types of residue were considered. The first was a densely-packed bed of very small (say 15 to 30 μm in diameter), polycrystalline titanium dioxide particles. The other materials assumed as possible insulative layers were fused silicon dioxide (SiO_2) and magnesium orthosilicate or Forsterite (Mg_2SiO_4). The thermophysical properties at 900°K of these materials are presented in Table 2 (see references 14 and 15). The finite difference calculations were conducted for a single shot and only up to the time of shot ejection. Calculations for temperature response during "blow-down" were not undertaken since very little heat transfer to the bore surface at the 43.5-in. location occurred after projectile exit.

Table 2. Thermophysical Properties of the Materials Assumed as Insulative Layers

Material	k (cal/cm sec °K)	ρ (g/cm ³)	c_p (cal/g °K)	α (cm ² /sec)
TiO_2	0.00836	4.11	0.210	0.00969
SiO_2	0.00592	2.20	0.270	0.00997
Mg_2SiO_4	0.00490	2.22	0.289	0.00764

RESULTS

Some results obtained from the heat transfer analysis are shown in Figure 4. These results show the effect of a titanium dioxide layer on the thermal response of the bore surface. Note that in this figure, and henceforth, use of the term "bore surface" will refer to the surface of the gun steel. Thus when a layer coats the gun steel, the bore surface temperature is really the temperature of the interface between the insulative layer and the gun steel. The surface over which the propellant gases flow will be called the "exposed surface." As shown in Figure 4, three cases were considered: no residue, and layers of 0.0012 and 0.0024 cm thickness deposited on the bore surface of the gun. Note the substantial reduction (272°K) in peak gun steel surface temperature that was caused by the 0.0012 cm titanium dioxide layer. In Figure 5, the temperature history of the inside exposed surface is shown. For the no-residue situation, the inside exposed surface is synonymous with the bore surface or gun steel surface. As must be the case, the exposed surface of a residue is at a higher temperature than that of the uncoated gun steel surface. This is a typical result, showing that an insulator cannot transmit heat as rapidly as a conductor. Figure 6 is particularly informative. This illustration shows the attenuation, due to the presence of a titanium dioxide residue, of the accumulative heat per unit area which passes through the inside exposed surface. For the 0.0012 cm coating, the total heat input through 10 ms was about 20 percent less than that associated with the uncoated situation.

The last set of results is presented in Table 3. Shown in this table is a performance comparison among the three candidate materials chosen as possible insulative bore surface coatings. Only the results for a layer thickness of 0.0012 cm are presented. For these materials at this residue thickness, the total heat input at 10 ms is between about 20 and 30 percent less than that experienced by an uncoated bore surface. A similar magnitude of heat transfer attenuation near the origin-of-bore has been reported in reference 6 for 5"/54 gun firings wherein a highly viscous silicone oil was utilized as the wear-reducing additive in a NACO propelling charge. As discussed in reference 6, the thickness of the residue (assumed to be fused silica) which was required to achieve this bore surface heat transfer reduction was about 0.0012 cm.

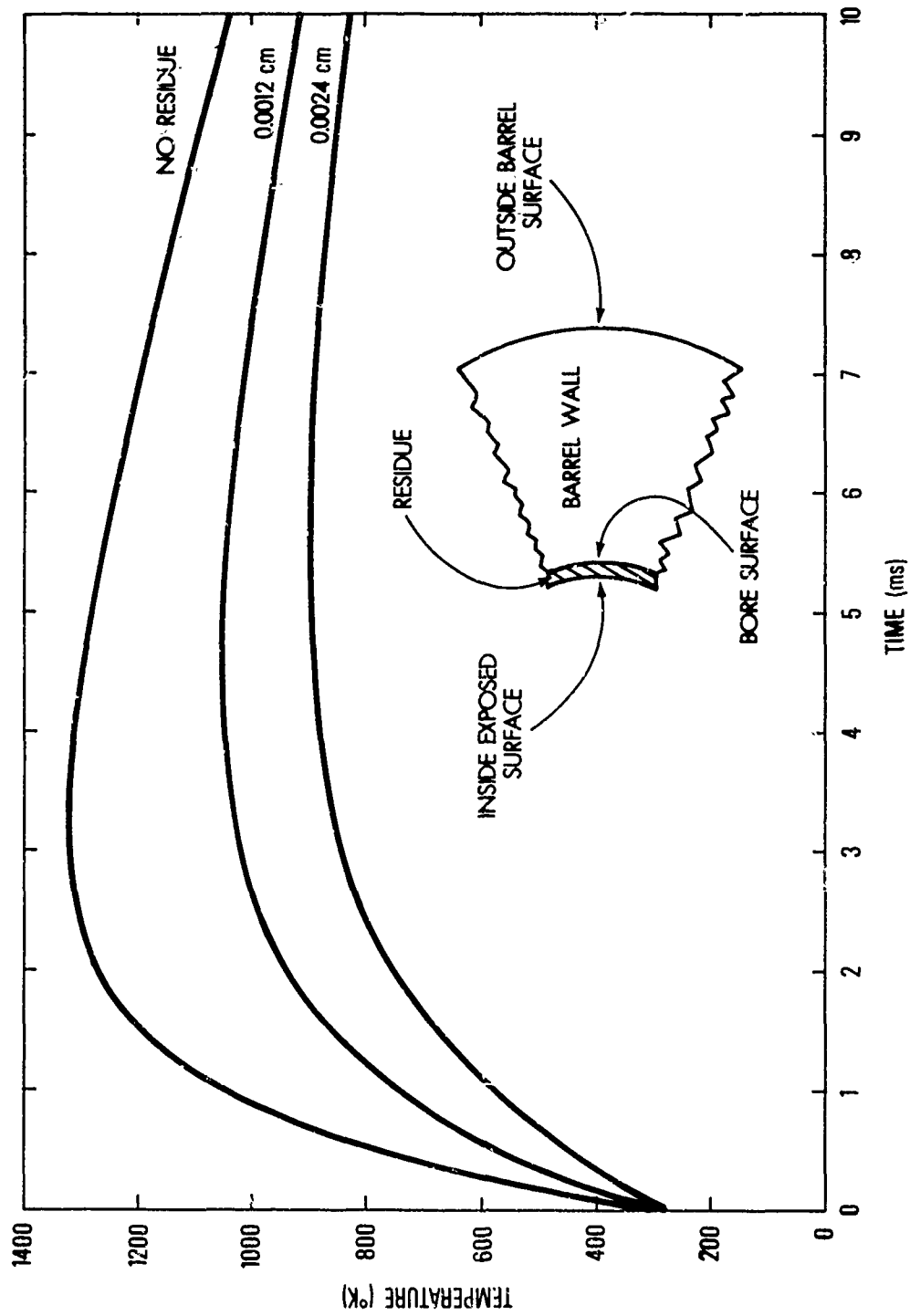


Figure 4. Computed Bore Surface Temperatures

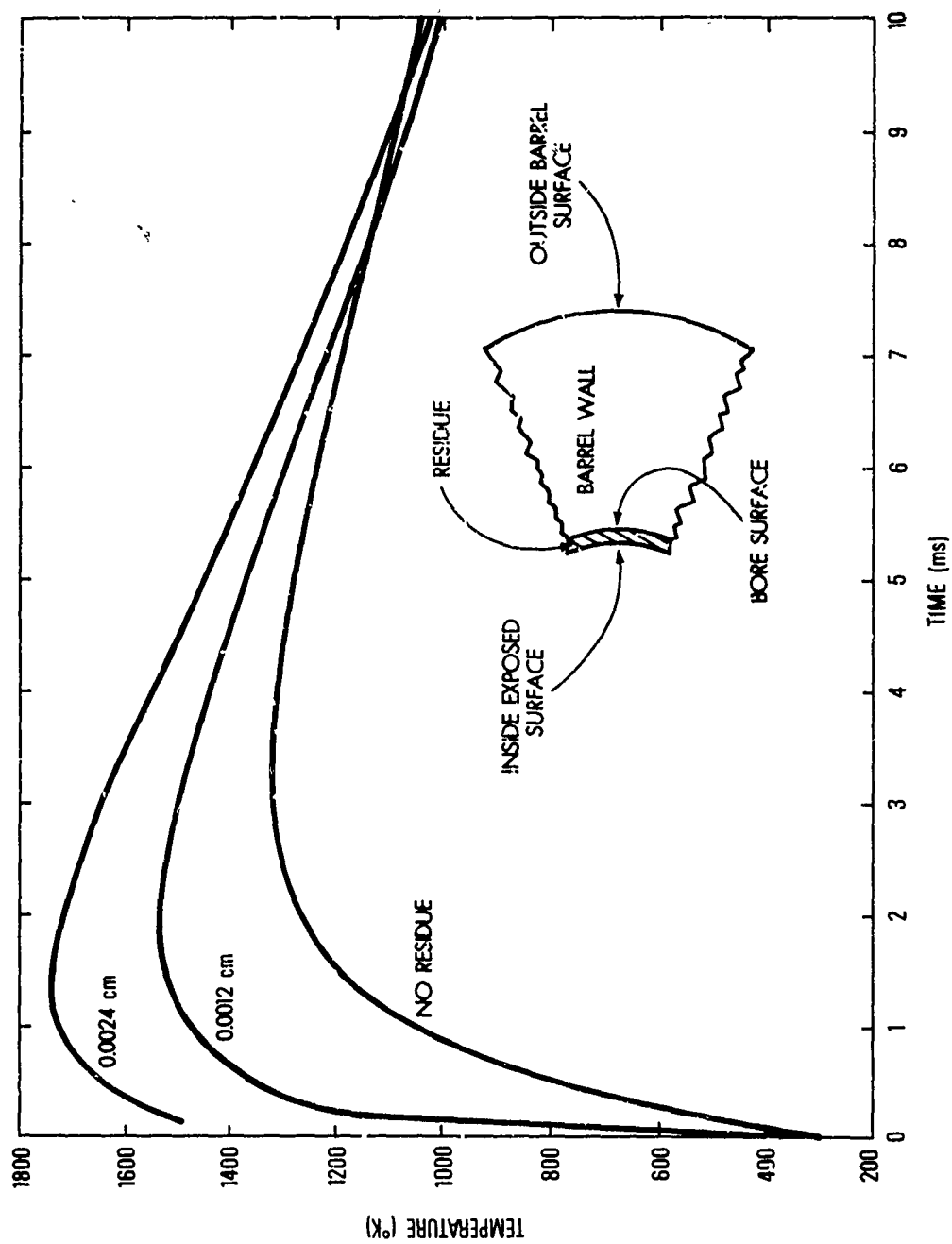


Figure 5. Temperature of the Inside Exposed Surface

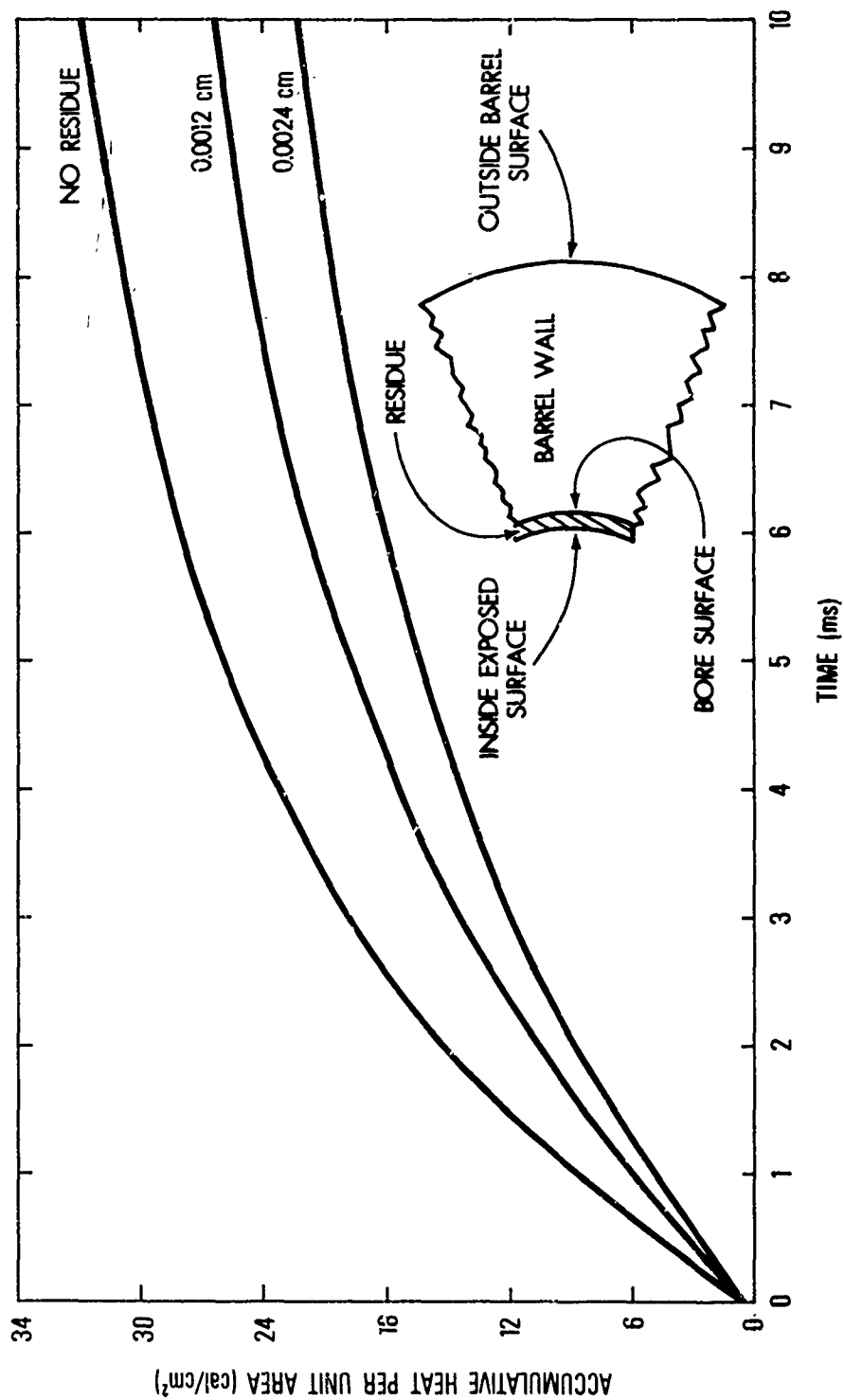


Figure 6. Accumulative Heat Per Unit Area Which Passes Through the Inside Exposed Surface

Table 3. Performance Comparison Among
Some Insulative Coatings

	<u>No Coating</u>	<u>0.0012 cm Coating</u>		
		<u>TiO₂</u>	<u>SiO₂</u>	<u>Mg₂SiO₄</u>
Peak Bore Surface Temperature (°K)	1321	1049	982	940
Peak Exposed Surface Temperature (°K)	1321	1538	1642	1704
Total Heat Input at 10 ms (cal/cm ²)	32.70	26.28	24.08	22.83

CONCLUSIONS AND RECOMMENDATIONS

It was concluded from this elementary analysis that certain bore coatings, on the order of 10 μ m in thickness and acting only as insulative thermal barriers, can reduce bore surface heat transfer to levels significantly below that present in gun barrels having no such coatings. Concurrent with this heat transfer attenuation is a reduction in the bore surface temperature attained during a gun firing.

The analysis specifically concerned the 5"/54 gun geometry and an M26 propelling charge; however, the above conclusions should be relevant to a variety of gun geometries and propelling charges. The materials (TiO₂, SiO₂, and Mg₂SiO₄) assumed as insulative layers were chosen because they were felt to be representative of the kinds of residues that might be present on the bore surface when the more successful wear-reducing additives are used in a charge assembly.

It is likely that the success of wear-reducing additives is based, to a large extent, on the establishment of a very thin insulative layer on the bore surface. This investigation, as well as the one described in reference 16, supports the reasonableness of this hypothesis. Other evidence supporting this hypothesis is presented in reference 6. As discussed in reference 6, the experimentally measured bore surface temperature at a given axial location in the 5"/54 gun showed a definite dependence on shot number. The peak temperature at a given point on the bore surface decreased from its value on the first shot and tended to asymptotically approach a final lower value after a few shots. A plausible explanation for this phenomena is that during the first few shots the rate of material deposition upon the bore surface is slightly in excess of the rate of residue removal from the bore surface. Then,

after a certain number of shots, a "dynamic" steady-state layer thickness is achieved wherein these two rates become equal.

The above conclusions lead directly to two recommendations for future work. The first recommendation is to more accurately define the thickness distribution and chemical composition of the bore surface residues created when wear-reducing liners or additives are used in propelling charge assemblies. As part of this effort, determination should be made of the thermophysical properties of these residues. Such quantitative experimental data would help greatly in an effort to definitely identify the mechanisms which are important in reducing heat transfer to the bore surface when a wear-reducing liner or additive is utilized. The second recommendation is to construct experiments which would identify the mechanisms controlling the process of particulate matter deposition from a hot, high-velocity gas stream on to a relatively cold wall.

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APPENDIX A
NOMENCLATURE

NOMENCLATURE

A_o	amplitude of the heat flux pulse
c	exponential decay rate
c_p	specific heat
k	thermal conductivity
h_i	convective heat transfer coefficient applicable to a given axial location on the inside of the gun barrel
h_o	outside convective heat transfer ccefficient
$\dot{q}_s''$	heat flux at the bore surface
r	radius
r_i	inside radius of the gun barrel
r_o	outside radius of the gun barrel
t	time
T	temperature
T_{amb}	ambient gas temperature
T_{bs}	bore surface temperature
T_g	temperature at the edge of the thermal boundary layer on the inside exposed surface of the gun barrel
T_{init}	initial temperature of the barrel
T_w	temperature of the outside surface of the gun barrel
α	thermal diffusivity
ρ	density