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THERMAL MANAGEMENT OF RAPID FIRE GUN BREECHES: THE CASE FOR HEAT PIPES

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The thermal management of rapid fire, large caliber gun breeches is addressed. It is shown that by means of heat pipes, the inside breech bore surface temperature can be kept below anticipated "cook-off" temperatures of even caseless ammunition. The design, materials and working characteristics of the suggested heat pipe are described in detail. An example for a 120mm tank gun is given.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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1. INTRODUCTION

The breech of a gun is subjected to very high heat input from the burning of the propellant charge. One consequence of this is the undesirable rise in the temperature of the bore surface. The heat buildup is alleviated, but only slowly, after the end of the ballistic cycle by convective, radiative, and conductive heat transfer processes. Due to the high specific heat of the breech material and low rates of the naturally occurring heat transfer mechanisms, considerable time elapses before appreciable cooling of the breech takes place, with an accompanying temperature drop of the inside bore surface. The problem is compounded in rapid fire weapons where the time between rounds is very short. For caseless ammunition this time is further shortened since extraction and ejection of spent cartridge cases no longer takes place. The accumulated heating due to repeated firing cycles results in a gradual buildup in temperature of the inside bore surface (see Conroy [1991] for details). Worse still, as time progresses, the loaded cartridge now comes into contact increasingly with a wall at an elevated temperature leading to the possibility of cookoff (i.e., the ignition of the propellant charge before the intended firing). It is imperative, therefore, to keep the breech inside surface temperature below a threshold which depends on the material of the charge.

To speed the cooling process, a number of hardware fixes have been tried. With a bore evacuator, the cooling process is enhanced but not changed appreciably. Schemes based on jacketed cooling with a circulating fluid have been proposed and tried but are not practical for many gun designs due to the required plumbing and the heat removal rates which can be achieved. Thermal conduction as the primary mechanism for displacing heat within the barrel does not work either since it is too slow to keep up with the huge heat loading of the breech inside surface of rapid fire weapons. (See the Appendix for an assessment of the efficacy of fins.) Spraying water onto the bore surface could be effective, but, depending on the surface temperature, unfavorable metallographic changes may occur as a result of the quenching, thereby weakening the bore.

Thus, the problem is not resolved; however, there exists a technology which may yet contribute toward a solution. This report investigates the feasibility of employing heat pipes for rapid heat dissipation out of a breech, using the 120-mm gun as the example.

2. THE PROBLEM

A 120-mm gun has an inside breech bore length of 0.39 m. The wall thickness is 7.62×10^{-2} m in the radial direction. For a typical propellant charge (Lawton 1988), 5×10^{7} W/m^2 of heat is transferred to the breech wall during the ballistic cycle, which here is taken to last for 8 ms. This heat load estimate can be verified by assuming a gas flow in the bore at a temperature of 3,000 K, typical of the burning propellant, and with an average flow velocity of 500 m/s. The heat transfer is calculated from the steady-state correlation given in Groeber, Erk, and Grigull (1957), for $10^4 \leq Re \leq 4.0 \times 10^5$, $0.1 \leq Ma \leq 1.0$, $Pr = 0.71$,

$$Nu = 0.0236 Re^{0.77} , \tag{1}$$

where Ma is the Mach, Pr is the Prandtl, and Nu is the Nusselt number; the latter is the ratio of the convective to the conductive heat transfer. Then the rate of heat transfer is given by

$$\dot{q} = \alpha \Delta T \times \text{area} , \tag{2}$$

where the convective heat transfer coefficient α is obtained from the steady-state correlation above.

For an inside breech bore surface area of 0.19 m^2, heat conductivity of the wall of 35 W/(mK), heat flow of the order of 10^5 J was calculated during the combustion process a value in line with Lawton's estimate. It is important to remember that the intense heat flow ceases with the extinguishment of the flame (i.e., with the consumption of the propellant). Thereafter, the cooling process sets in.

The natural convection and conduction processes are inherently slow and incapable of removing sufficient heat from the bore in a timely manner especially under rapid fire conditions. Thus, without outside intervention, the bore surface rises rapidly exceeding the cookoff temperature of the commonly used propellants.

In the following, we discuss an alternative solution of breech cooling to that advocated in the past, none of which were successful for rapid fire, large-caliber guns. We will show that an embedded and

properly designed heat pipe in the breech is able to keep the bore surface below the desired temperature limit. In addition, the temperature control device is maintenance free and environmentally friendly.

3. THEORY OF HEAT PIPES

3.1 Background. Cooling via heat pipes was first proposed by Gaugler (1944) in a U.S. patent. The concept is simple and its heat transfer capability impressive. Imagine a tube (Figure 1) containing a wick on the inside wall with a vapor space in the middle and extending the length of the tube. One end of the tube is in contact with a heat source, the other end exposed to the ambient atmosphere. Heat enters the tube, vaporizes the liquid in the wick. The evaporated liquid absorbs heat equivalent to the latent heat of evaporation. The hot vapor, due to the created pressure difference in the tube, travels to the cooler end where it condenses and liberates the heat absorbed at the evaporator end. The released heat in turn is passed through the wall from where it is dissipated by natural convection and radiation to the ambient atmosphere.

The liquid which condensed onto the wick is then returned by capillary action to the hot end where the cycle is repeated.

Thus, heat pipes are a very simple and efficient means of moving large quantities of heat without the use of outside motive power. Indeed, the effective heat conductivity of a heat pipe can be several orders of magnitude larger than that of a copper rod.

Heat pipes gained prominence after considerable development at Los Alamos (Cotter 1964; Grover 1964; Trefethen 1962; Dunn and Reay 1976). The Russian contribution and interest has also been considerable, especially in the use of alkali metals for the working fluid (Krillin 1990).

3.2 Modus Operandi of Heat Pipes. In broad outlines, the operating principle of a heat pipe has been described in Section 3. Here some of the mathematical details are given.

To operate, the pressure drop in the heat pipe must obey the following relationship:

$$\Delta p_c \geq \Delta p_l + \Delta p_v + \Delta p_g, \qquad (3)$$

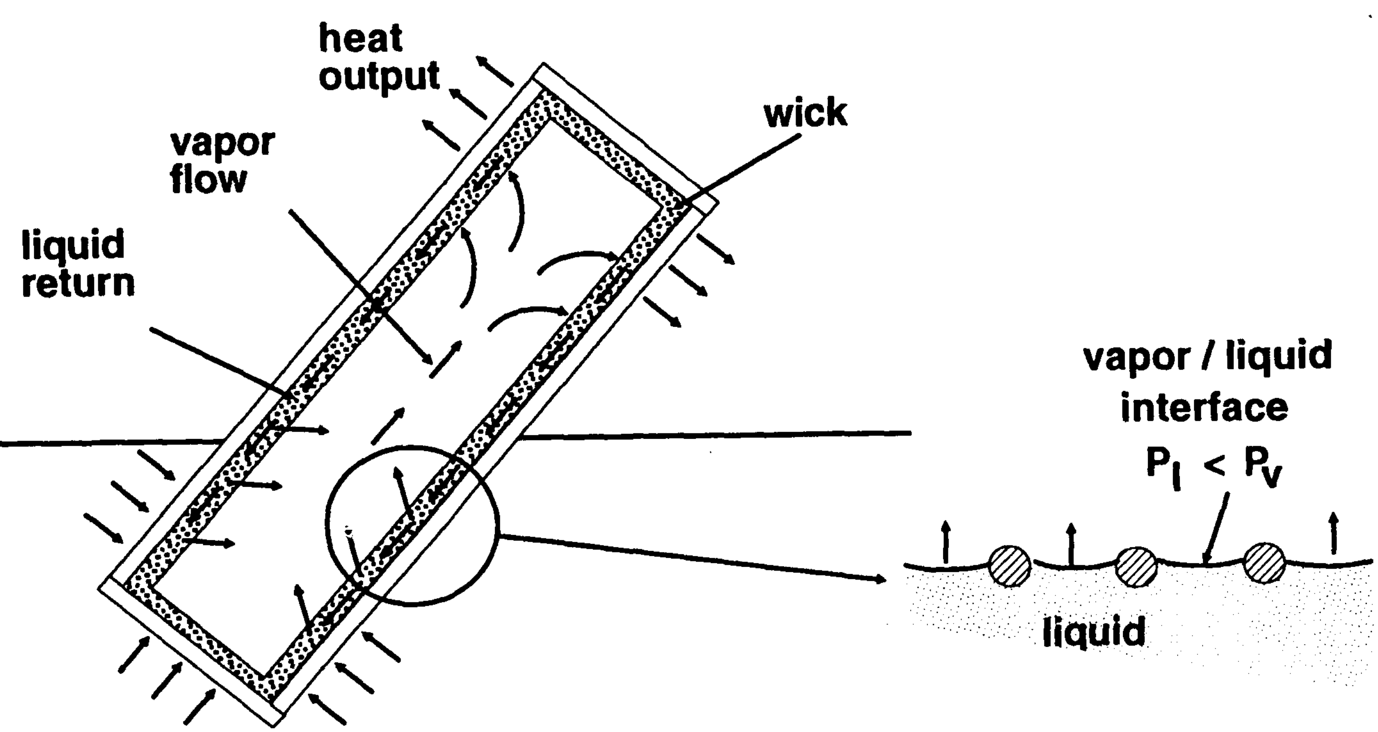

Figure 1. Schematic of a Generic Heat Pipe.

where

Δp_c = capillary pumping head

Δp_l = pressure drop required to return the condensate (liquid) to the evaporator end

Δp_v = pressure drop in the vapor

Δp_g = gravitational head (if any).

The capillary pumping head is calculated on the basis of

$$\Delta p_c = \sigma_l \left(\frac{1}{R_1} + \frac{1}{R_2} \right), \tag{4}$$

where σ_l is the surface tension of the liquid, R_1 and R_2 are the radii of curvature of the liquid surface. Usually, $R_1 = R_2$ so that the pressure drop across the curved liquid interface is

$$\Delta p_c = \frac{2\sigma_l}{R} . \tag{5}$$

If the contact angle between the liquid and the bounding surface is ϕ, the capillary head is

$$\Delta p_c = 2\sigma_l \frac{\cos\phi_l}{R_l} . \tag{6}$$

The capillary head between the evaporator and the condenser, where e and co refer to the evaporator and condenser respectively, is then

$$\Delta p_c = 2\sigma_l \left(\frac{\cos\phi_l}{R_e} - \frac{\cos\phi_l}{R_{co}} \right) . \qquad (7)$$

Once the temperature regime of operation and the geometry of the pipe has been determined, the choice of the working fluid needs to be specific.

3.3 Working Fluids and Materials. Working fluids are classified according to a merit number, M, defined as

$$M = \frac{\rho_l \sigma_l L}{\mu_l}, \qquad (8)$$

where,

ρ_l = density of the working fluid

σ_l = surface tension

L = enthalpy of vaporization (latent heat)

μ_l = viscosity of the liquid.

The variation of the value of M of a number of working fluids is given in Figure 2 as a function of temperature.

The higher the merit number for a given temperature the more suitable the liquid is for the given application. Table 1 gives a sampling of a representative list of heat pipe working fluids.

Next we turn to the flow of the liquid.

In a steady, laminar flow, the Hagen-Poiseuille equation applies and the mass rate of flow is given by

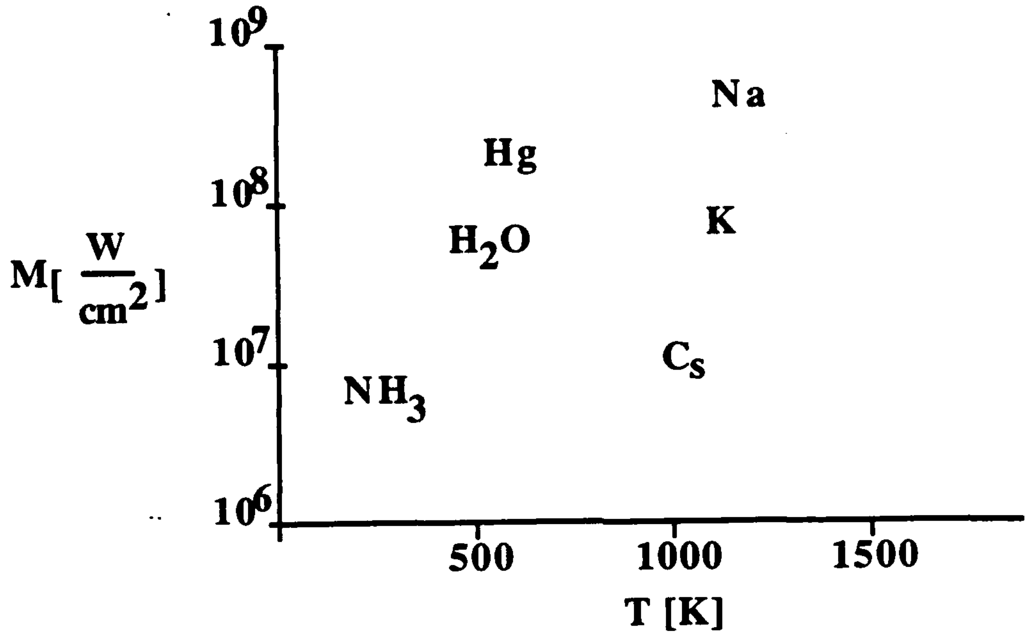

Figure 2. Working Fluid Merit Numbers as a Function of Temperatures.

$$dm/dt = \pi \rho a^4 \Delta p/(8\mu l) \tag{9}$$

where l is the tube length and a is the tube radius. For flow through a porous material, Darcy's law applies:

$$\Delta p_l = (\mu_l l_{eff} dm/dt)/\rho_l KA \ , \tag{10}$$

here K is the wick permeability and A the wick cross-sectional area.

3.4 Performance Limitations. Heat pipe performance is limited by several factors:

a. sonic limit of the gas flow
b. entrainment of the gas by the liquid
c. boiling limitation
d. pressure gradient within the wick

Table 1. Heat Pipe Working Fluids

Melting Point (°C)	Fluid	Operating Range (K)	Latent Heat (kJ/kg)	ρ_g (kg/m^3)	ρ_l (kg/m^3)	$\mu_l \times 10^{-4}$ (Pa - s)	$\sigma_l \times 10^{-3}$ (N/m)	Thermal Conductivity (W/mk)
−209.86	N_2	70–113	199	4.6	810	0.14	8.9	0.14
0.0	Water	303–473	2,258	0.6	958	2.8	59	0.680
—	Thermex	423–668	297	5.4	850	2.6	15	0.112
−38.89	Hg	523–923	298	5.3	12,740	8.8	380	12.2
63.25	K	773–1,273	1,935	0.51	672	1.1	50	35.8
97.81	Na	873–1,473	3,920	0.28	747	1.7	110	53.8
108.54	Li	1273–2,073	19,700	0.06	420	2.3	270	69.0

A brief discussion of each of these effects follows.

3.4.1 Sonic Limitation. When the fluid in the vapor phase, moving from the evaporator to the condenser section, achieves sonic velocity, the heat transfer limit of the heat pipe is reached. Busse (1973) derived an equation giving the limit of achievable heat transfer:

$$dq/dt = 0.474\, A_v\, L\, (\rho_o p_o)^{0.5}, \tag{11}$$

where A_v is the cross-sectional area of the vapor passage, L the latent heat of the working fluid, ρ_o the vapor density at temperature T_o at the evaporator end of the heat pipe, and ρ_o is the vapor pressure. Viscous losses in the vapor stream can prevent sonic flow from being attained. Viscous limits increase with temperature as the square of the vapor density, whereas sonic limits increase directly with vapor density.

3.4.2 Entrainment. At the interface between the wick surface and the vapor flow, a shear force is exerted on the liquid. One of the possible results of this interaction is that liquid droplets may be entrained and transported to the condenser end. The entrainment is resisted by the surface tension of the liquid. Should it not be sufficient, performance degradation may be observed. One common measure of the entrainment is the Weber number, We, which relates the surface tension to the gravity force and is defined as

$$We = \frac{\rho_v u^2 Z}{2\pi\sigma_l}, \tag{12}$$

where u is the vapor velocity, σ_l the surface tension, and Z a parameter characterizing the liquid vapor surface such as the wick spacing.

Generally, it is assumed that entrainment takes place at We = 1, from which the limiting vapor velocity can be calculated. Consequently, the axial entrainment limited energy flux (Dunn et al. 1976) is given by

$$q = \sqrt{2\pi \rho_v L^2 \sigma_l / Z} \quad . \tag{13}$$

3.4.3 Boiling Limitation. At the evaporator of the heat pipe, the liquid pressure is equal to the saturation pressure of the liquid-vapor interface less the capillary pressure. As the radial heat flux increases, the pressure difference across the interface increases, eventually leading to the formation of bubbles. Such a situation needs to be avoided since bubbles impede the heat transfer and the liquid circulation within the wick. The heat flux at which this situation arises is termed the boiling limit. It may be shown that the maximum heat flux, without bubble formation, is given by

$$q_{bubble,max} = \frac{2\pi_l k T_v}{L \rho_v / n(r_i / r_v)} \left(\frac{2\sigma}{r_n} - p_c \right) , \tag{14}$$

where k is the thermal conductivity of the wick, p_c the capillary pressure, l the evaporator length, r_n the nucleation radius of bubbles, usually of the order of (10^{-7}) m.

3.4.4 Wicking Limit. For a heat pipe to function properly, the following pressure relationship must be obeyed:

$$\Delta p_c \geq \Delta p_l + \Delta p_v + \Delta p_g . \tag{15}$$

Assuming that the wick is uniform along its length and the pressure drop due to the vapor flow is small in comparison to the other terms, the fluid mass flow rate is

$$(dm/dt)_{max} = \frac{\rho_l \sigma_l}{\mu_l} \left[\frac{K A_w}{r} \right] \left[\frac{2}{r_l} - \frac{\rho g_l}{\sigma_l} \sin\phi \right] , \tag{16}$$

and, of course, the maximum heat transport is

$$q_{max} = (dm/dt)_{max} L \, . \tag{17}$$

Note that $\rho_l \sigma_l L/\mu_l$ is the figure of merit, M, of the fluid, while KA_w/r describes the wick geometrical properties. See Table 2 for typical wick properties.

Table 2. Typical Wick Data

Material	Permeability (10^{-10} (m^2))	Pore Radius (10^{-6} (m))	Porosity (%)
Mesh, Ti	0.46	15	67
Screen, s.s., 200 mesh	0.52	58	73
Screen, nickel	0.77	64	67
Foam, Cu	23.2	241	91
Foam, Ni	37.2	229	96
Powder, Cu 45–56 μ	1.74×10^{-2}	9	52

4. DIMENSIONING OF A HEAT PIPE FOR GUN BREECH APPLICATION

Given their excellent heat transfer capability, heat pipes appear to be the logical vehicle for the rapid movement of heat from the breech inside surface to a location where it can be readily dissipated. A large number of shapes for the breech heat pipe are possible. Here the principle of its use is illustrated by the adoption of a torus-shaped device which is embedded in and girdles the breech. The encirclement is important to prevent unsymmetrical heat stresses and the possible bending of the tube-breech assembly from occurring and thus affecting the accuracy of the gun.

A direct application of the design will be illustrated under the assumption that it has been incorporated into a 120-mm gun with an autoloader to permit rates of fire of 12 rounds per minute or greater. The 120-mm gun is standard on the M1A1 Abrams tank.

4.1 The Geometry. The following variables are assigned these values for the sake of example only. The geometry of the heat pipe for breech block cooling may take several forms. Here the basic principle is illustrated by a torus-shaped heat pipe girdling and embedded into the breech (Figures 3 and 4).

breech inside diameter	0.12 m
breech outside diameter	0.31 m
outside length of breech along tube axis	0.48 m
width, along the breech axis of the temperature control device	0.02 m
surface area of the temperature control device parallel to the breech base	0.131 m^2
outside diameter of temperature control device	0.92 m
depth of entry into breech of temperature control device	0.03 m
mesh pore size for liquid return	0.01×10^{-3} m
heat loading of breech	$< 5 \times 10^7$ W/m^2

The working fluid should preferably have a high heat of vaporization, low viscosity to ensure minimum hydraulic drag, and high surface tension which produces high capillary pressure and provides good wetting of the wick.

Typical materials to be used are as follows:

mesh material: stainless steel
tube material: stainless steel
working fluid: water (many other choices are also available dictated by the desired temperature regime of operation)

liquid density:	0.958×10^3 kg/m^3
surface tension:	0.059 N/m
liquid viscosity:	0.28×10^{-3} Pa-s
melting temperature:	273 K
boiling temperature:	373 K
latent heat of evaporation of liquid:	2,258 kJ/kg

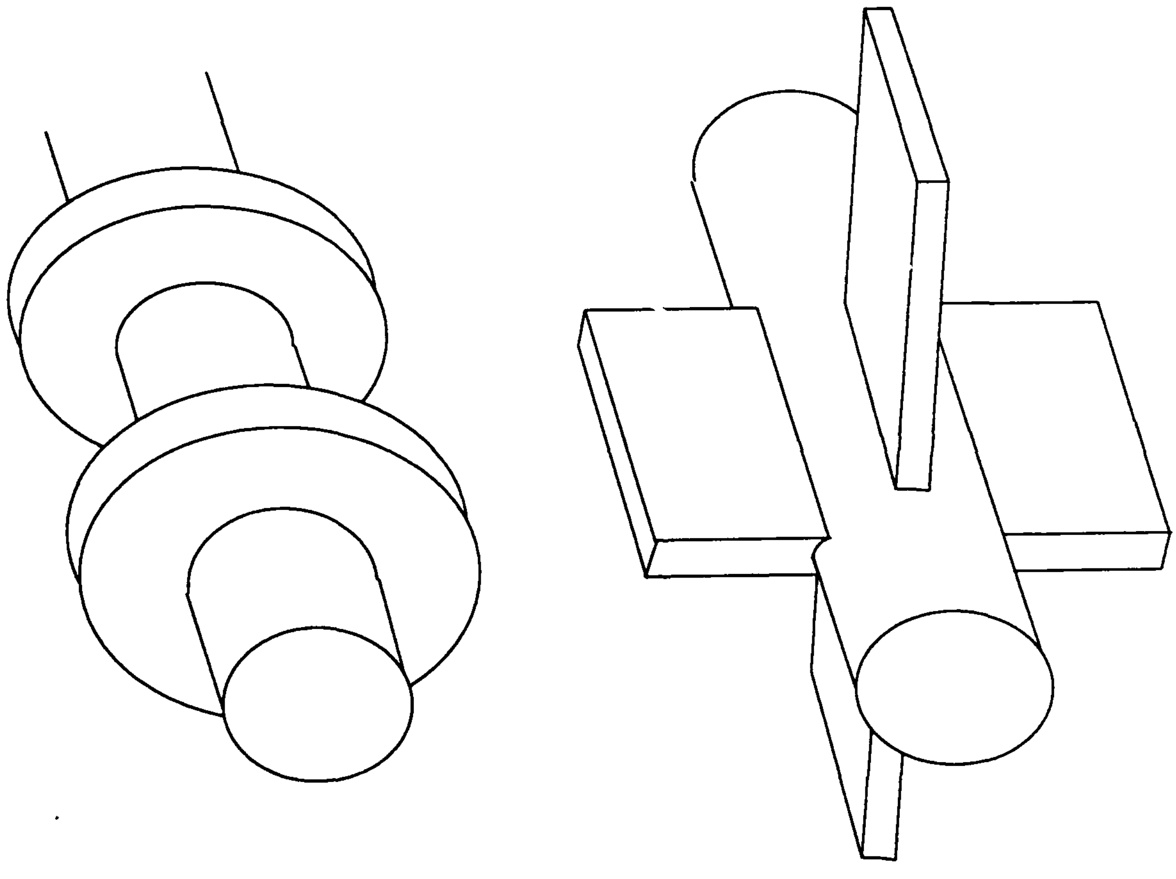

Figure 3. Heat Pipe.

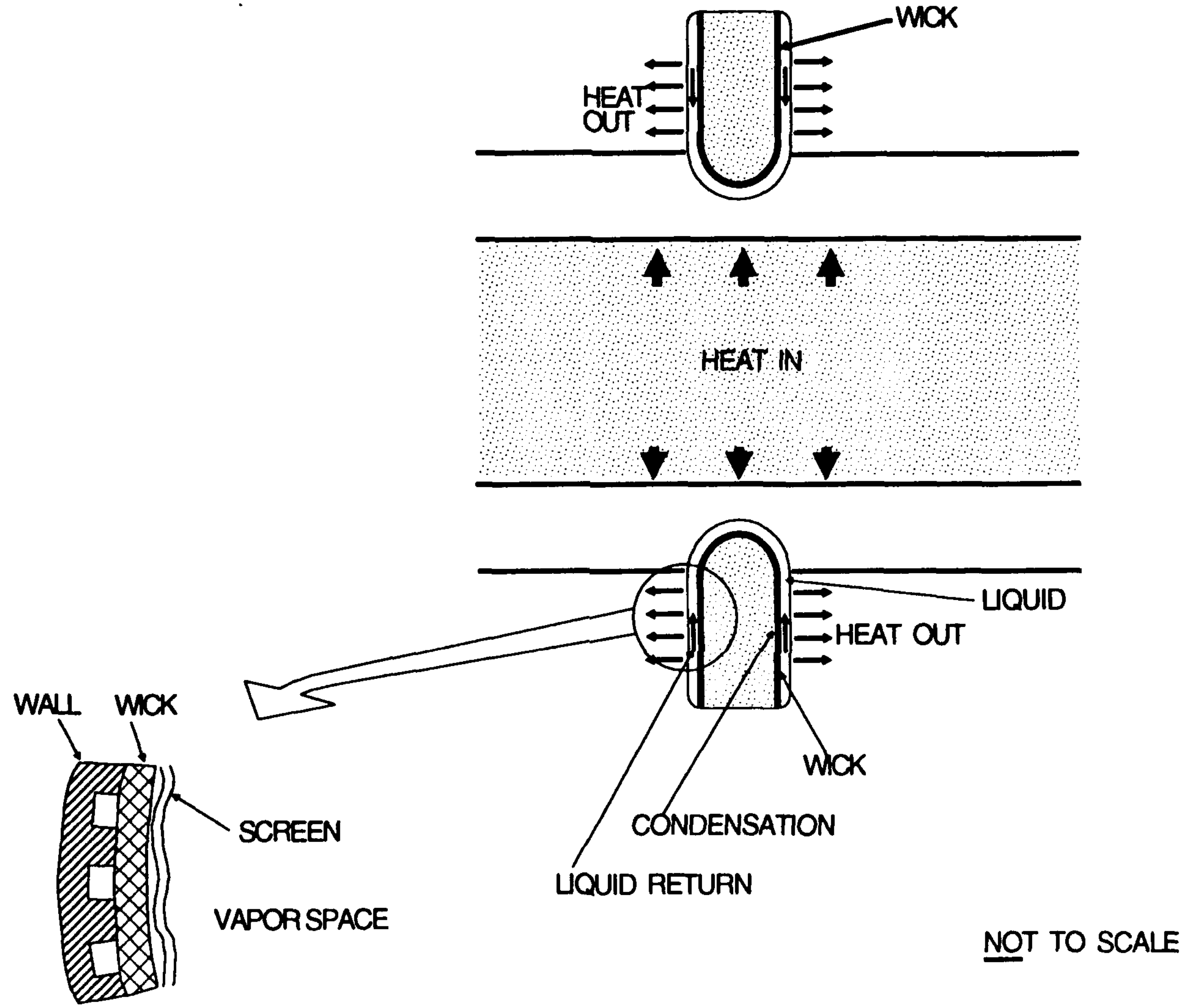

Figure 4. Heat Pipe Detail.

4.2 Performance Assay. Properties of the wick:

Let l_{eff} = effective length of the pipe, subscript e denotes evaporator, c the condenser, w the wick, A_w the cross section of the wick, K its permeability, r a radius with subscript i denoting interior, v the vapor space. Typically,

$$l_{eff} = (l_e + l_c)/2 = 0.15 \text{ m} \tag{18}$$

$$\begin{aligned} A_w &= \pi(r_i^2 - r_v^2) \\ &= 3.411 \times 10^{-5} \text{ m}^2 \\ A_w K &= 3.411 \times 10^{-15} \text{ m}^4. \end{aligned} \tag{19}$$

Pressure drop:

$$\begin{aligned} \Delta p_c &= 2\sigma / r_m \\ &= 1.180 \times 10^4 \text{ N/m}^2, \end{aligned} \tag{20}$$

where σ is the surface tension, r_m the pore radius, here taken as 0.01×10^{-3} m. Mass rate of flow which gives this pressure drop (from Darcy's law):

$$\begin{aligned} dm/dt &= \frac{\Delta p_c \rho_l A_w K}{\mu_l l_{eff}} \text{ kg/s} \\ &= 0.092 \times 10^{-2} \text{ kg/s}, \end{aligned} \tag{21}$$

where K is the permeability of the wicking material and the subscript l refers to the liquid.

Rate of heat removal:

$$Q = dm/dt \times \text{heat of vaporization} = 2.077 \times 10^3 \text{ J/s}. \tag{22}$$

In 5 seconds, the time between firings of a round, 1.038×10^4 J per heat pipe could be removed. If several heat pipes were used per breech, for the case of the 120-mm gun, the heat removal capacity is larger than the heat loading of the breech from a fired round. This takes into account the fact that the heat loading occurs only for 8 ms or less. Thus, the heat removal rate is adequate to ensure that residual heat buildup does not take place within the breech. Calculational checks also indicate that the heat removal is within the limits discussed in Section 3.4. A comparison of the heat pipe performance using several different working fluids is given in Table 3.

Table 3. Comparison of the Differences in Performance With a Change of Working Fluid

Working Fluid	Temperature Range (K)	dm/dt (kg/s)	Heat Removing Capacity (J/s)	Remarks
Water	300–473	0.092×10^{-2}	2.077×10^3	Would need plurality of heat pipes
Mercury	523–923	2.456×10^{-2}	7.584×10^3	Single heat pipe sufficient
Sodium	873–1,473	0.238×10^{-2}	1.04×10^4	Suitable at higher temperatures

It is instructive to compare the heat pipe heat transfer rate with that achievable with a circular solid fin on the breech. As shown in the Appendix, the heat pipe confers considerable advantage in the rate of heat removal.

4.3 Strength of Material Aspects. Strength of materials considerations: the insertion into the breech wall of helical, concentric or longitudinal grooves weakens the breech. To estimate the wall strength degradation, a finite element computer code was exercised. Under a worst case scenario (i.e., for a 155-mm gun), the result of a calculation of tube wall stresses under typical gun tube pressures are as follows: for a 6.19-inch inner diameter tube with a wall thickness of 3 inches, a 0.75-inch wide and

1.25-inch deep slot is specified to accommodate the heat pipe described above. It was found that under typical gun tube pressure the highest stresses in the various directions, where y is along the tube axis, x is radially, are σ_x = 339 psi, σ_y = 14,431 psi, σ_{xy} = 4,364 psi. Gun tubes of this caliber are designed to withstand pressure in excess of 120 ksi. Figures 5–7 present the stress distribution in the wall of a gun tube calculated for this simulation. Thus, no deleterious effect on the gun tube strength was found.

The manufacturing process, especially the autofrettage, imposes residual stresses upon the gun tube. Even with their inclusion, the total stress in the breech in the presence of the heat pipe cavity remains considerably below allowable limits.

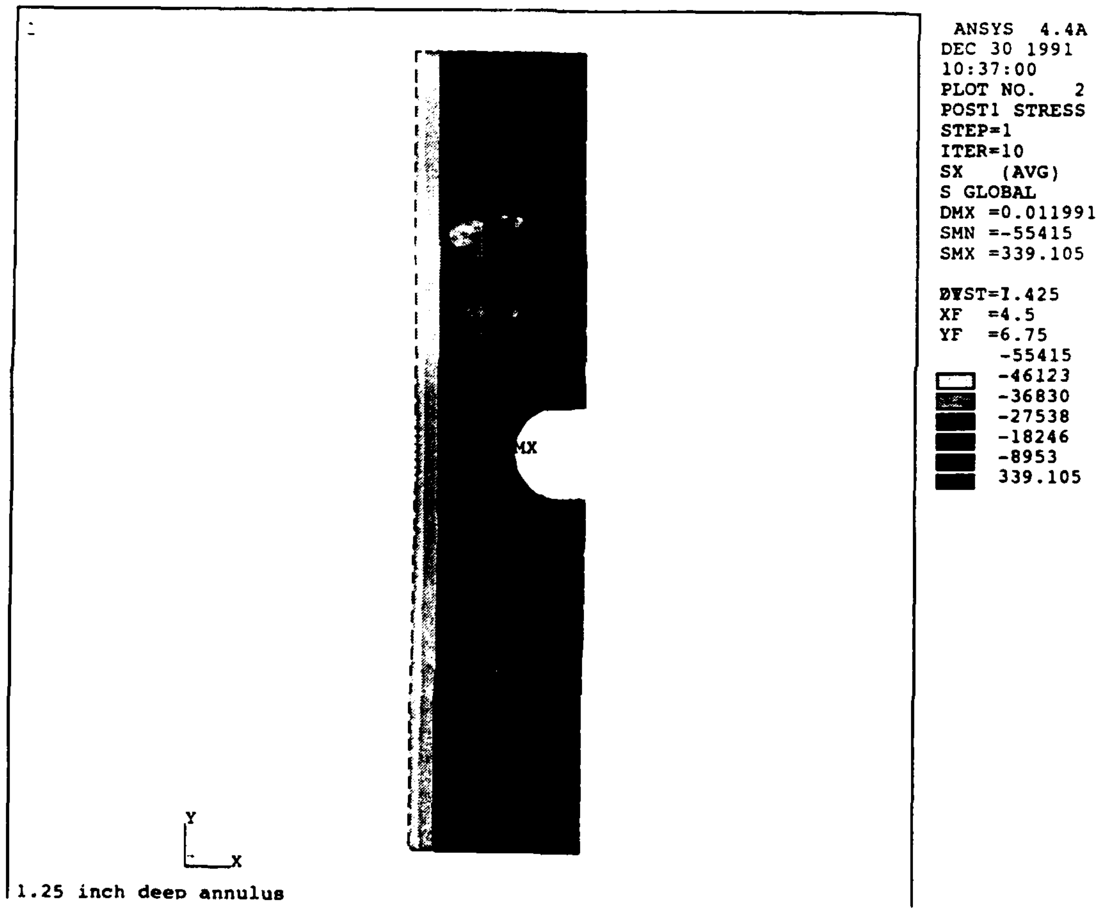

Figure 5. Gun Barrel Stress, σ_x, Under Typical Firing Conditions.

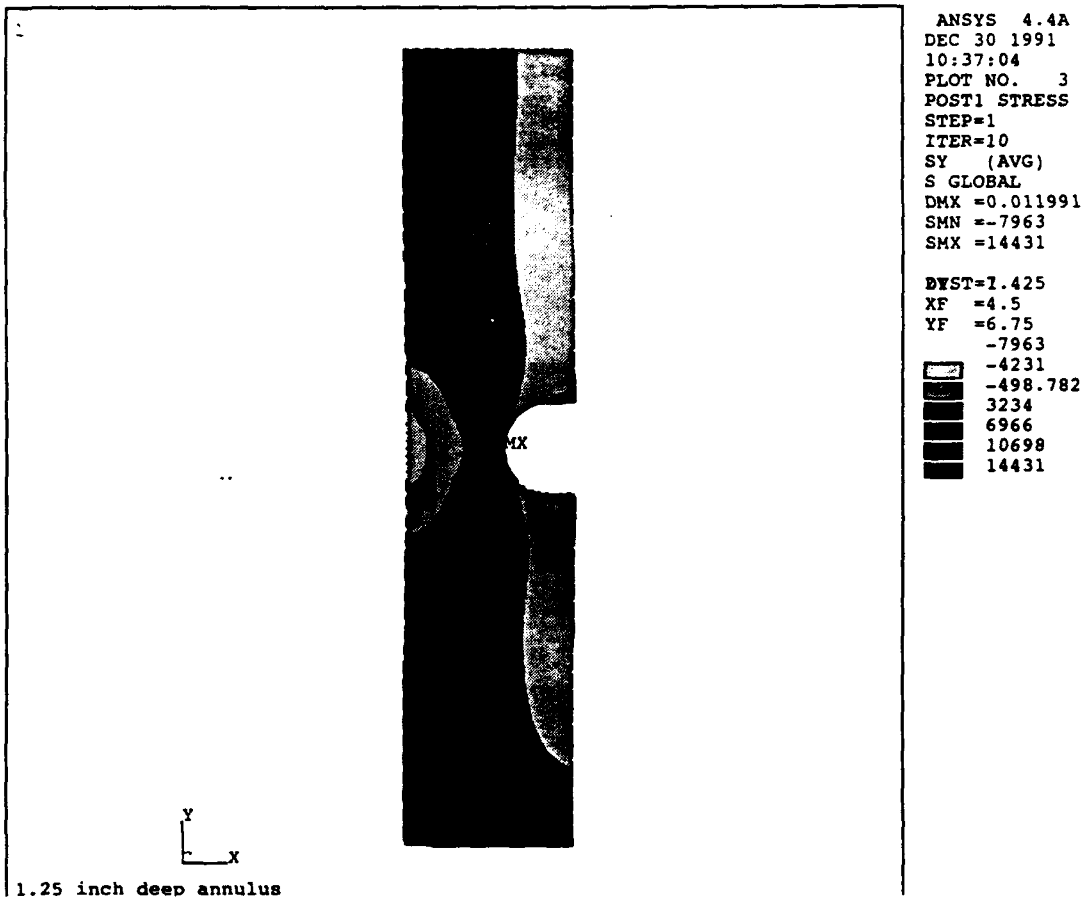

Figure 6. Gun Barrel Stress, σ_y, Under Typical Firing Conditions.

4.4 Heat Removal from the Condenser Section.

4.4.1 Radiation and Natural Convection. For a howitzer (i.e., a weapon not in an enclosed structure), natural convection and radiation transport the heat away from the outside of the temperature control device attached to the breech into the ambient surroundings. The outside surface of the heat pipe functions both as a radiator and the site of the natural convection.

Heat transfer based on natural convection is usually expressed in relations correlating Nusselt, Grasshof, and Prandtl numbers. We recall that the Grasshof number relates the buoyancy force to the viscous force, i.e.,

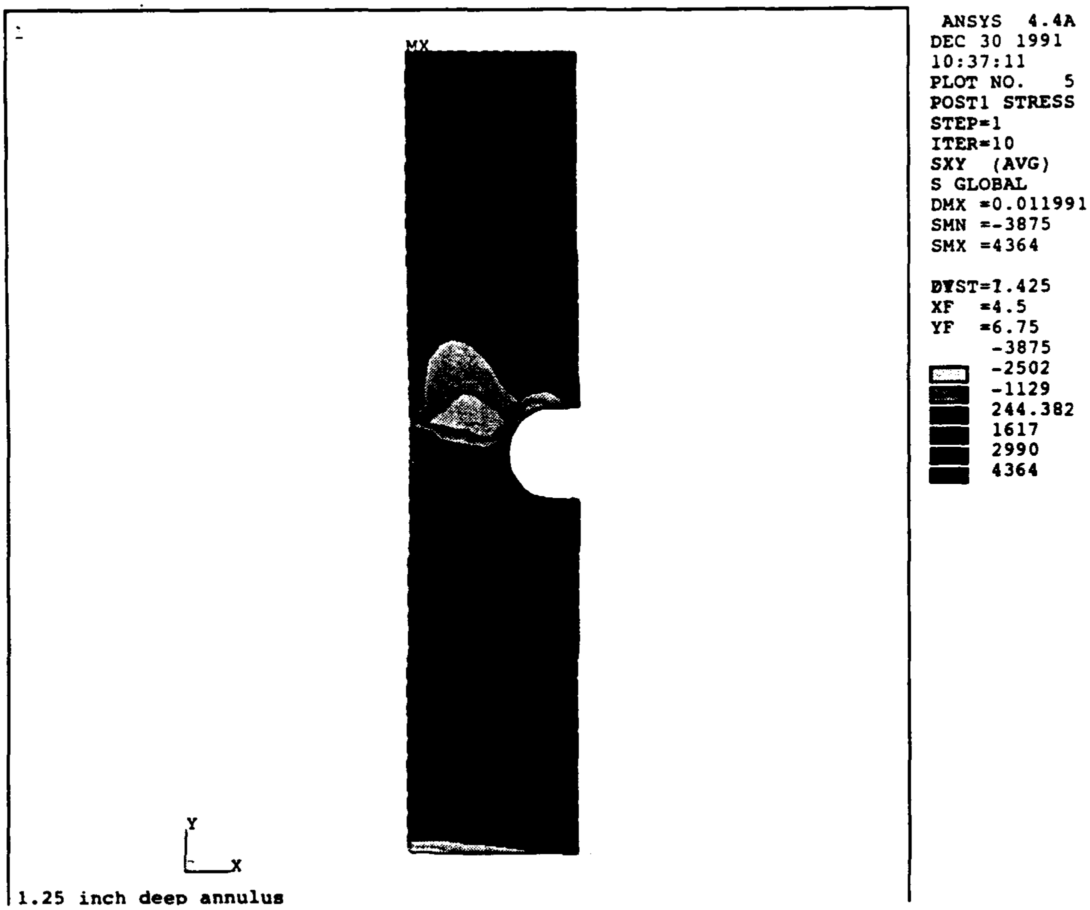

Figure 7. Gun Barrel Stress, σ, Under Typical Firing Conditions.

$$Gr \equiv \frac{g\beta\Delta Tl^3}{\nu^2}, \tag{23}$$

where g is the acceleration due to gravity, β the expansion coefficient, ΔT is the temperature difference, l a length scale, and ν the viscosity. The Prandtl number relates the momentum diffusivity to the thermal diffusivity while the Nusselt number is the ratio of the total heat transfer to the conductive heat transfer. In air, $Pr = 0.74$ and for $GrPr > 2 \times 10^9$, Groeber, Erk, and Grigull (1957) suggest the following relationship:

$$Nu = 0.10\ [Gr\ Pr]^{1/3}. \tag{24}$$

Knowing that $Nu = \frac{\alpha l}{\lambda}$, a value of α is calculated and then using

$$\dot{q} = \alpha \Delta T \times \text{area}, \tag{25}$$

where the area refers to the heat pipe area exposed to the ambient environment, a value of the heat transfer by natural convection is obtained. For a value of Nu of 164, recalling that for gun tube steel λ has a value of 35 W/(m K), a ΔT of the order of 100 K, a cooling area of 0.56 m^2, the value of q is typically around 4.322×10^5 W. Thus, in 5 seconds the time between rounds for the case under consideration, a quantity of heat greater than 10^6 J can be transferred. In addition, heat loss also occurs due to radiation and must also be included in the balance.

Assuming that the outside surface of the heat pipe is oxidized iron and can be approximated as a black body, the total energy radiated can be calculated from

$$E_T = C_S \left(\frac{T}{100} \right)^4 \tag{26}$$

where C_S is the radiation constant for black bodies, usually given as 5.775×10^{-4} W/cm^2 deg^4. For the case at hand, heat loss due to radiation is of the order of 10^4 [W/m^2], which must be added to the natural convective losses. The bottom line is that indeed, the heat losses can keep up with the bore surface heat input under the stipulated conditions.

4.4.2 Enclosed Crew Compartment. If the gun were located in a crew compartment, provisions must be made for the removal of the heat generated during firing which has been transferred from inside of the breech and dumped into the crew compartment. The air volume of the turret and the driver's station in a M1A1 is 5.566 m^3. Even under the assumption of complete mixing of the heat liberated during the firing of 12 rounds in 1.0 minute, a steep temperature rise inside the compartment can be expected.

However, an air conditioner rated at 1.5 tons could remove all the heat transferred and maintain the crew compartment at a comfortable level.

With a conventional 120-mm gun, 0.01 m^3 of space is required to accommodate the temperature control device on the outer periphery of the breech. In an M1A1, clearance between the breech and the turret roof is sufficient to accommodate the device. Since the heat control device on the breech is far enough to the rear, interference during recoil between the device, turret, and the recoil mechanism does not occur and a redesign of the latter is not needed.

4.5 Heat Transfer Analysis. An estimate of the attainable temperature reduction in this gun breech was obtained by conducting a simple heat transfer analysis (i.e., where the temperature history on the barrel surface with and without the heat control device is illustrated). The lower the temperature in the breech desired, the lower the boiling point of the liquid chosen has to be.

Exercising the gun barrel heat transfer algorithm of Polk (1980), the effect of the presence of an embedded heat pipe on the transfer of heat away from the breech surface was tested. Runs were made for the following conditions: breech without a heat pipe, heat pipe embedded to depths of 2.0 inches, 1.0 inch, and 1/2 inch from the outer surface. The gas flame temperature was taken as 3,000 K and the duration of the heating cycle was 10 ms. Polk (1980) recommends a heat transfer coefficient of 2 cal/(cm^2s K). The code was run for 110 firing cycles following the pattern indicated in Figure 2 of Conroy (1991), with each cycle taken as 10 seconds. This included both the heating and cooling of the breech.

Results are shown in Figures 8–10. In Figure 8, the inner and outer wall temperatures for an M203 charge in a 155-mm howitzer, at a rate of firings of 6 rounds per minute for 3 minutes followed by 3 rounds per minute continuous was simulated. When compared with Figures 2 and 3 of Conroy (1991), one sees that the present simulation is very close to the experimental results reported there which were taken from Vottis and Hasenbein (1979). The upper curve in Figure 8 shows a repeating cyclical pattern of a maximum temperature attained at the inner bore surface followed by a subsequent drop, as cooling takes place. As the firing continues, both the instantaneous peak and the final bore surface temperature at the end of the cycle are gradually increased. The lower curve, almost linear, is the temperature of the outside surface of the breech which rises in an almost linear fashion as the firing sequence continues.

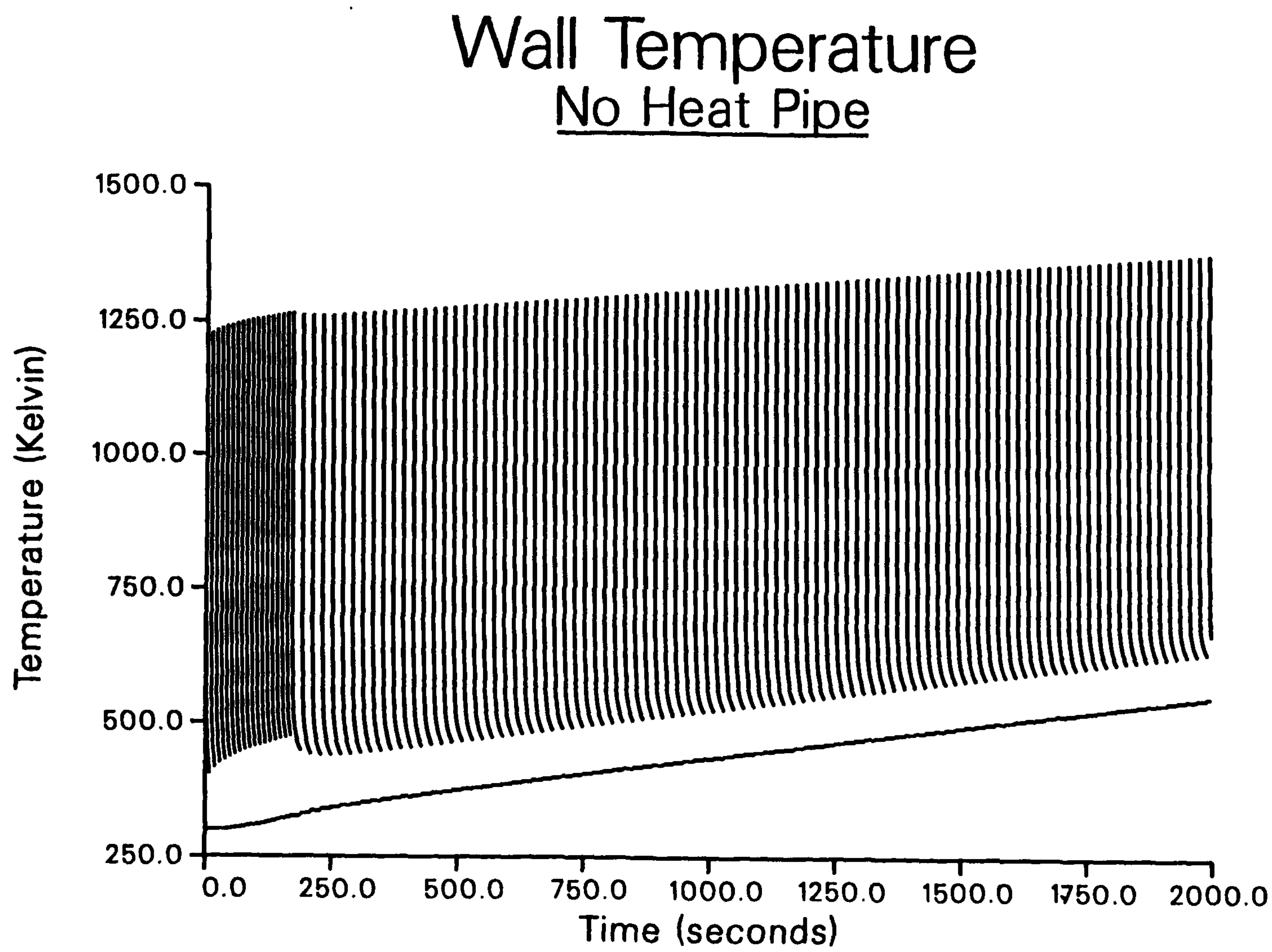

Figure 8. Bore Surface Temperature vs. Time Without a Heat Pipe.

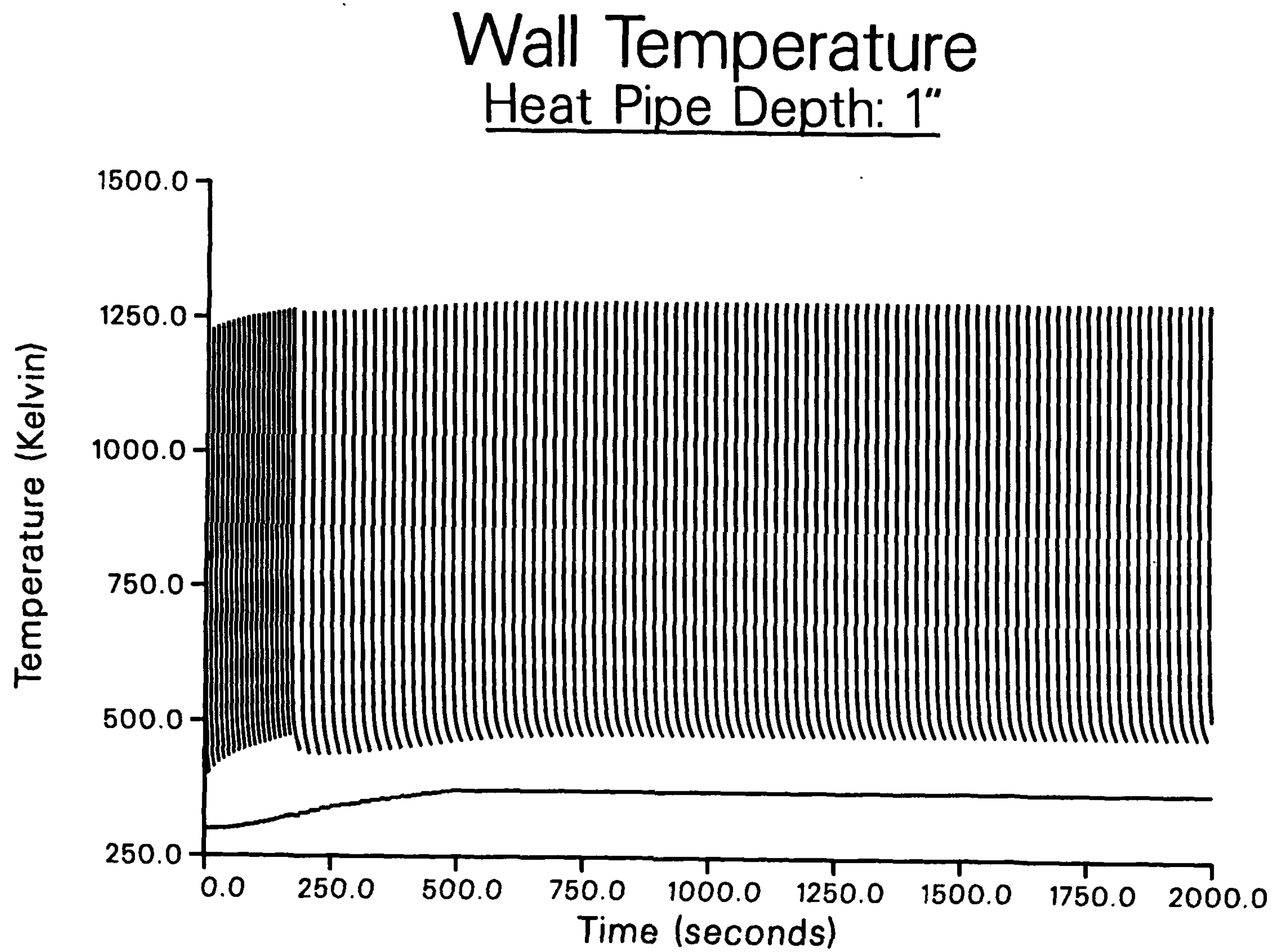

Figure 9. Bore Surface Temperature vs. Time With Heat Pipe Embedded at a Depth of 1 Inch.

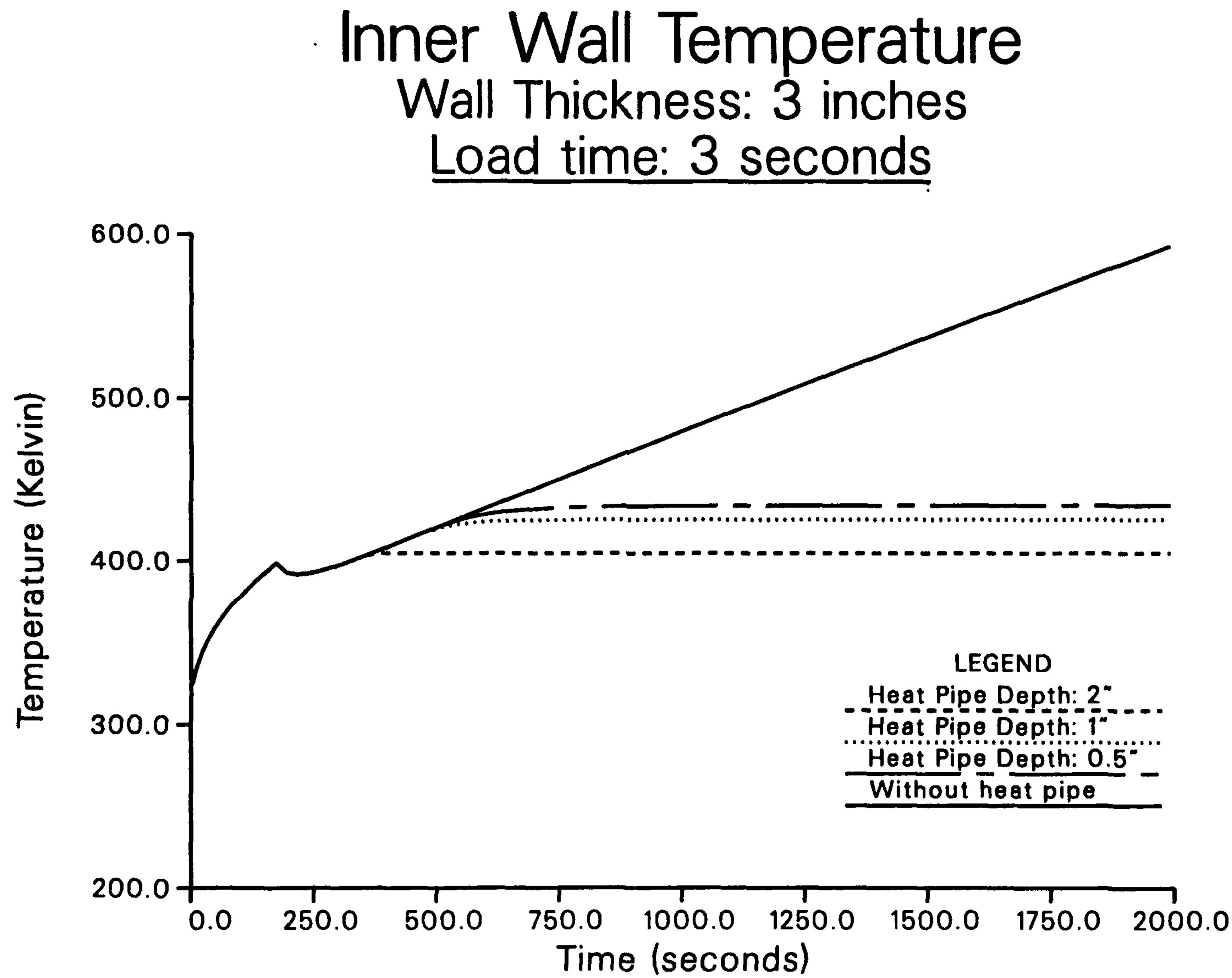

Figure 10. The Effect of the Presence of an Embedded Heat Pipe: Temperature vs. Time.

Figure 9 shows a similar calculation but with a heat pipe of 1-inch depth included. Both the inner and outer wall temperatures are reduced in comparison with Figure 8.

In Figure 10, the inner wall temperature without an installed heat pipe, with a heat pipe with water as a working fluid, embedded to depths of 2 inches, 1 inch, and 1/2 inch are shown. In addition, a case where the heat pipe is embeded to only 1/2 inch from the outer breech wall, which is 3 inches in thickness, is shown. It is seen that, even in this case, the heat pipe works well and keeps the inner bore surface below the anticipated cookoff temperature taken as 480 K. In all these simulations, the reload time was taken as only 3 seconds. The reload time has to be unrealistically short (i.e., less than 0.5 seconds) before the inner bore surface climbs above the cookoff temperature under sustained firing conditions.

Independent confirmation of the results (see Acknowledgment) are shown in Figure 11 which were obtained by exercising the XBR-2D code. The calculations were for a 155-mm gun, a 1,400-in^3 breech volume and using a zone-6 Unicharge at a firing rate of 12 rounds per minute for 5 minutes. For reality, an outside wind velocity high enough to maintain ambient conditions on the outside gun surface was assumed. To model the effect of different heat pipe depths, the calculation was run using different wall thicknesses (1 inch and 2 inches were studied) with ambient temperature maintained at the exterior. The four curves in the figure show the gun tube surface temperatures at the inner and outer walls. At the 2-inch wall thickness, the inside wall temperature approaches 450 K, while for the 1-inch wall thickness, the temperature approaches 353 K. It can be seen that the heat pipe is able to establish steady temperature conditions on the bore surface below the anticipated cookoff temperature. It is worthwhile noting that the heat loading conditions imposed here are the most severe of any rapid firing weapon which are likely to be encountered.

Although the heat pipe design has been discussed with a specific configuration, the design is not limited to this embodiment or to the configuration mentioned. For example, it will be apparent that the liquid used as well as the wicking or even the shape of the heat transfer device can be changed without changing the nature of the device. Also, it should be understood that various changes and substitutions, particularly with respect to construction details, can be made in the arrangement of several elements without departing from the basic heat pipe concept.

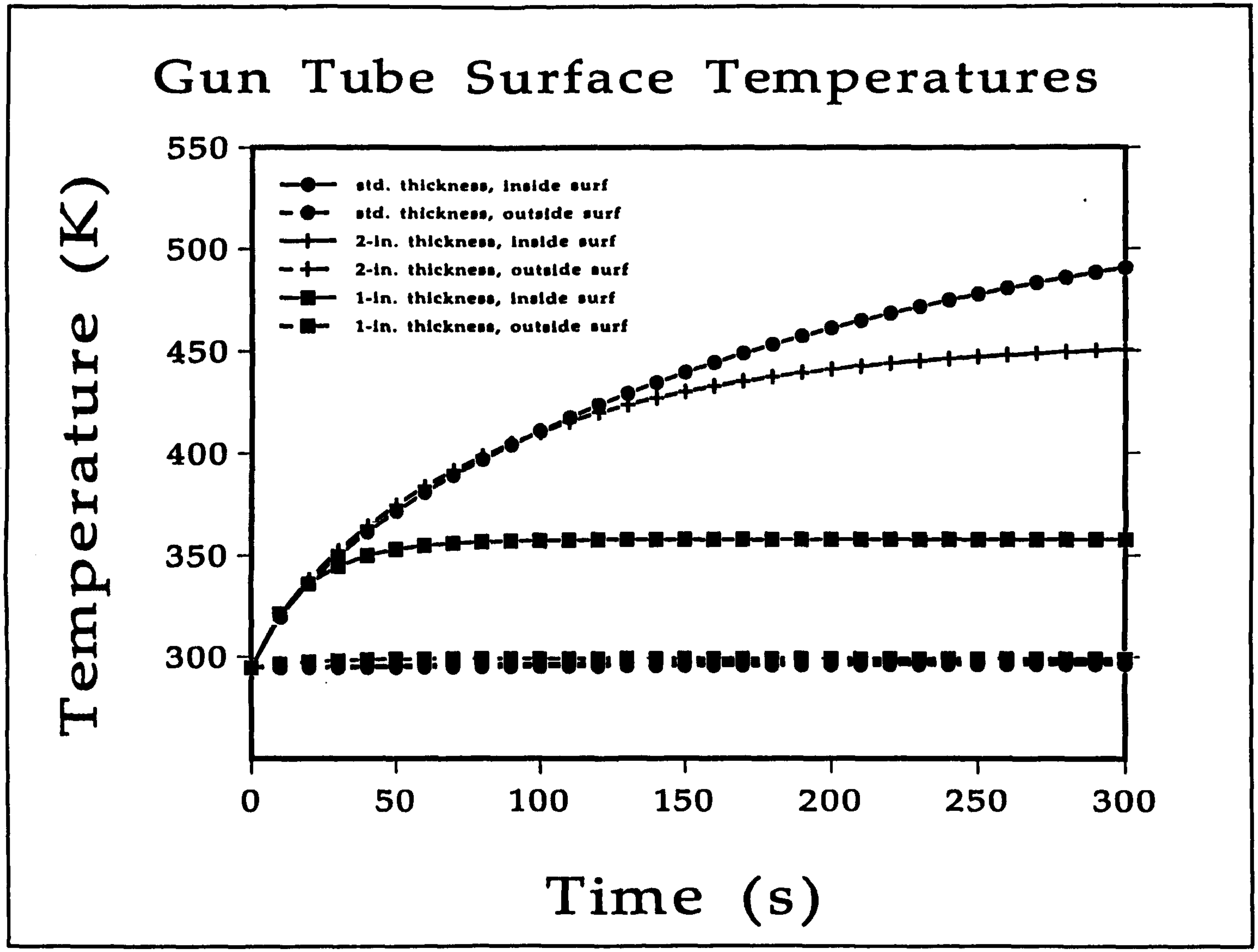

Figure 11. Comparison of the Temperature History of the Breech With and Without the Temperature Control Device in Place.

5. POTENTIAL PROBLEMS AND SOLUTIONS

5.1 Choice of Geometry and Number of Devices. The embedded heat pipe establishes a temperature gradient in the environment in which it is embedded. Depending on its geometry, size, working fluid, etc., the region of its influence will vary. The degree of temperature control desired will determine ultimately the size and the number of units employed and has to be worked out on a case by case basis. The depth to which the device is embedded into the breech is another variable. The deeper the device penetrates, the greater is the temperature control. On the other hand, the deeper the penetration, the larger are the wall stresses that are setup in the breech. However, as shown in Figure 10, the inside breech bore temperature can be kept below the cookoff temperature even if it is put only to a depth of 1/2 inch from the outside of the breech. These competing requirements have to be balanced, depending on the temperature control that is desired.

5.2 Miscellanea. Last we address the question of the effect of gravity forces on both the structural integrity and operational safety of the heat control device. G forces are of concern where the device is hinged onto the breech (i.e., Can the fasteners withstand the induced stresses?) Since the heat control device resides in a groove on the recoiling breech, no hinges internal or external are used; therefore, its structural integrity is assured. Also, there are intentionally no parts which can come loose within the device.

There could be a problem with the fluid response to the barrel motion during firing and recoil. Splashing of the liquid could interfere with the wicking action and could cause fluid migration and concentration. A porous screen in front of the wick could help in two ways—minimizing the entrainment and acting as a barrier to fluid migration. Actual tests will have to be run to determine the optimum geometry of the splash shield.

6. CONCLUSIONS

The design of a large-caliber gun breech with an embedded heat pipe which can keep the inside breech surface temperature below a specified limit has been presented. Our engineering estimates show that the proposed approach may well be the rapid heat dissipation solution which has eluded gun designers up until now, and which may well make rapid firing of large-caliber weapons a reality.

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7. REFERENCES

Brown, A. "Optimum Dimensions of Uniform Annular Fins." International Journal of Heat Mass Transfer, vol. 8, pp. 655–661, 1965.

Busse, C. A. "Theory of the Ultimate Heat Transfer Limit of Cylindrical Heat Pipes." International Journal of Heat and Mass Transfer, vol. 16, pp. 169–186, 1973.

Conroy, P. J. "Gun Tube Heating." BRL-TR-3300, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1991.

Cotter, T. P. "Theory of Heat Pipes." LA-3246-MS, Los Alamos Scientific Laboratory, University of California, 1965.

Dunn, P., and D. A. Reay. Heat Pipes. Oxford: Pergamon Press, 1976.

Gaugler, R. S. Heat Transfer Devices. U.S. Patent 2350348.

Groeber, H., S. Erk, and U. Grigull. Waermeuebertragung. Berlin: Springer Verlag, 1957.

Grover, G. M., T. P. Cotter, and G. F. Erickson. "Structures of Very High Thermal Conductivity." Journal of Applied Physics, vol. 35, pp. 1190–1191, 1964.

Kemme, J. E. "Vapor Flow Consideration in Conventional and Gravity Assisted Heat Pipes." Proc. 2nd Int. Heat Pipe Conference. Noordwijk: ESA Scientific and Tech. Info Branch, The Netherlands, pp. 11–22, 1976.

Kirillin, V. A (Editor). Liquid-Metal Coolants for Heat Pipes and Power Plants. New York: Hemisphere Publishing Corporation, 1990.

Lawton, B. "Heat Transfer in Gun Barrels." Imperial College, London, Mechanical Engineering Department Report, September 1988.

Polk, J. F. "An Algorithm for Heat Transfer in Gun Barrels." ARO Report 80-1, U.S. Army Research Office, 1980.

Trefethen, L. "On the Surface Tension Pumping of Liquid or a Possible Role of the Candle Wick in Space Exploration." General Electric Co. Tech. Inf. Ser. No. 615-0114, February 1962.

Vottis and Hasenbein. "Thermal Warning Device (TWD) for the M198 155-mm Howitzer." DRDAR-LCB-DA, Benet Weapons Laboratory, Watervliet, NY, August 1979.

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APPENDIX:

COMPARISON BETWEEN COOLING FIN
AND HEAT PIPE PERFORMANCE

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An appreciation of the advantage conferred by a heat pipe over an annular fin of the same base area is readily demonstrated. Based on the formulas of Brown (1965), the rate of heat rejection through an annular fin of radial length l, width 2δ, base temperature T_w, and surrounding temperature T_a is given by

$$q_w = r_1\sqrt{hk\delta}\;(T_w - T_a)\;\frac{4\,I_1(mr_t)\,K_1(mr_1) - I_1(mr_1)\,K_1(mr_t)}{\pi\,I_o(mr_1)\,K_1(mr_t) + I_1(mr_t)\,K_o(mr_1)}\,, \qquad \text{(A-1)}$$

where r_t is the radius from the center of the tube to the end of the fin, r_1 is the radius from the center of the tube to the base of the fin, h is the heat transfer coefficient, k the thermal conductivity, $m = \sqrt{h/k\delta}$. I_1 and K_1 are the Bessel functions of the first and second kind.

For illustration and comparison with the heat pipe discussed, k is taken as 35 $\frac{W}{mK}$ and a typical value of h is 15 $\frac{W}{m^2K}$. The rate of heat transfer with the fin is 420 W, while the heat pipe performs at 2.077×10^3 W, a five-fold improvement.

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LIST OF SYMBOLS

a	area
A	area
g	acceleration due to gravity
h	heat transfer coefficient
k	thermal conductivity
K	permeability
l	length scale
L	latent heat
m	mass
M	merit number
p	pressure
q	heat
r	radius
R	radius of curvature
t	time
T	Temperature
u	velocity
Z	dimension (length scale)

Greek

α	heat transfer coefficient
β	expansion coefficient
δ	half width
λ	heat conduction coefficient
μ	viscosity
ν	kinematic viscosity
σ	surface tension
ϕ	contact angle
ρ	density

Subscripts

c	condenser
e	evaporator
eff	effective
g	gravity
l	liquid, radius from center line to base of fin
o	reference condition
t	center line to fin tip
v	vapor
w	wick, wall

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