DDS 072-9

DESIGN DATA SHEET

NUCLEAR THERMAL RADIATION PROTECTION DATA

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362-5101

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26 APRIL 1989

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1. Bergman,P., et al.,"Temperature Response Charts for Opaque Plates Exposed to the Thermal Radiation Pulse from a Nuclear Detonation", Lab Project 840-105 Progress Rep 10, Naval Applied Science Laboratory(NASL), Brooklyn, N.Y. July 1969 UNCLASSIFIED
2. Smith, N., et al.,"ABLATE-A Fortran Program to Analyze Transient Temperature Distributions in a Flat Plate Covered with an Ablating Layer Subjected to a Radiant Heating Flux", Report 872 Sep 1969 Dynatech R/D Company, Cambridge, MA. UNCLASSIFIED
3. Wilson, D.M.,"The Distribution and History of Temperature in Circular Cylinders Exposed to the Thermal Radiation Pulse", NOLTR 71-61 NSWC/WO June 1971 UNCLASSIFIED
4. Kaufman, R., and R.J. Heilferty,"Equations and Computer Program to Calculate the Temperature Distribution and History in a Cylinder Subject to Thermal Radiation from a Nuclear Weapon", Lab Project 940-105, Progress Rep 8, July 1968 NASL UNCLASSIFIED
5. Gray, H.P,"A Computer Program to Calculate Temperature Distribution History of Thermally Thin Tee Beam Exposed to the Thermal Radiation Pulse of a Nuclear Weapon", Encl.(1) to NSRDC ltr Ser 71-1740-1486 of 13 May 1967 CONFIDENTIAL
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7. Wang, S.L.,"Thermal Protection Coatings for Shipboard Systems", DTRC Tech Note SSPD-88-174-2 Oct 1987 UNCLASSIFIED
8. "Ship Protection from Nuclear Thermal Pulse",Decisions and Designs,Inc. Technical Report DDI/TR 87-12-10.112 prepared for DTRC,July 1987 UNCLASSIFIED

072-9-b. Introduction

Navy surface combatant's topside equipments and exterior surfaces exposed to the atmosphere will encounter a thermal radiation pulse if a nuclear weapon is detonated nearby. This Design Data Sheet (DDS) provides a methodology for assessing the nuclear thermal radiation effect on ship structures and topside equipments and describes a hardening procedure. Under nuclear airblast, exposed structure or equipment is subjected to the combined mechanical effects of airblast, thermal radiation, and airblast-induced shock (ABIS). A hardened design must be able to withstand all three effects at the design threat level, including their synergism, if any. While this DDS addresses the nuclear thermal effects only, the designer should be cognizant of the airblast and ABIS effects so that the final design represents the most efficient way of resisting the combined effects.

072-9-c. Definitions

Arrival Time. Time of the blast wave arriving at the front face of the target.

Blast Wave. A shock wave in air with a sharp increase in pressure at the front, emanated from an explosion.

Thermal Fluence. The total amount of thermal radiation energy received per unit area of exposed surface.

Thermal Flux. Rate of fluence received at an exposed surface.

Overpressure. The free-field pressure produced by a blast wave in excess of the ambient pressure at a target point.

Thermal Radiation. The radiation emitted from the fireball in the ultraviolet, visible, and infrared spectral region.

Transmittance. The ratio of the thermal energy received at a given location through the atmosphere to the thermal energy received if no atmosphere were present.

Weapon Yield. The total prompt energy released in a nuclear explosion, usually expressed in terms of an equivalent tonnage of TNT that produces the same amount of energy.

072-9-d. Symbols and Abbreviations

Symbol	Parameter	Unit
a	Absorptivity	--
c	Specific heat	cal/gm-°C
D	Slant range	km
H	Burst height	km
H_m	Maximum thermal flux	cal/cm^2-sec
h	Thickness	cm
K	Thermal conductivity	cal/sec-cm-°C
Q	Thermal fluence	cal/cm^2

R	Radius; or horizontal range	cm or km
T	Temperature	^oC
T_∞	Ambient temperature	^oC
T_m	Maximum temperature	^oC
t	Time	sec
t_a	Blast arrival time	sec
t_m	Time of maximum flux	sec
W	Weapon yield	KT (metric tons)
α	Diffusivity	cm^2/sec
ρ	Density	gm/cm^3
τ	Transmittance	--
Pa	Pressure, stress	N/m^2

072-9-e Nuclear Thermal Environment

From a nuclear detonation, a thermal pulse, traveling at the speed of light, reaches the target ahead of the blast wave which travels at a shock velocity approximately equal to the speed of sound in air. The general shape and the arrival times of these pulses are illustrated in Figure 1. The actual times depend on the weapon yield and target range. The thermal pulse has two phases, the first one being of very short duration and small energy content, and roughly one percent of the second phase thermal energy. The thermal energy per unit area delivered to the target, known as the fluence, depends on the magnitude of the weapon yield, the transmissibility, and the distance between the weapon and the target. That fluence may be calculated from

$$Q = \frac{2.8\ W \tau}{D^2} \qquad (1)$$

where Q = thermal fluence (cal/cm^2)

W = weapon yield (KT)

D = slant range (km) $= \sqrt{R^2 + H^2}$

R = horizontal range (km)

H = burst height (km)

τ = transmittance which can be estimated from Figure 2

The maximum thermal flux and the time of its occurrence can be estimated by

$$H_m = \frac{Q}{2.6\ t_m} \qquad (2)$$

$$t_m = 0.0417\ (W^{0.44}) \qquad (3)$$

where H_m = maximum flux (cal/cm^2-sec)
t_m = time of maximum flux (sec)

For example, as shown in Figure 3, for a 1 MT weapon at 50 km visibility and 35 KPa overpressure, it is seen that at an optimum height of burst the fluence is about 45 cal/cm^2, while the fluence from a surface burst at that pressure level can be as high as 120 cal/cm^2.

072.9.f Radiant Energy Absorption

When any object or material is subjected to thermal radiation, a certain degree of absorption takes place. The remaining portions of thermal radiation will either be reflected by the object or simply pass through the object. The portion of thermal radiation that is absorbed is that which causes a dramatic increase in heat and thus the possibility of damage.

The degree of absorption for a particular material depends largely upon certain characteristics of the material, such as color and thickness. A black material will tend to absorb much more thermal radiation as opposed to the same material that is white. A thin object will tend to allow thermal radiation to pass through it where as a thicker object with the same surface area will absorb more of the radiation. Also, transparent materials will tend to allow thermal radiation to pass through them. The values of thermal absorptivity for metals such as steel, aluminum and copper, etc are given in Table I. Other thermophysical constants such as specific heat, thermal conductivity and diffusivity for various metals are shown in Table II.

072.9.g Thermal Damage Mechanisms

Thermal Damage In Metals. The sudden burst of thermal radiation will cause various metals to decrease in yield strength, potentially causing failure when the airblast overpressure strikes the metal (or structure). The elevated temperature causes varying degrees of degradation in the mechanical properties of materials which are important for blast resistance. Figures 4 through 8 indicate the reduced yield strength and Young's modulus in terms of the room temperature value for various aluminum alloys and steels.

Thermally Thin Plates. Temperature rise in flat plates and simple structural shapes due to thermal radiation can be calculated from heat transfer principles outlined in reference (1). A plate is considered thermally thin if the temperatures on the front (exposed) and the back faces are approximately the same. The temperature history in a thermally thin plate is shown in Figure 9. If heat dissipation is ignored, the temperature T approaches a maximum temperature, T_m, asymptotically, as time t increases. The abcissa of Figure 9 is a dimensionless time parameter t/t_m where t_m is the time of peak flux defined previously. The ordinate of Figure 9 is a dimensionless temperature parameter $(T - T_\infty)/(aQ/\rho ch)$, where T_∞ is the ambient temperature, a is the absorptivity, ρ is the density, c is the specific heat and h is the thickness of the plate. Figure 9 shows that for practical purposes, T_m is reached after $t = 16t_m$.

Thermally Thick Plates. A plate is said to be thermally thick when there is a significant difference between the temperature on the front face of the plate and the back face. This can be accounted for by sufficient thickness and/or low diffusivity of the plate. The temperature history for the front face of a thermally thick plate is given in figure 10. The ordinate of that figure is the dimensionless temperature parameter $(T - T_\infty)/(aH_m\sqrt{\alpha t_m}/K)$, where α is the diffusivity and k is the thermal conductivity of the material. These two can be related by $\alpha = K/\rho c$, with the other parameters defined previously. Figure 10 shows that the maximum temperature in a thermally thick plate occurs shortly after the time of peak flux (t/t_m is approximately equal to 1). The temperature is significant if it does permanent damage to the material or system performance. Otherwise, it is of no consequence (as for most metal plates) since it is merely a transient phenomenon with the temperature falling off rapidly after T_m. The most significant temperature of concern is that at the time of blast arrival and during the blast response. The temperature at the back of a thermally thick plate is given by Figure 11 as a function of time. Figure 12 shows how to determine whether a plate is thermally thin or thick according to the values of the parameters t/t_m and $\alpha t_m/h^2$

A computer program, such as ABLATE (Reference 2), can be used to calculate the transient temperature distribution and history for a plate, with or without an ablative or reflective coating, subjected to a nuclear thermal pulse.

For cylinders the peak temperature on the front surface at normal incidence can be obtained from Figure 13 using the dimensionless parameters, a tm/R_o^2 and R_i/R_o, where R_i and R_o are the inner and outer radii of the cylinder, respectively. If the temperature distribution and time history along the circumference are needed, charts in reference 3 can be used.

A computer program, such as CYCTEMP (reference 4), can be used to evaluate the transient temperature distribution and history in a cylinder subjected to a nuclear thermal pulse. For tee-beams and box beams, the temperature profile can be calculated using the computer programs TEMP (reference 5) and BOXBM (reference 6), respectively. For complex structures, finite element programs such as ABAQUS, NASTRAN, or ADINAT may be used.

Thermal Damage In Composite Materials. The temperature in composite flat plates can be estimated in a similar way as for metal plates with the charts in Figures 9 and 10. The composite plates usually belong to the thermally thick category because of their low diffusivity. Consequently, under a nuclear thermal pulse the surface temperature can be hot enough to cause charring and permanent loss of structural strength. The absorptivity of glass reinforced plastics (GRP) is shown in Table III. Table IV lists the thermophysical constants of four laminates and Table V lists those of common resins for radome application. Tables VI and VII indicate the mechanical properties of various GRP laminates and core materials of sandwich construction, respectively, as a function of temperature. Table VIII shows the self-ignition temperature for GRP laminates. Table IX shows the distortion temperature and charring temperature for resins. The distortion temperature is the temperature at which the plastic material will either extend or shrink by 2% when subjected to ASTM D 1637 test.

The computer codes ABLATE, CYCTEMP and BOXBM are applicable tools for calculating the temperature distribution and history in plates and simple structural shapes with known thermophysical material properties.

072.9.h Thermal Effects On Ship Structures and Equipment

Thermal radiation will heat up the exposed material on a ship's structure. The elevated temperature could degrade the mechanical properties of the materials and, in severe cases, could cause thin metals to melt or plastics to burn. Even at relatively low fluence levels, the surface layer of plastic radomes can be easily charred by the thermal radiation.

If the structure survives the thermal pulse, it can still fail by the blast pulse because the material is weakened by the elevated temperature. In most cases, one can decouple the structural analyses under blast/thermal pulses by finding the peak temperatures in the exposed materials and their corresponding mechanical properties first, and then determine the structural response due to the airblast. This is a reasonable approach when no significant thermal stress is produced.

Besides the possible failure mechanisms of buckling and rupture from excessive stress under blast and thermal pulses, either singly or in combination, the equipment may suffer unacceptable functional impairment due to excessive permanent deformation or distortion. This is more serious for equipment sensitive to alignment for their proper operation, such as search radars and weapon launchers.

072.9.i Protection Methods

Faced with a nuclear protection requirement, one should consider the combined environment of thermal radiation and airblast loading at the design threat level for a hardened design, rather than treat them as unrelated events. The following design choices are listed in the order of the decision process that the designer would consider in meeting the thermal protection requirement.

The Configuration of Material. The general shape and presented area of a structure or equipment can affect the blast loading and temperature profile on the target. In most cases, the system configuration is dictated by functional considerations, but sometimes alternative choices are available. In general, small presented area and curved surfaces can reduce the blast loading and thermal fluence on the target.

Material selection. Just as high strength materials are beneficial to blast resistance, heat-resistant materials are helpful to thermal resistance. Ideally, the selected material should have the combined virtues of both features, but weight, cost, and functional considerations may lead to some other choice. For metal structures, steel is superior to aluminum in terms of blast and thermal resistance. Steel ship structures designed for blast can be inherently resistant to thermal pulse effects. But this should be verified through calculations for individual designs. For aluminum, which will likely continue to be used in topside equipment and selected structures, the use of high grade alloys will help to resist the blast and thermal pulses.

The above general observations apply to non-metals as well, however, their choice is often governed by the design criteria other than protection considerations. Various kinds of heat resistant composites, such as graphite/polymide and ceramics are developed and used in the aircraft and space industry. They can be used shipboard if they meet operational requirements.

Thermal Coating. For various reasons, the material finally selected may still suffer considerable degradation under the thermal pulse. This situation can occur where an equipment must have certain exposed non-metallic components or thin metal elements. Due to the low conductivity of most non-metallic materials, they are highly susceptible to surface charring under the thermal pulse. The best remedy in these cases is to apply a thermal coating to the substrate. A reflective coating could reduce the fluence reaching the substrate by as much as 50 percent. In the case of radome application, the coating must not contain metallic particles which would affect RF transmission. The residual surface material after thermal exposure also must not interfere with the radome performance. One should also check the impact of thermal coating on other protection considerations, such as IR and radar cross section signature and CBR contamination. Ideally, the same coating will satisfy these other protection considerations. If thermal protection is achieved by the use of an ablative coating, it is possible to use a suitable top coat to meet the other requirements, including the color and gloss standards. Requirements for naval coatings and available test facilities are outlined in references 7 and 8.

Member Thickening. Increasing the thickness of a metal plate or shell would serve the dual purpose of reduced temperature and increased blast resistance. The main drawback of this hardening method is the weight penalty. For non-metallic members, thickening is not an alternative thermal hardening measure because the reduction of the surface temperature would be very limited due to low conductivity. The major benefit of thickening in that case derives from increased blast resistance. As in any design change, its impact on system performance must always be evaluated to make sure that it is acceptable. This may be a concern, for instance, in selecting the thickness of a radome material.

Alternatives. Other methods for thermal protection include enclosing the entire system of concern with a shield for thermal protection and airblast deflection as well. Cooling water spray systems, similar to countermeasure washdown systems on ships, have also been assessed to be potentially effective in reducing nuclear thermal temperatures on equipments/systems. Technical problems are associated with such systems in that they must be activated promptly in a nuclear attack. The water system must also be capable of reaching equipment mounted high on masts, and must provide a sufficient quantity of water in a very short time.

TABLE I. Thermal Absorptivity of Metals

Material/Surface	Absorptivity
Aluminum	
Commercial sheet	0.09
Polished	0.06
Heavily oxidized	0.33
Brass	
Polished	0.07
Dull plate	0.22
Oxidized	0.56
Chromium	
Polished	0.27
Copper	
Polished	0.04
Slightly polished	0.12
Dull	0.15
Black oxidized	0.76
Steel	
Mild steel,polished	0.32
Sheet steel,ground	0.55
Sheet steel,rolled	0.66
Sheet steel,roughly oxidized	0.80
Stainless,polished	0.17
Stainless,after repeated heating & cooling	0.70
Tin	
Polished sheet	0.05
Zinc	
Galvanized,grey	0.28
Dull	

TABLE II. Thermophysical Properties of Metals

Material	Density gm/cm^3	Sp.heat cal/gm-^{o}C	Conductivity cal/sec-cm-oC	Diffusivity cm^2/sec
Aluminum	2.7	0.22	0.49	0.83
Copper	8.92	0.094	0.92	0.11
Lead	11.34	0.031	0.084	0.24
Steel,mild	7.85	0.11	0.107	0.124
Tin	6.55	0.056	0.140	0.38
Zinc	4.10	0.098	0.273	0.68

TABLE III. Thermal Absorptivity of GRP laminates

Surface color	Absorptivity
Light colored	0.25-0.5
Darker colors	0.4-0.7

TABLE IV. Thermophysical Properties of GRP laminates.

Type	Density (gm/cm^3)	Sp.Heat (cal/gm-^{o}C)	Thermal Conductivity (cal/sec-cm-^{o}C)	Thermal Diffusivity (cm^2/sec)
TAC Polyester	1.9	0.32	.0000163	.0000263
Epoxy-Glass	1.76	0.2	.000072	.0000205
Phenolics-Glass	1.08	0.28	.000038	.0000890
Polymide Glass	1.65	0.22	.000041	.000114

TABLE V. Thermophysical Properties of Common Resins for Radome application

Type	Density (gm/cm^3)	Sp.heat (cal/gm-°C)	Thermal Conductivity (cal/sec-cm-°C)	Thermal Diffusivity (cm^2/sec)
Polyester resin	1.2	.2	.0000136	0.000057
Epoxy resin	1.1-1.4	.15	.0000136- .000068	0.000082- 0.00012
Phenolic resin	1.2	.36-.4	.0000136- .000068	0.000031- 0.00014
Silicon resin	1.1	.2	.0000136	0.000062
Polymide resin	1.36-1.43	.18	.000023- .000068	0.000094- 0.00010

TABLE VI. Mechanical Properties of GRP Laminates

Material	Density (Kg/m^3)	Temp (°C)	Flex. Modulus (KPa)	Strength (KPa)		
				Flex.	Tens.	Comp.
TAC Polyester	1910	21	2.41×10^5	4650	3790	3450
		260	1.79×10^5	2760	2760	2070
Epoxy	1781	21	2.21×10^5	5170	3310	3450
		260	1.37×10^5	1720	3100	690
Phenolic Gr.A	1700	21	2.07×10^5	3450	2760	2410
		260	1.72×10^5	3100	2620	2070
Gr.B	1700	21	2.41×10^5	5030	3170	4000
		260	2.07×10^5	4820	3030	3660
Polymide	1683	21	2.07×10^5	4820	4140	2900
		250	1.66×10^5	3450	2970	2070

TABLE VII. Mechanical Properties of Core Material for Sandwich Construction

A. Honeycomb Core:

Material	Avg. Density (Kg/m^3)	Temp. (°C)	Comp. Modulus (KPa)	Comp. Strength (KPa)	Shear Modulus (KPa)	Shear Strength (KPa)
Glass fabric-expanded Silicone Resin	138.6	25	10068	3724	572	1724
		120	5586	1517	83	--
		175	3172	1310	62	552
Glass fabric-expanded tight bias weave, Polymide Resin	87.4	25	2759	3655	993	1931
		200	2759	3577	910	1793
		230	2759	3448	807	1655
		370	2207	3379	669	1586

B. Foamed Core

Material	Avg. Density (Kg/m^3)	Temp. (°C)	Comp. Modulus (KPa)	Comp. Strength (KPa)	Shear Modulus (KPa)	Shear Strength (KPa)
Foamed in place-Silicone Resin	249.2	25	-	931	262	-
		260	-	310	76	-
		370	-	207	21	-
Foamed in place-Epoxy-phenolic Resin	291.0	25	3655	2345	1972	2069
		260	-	1690	896	1172
		370	-	1000	524	759

TABLE VIII. Self-Ignition Temperature for GRP Laminates

Material	Self - Ignition temperature		Burning rate
	°C	°F	
Polyester	400 - 490	750 - 920	Slow to self-extinguishing
Epoxy	550 - 600	1020-1110	Slow to self-extinguishing
Phenolic	570 - 580	1060-1080	Slow to self-extinguishing
Polymide	630 - 650	1160-1200	Slow to self-extinguishing

TABLE IX. Distortion Temperature and Charring Temperature for Resins

Material	Distortion Temperature		Charring Temperature	
	°C	°F	°C	°F
Epoxy resin	260	500	430	800
Polyester resin	150-180	300-350	360-370	680-700
Phenolic resin	200	400	460	850
Polymide resin	260-320	500-600	510	950

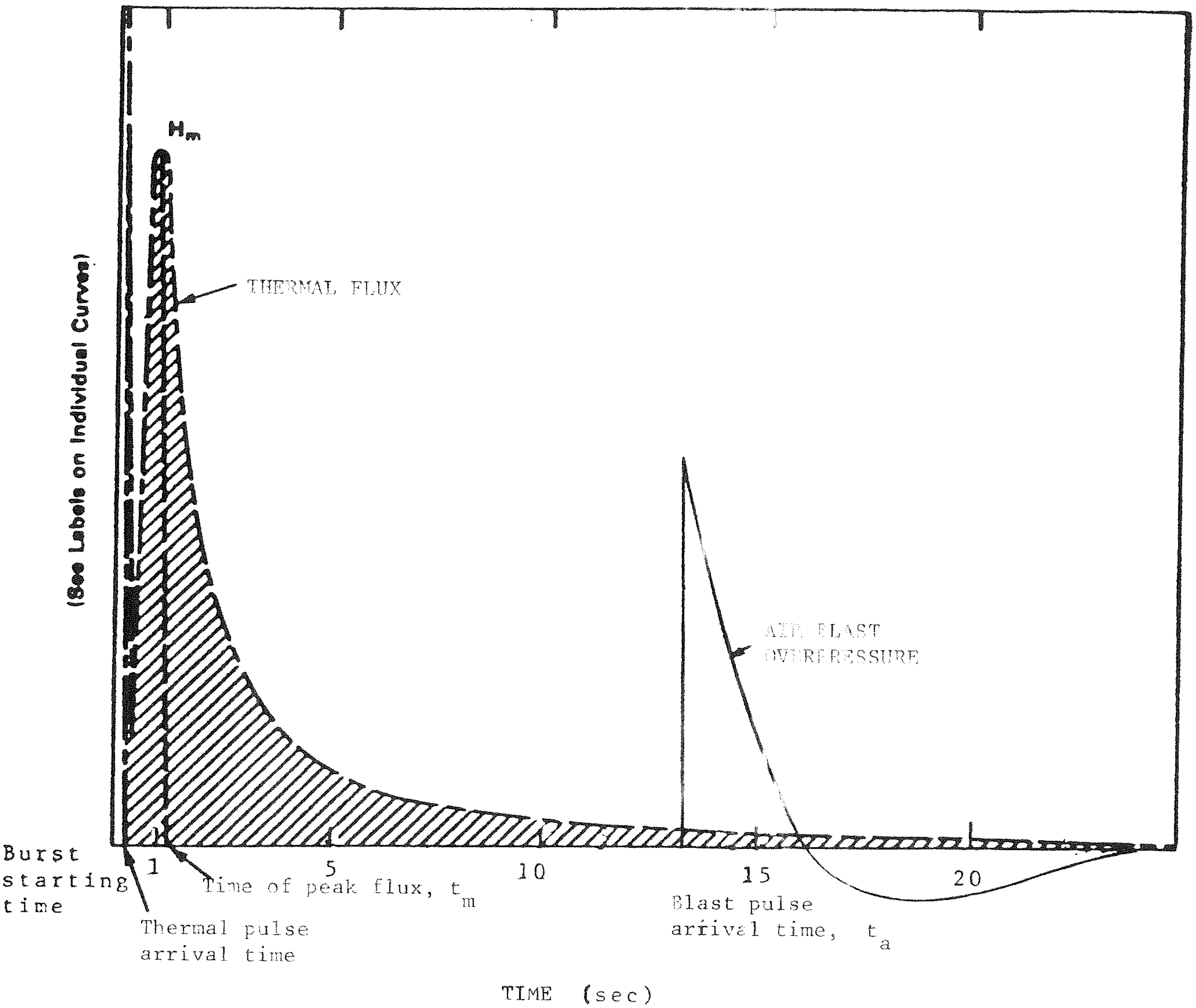


Figure 1 - Typical Thermal and Blast Pulse Characteristics

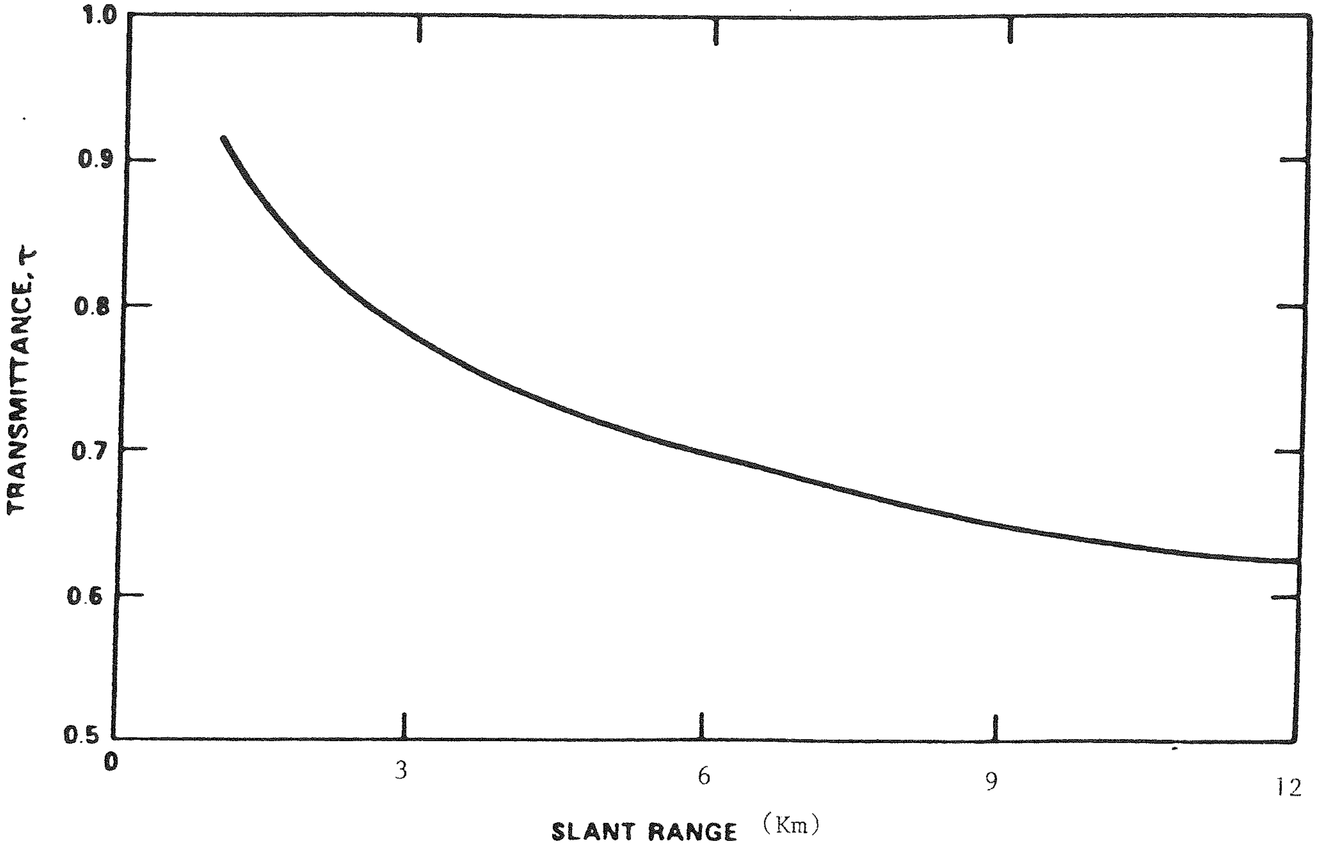


Figure 2 - Transmittance as Function of Slant Range to Target
(Visibility: 50 km)

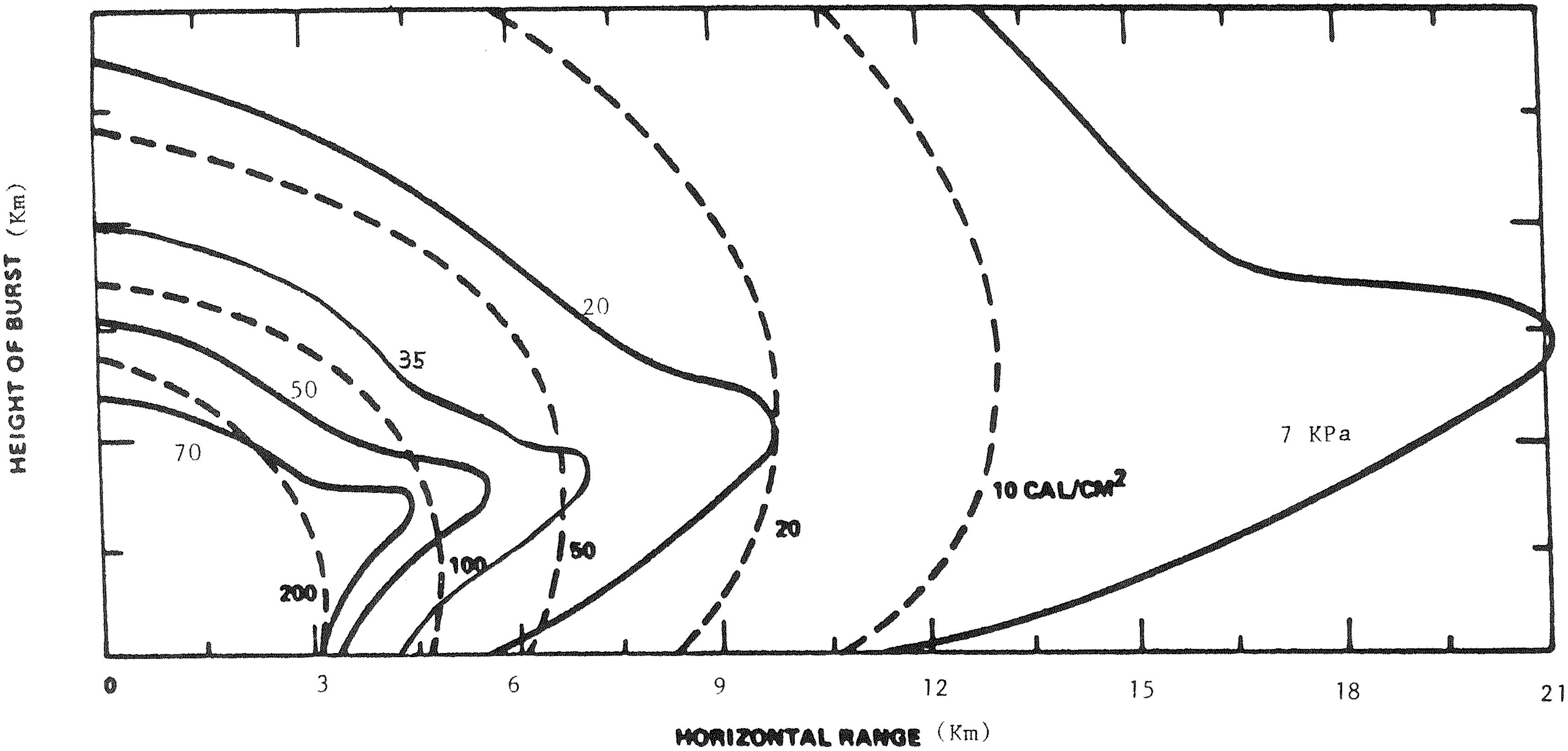


Figure 3 - Overpressure and Thermal Radiation for 1 MT Burst
(Visibility: 50 km)

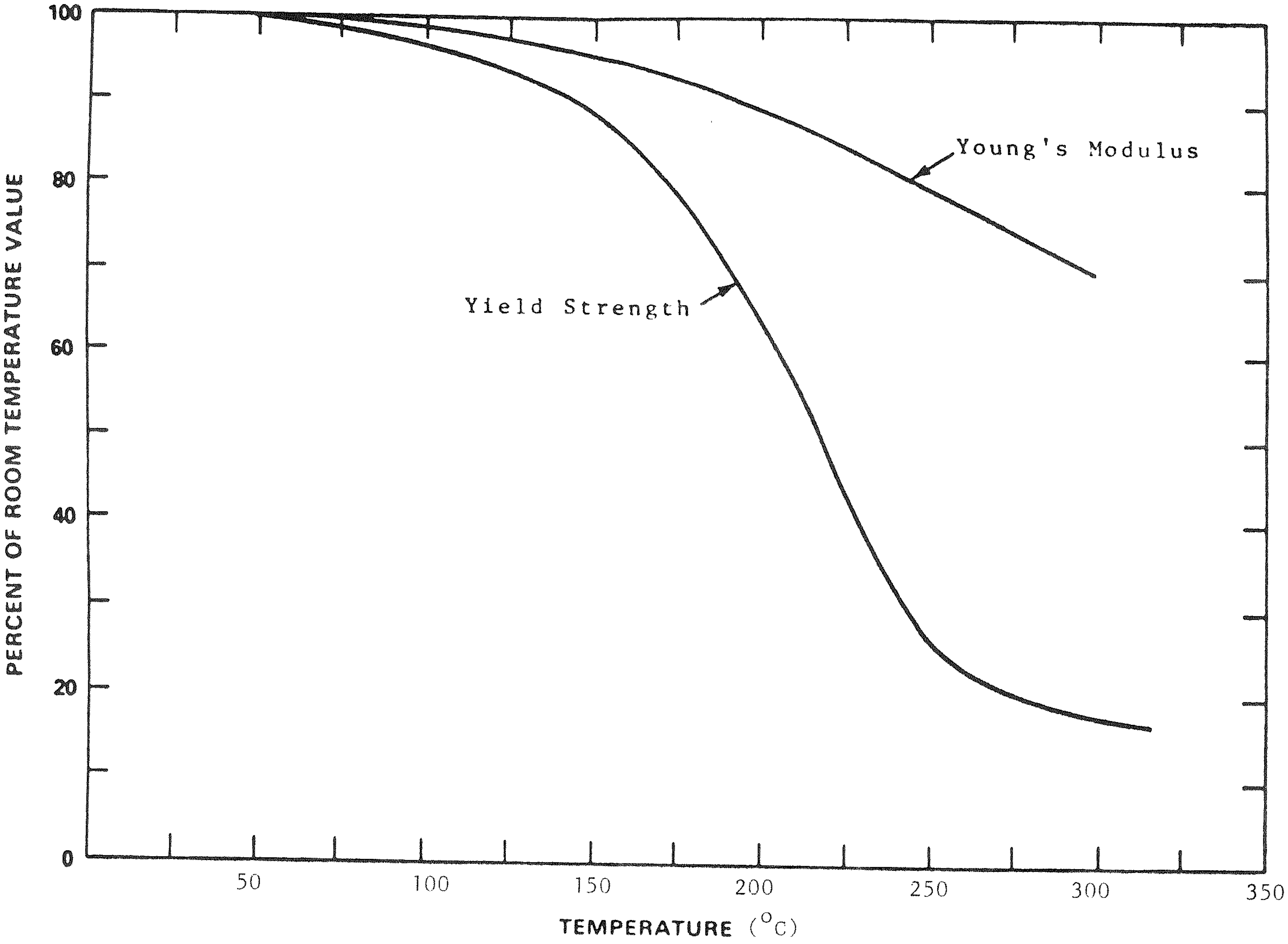


Figure 4 - Temperature Effect on Aluminum Alloy 2014-T6
(½ hour soak)

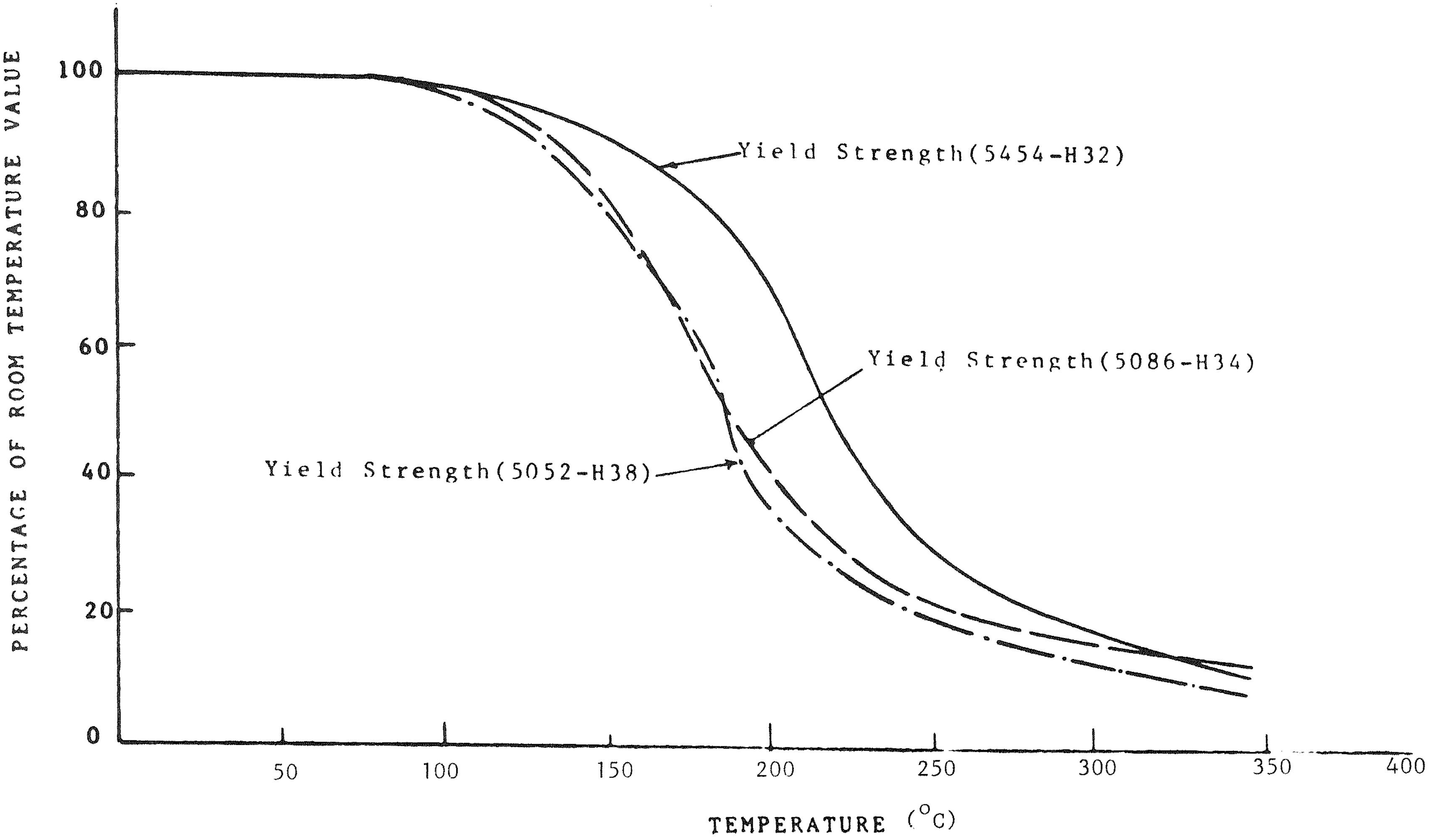


Figure 5 - Temperature Effect on Yield Strength for Aluminum Alloy .5000 Series (½ hour soak)

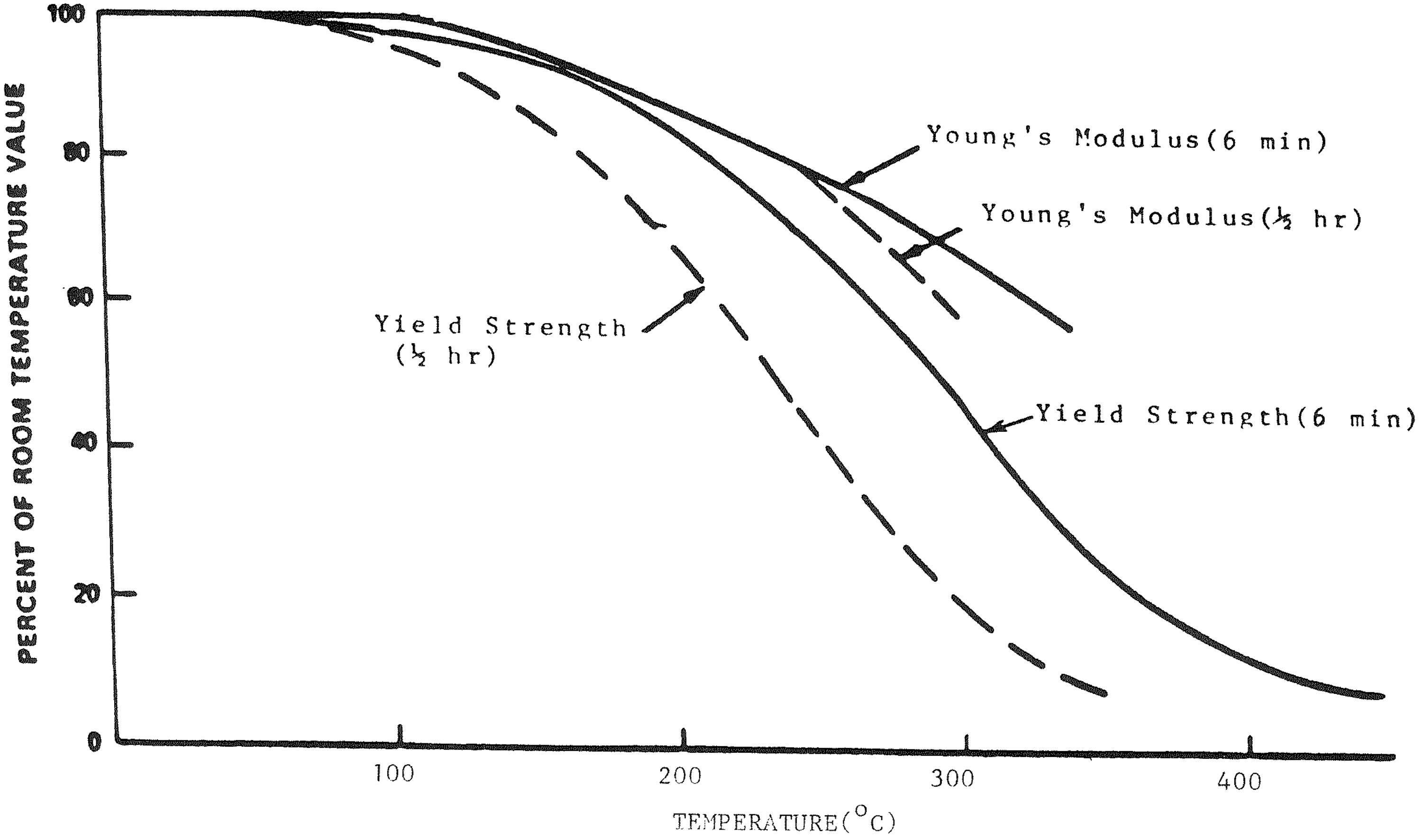


Figure 6 - Temperature Effect on Aluminum Alloy 6061-T6 (6 minutes and ½ hour soak)

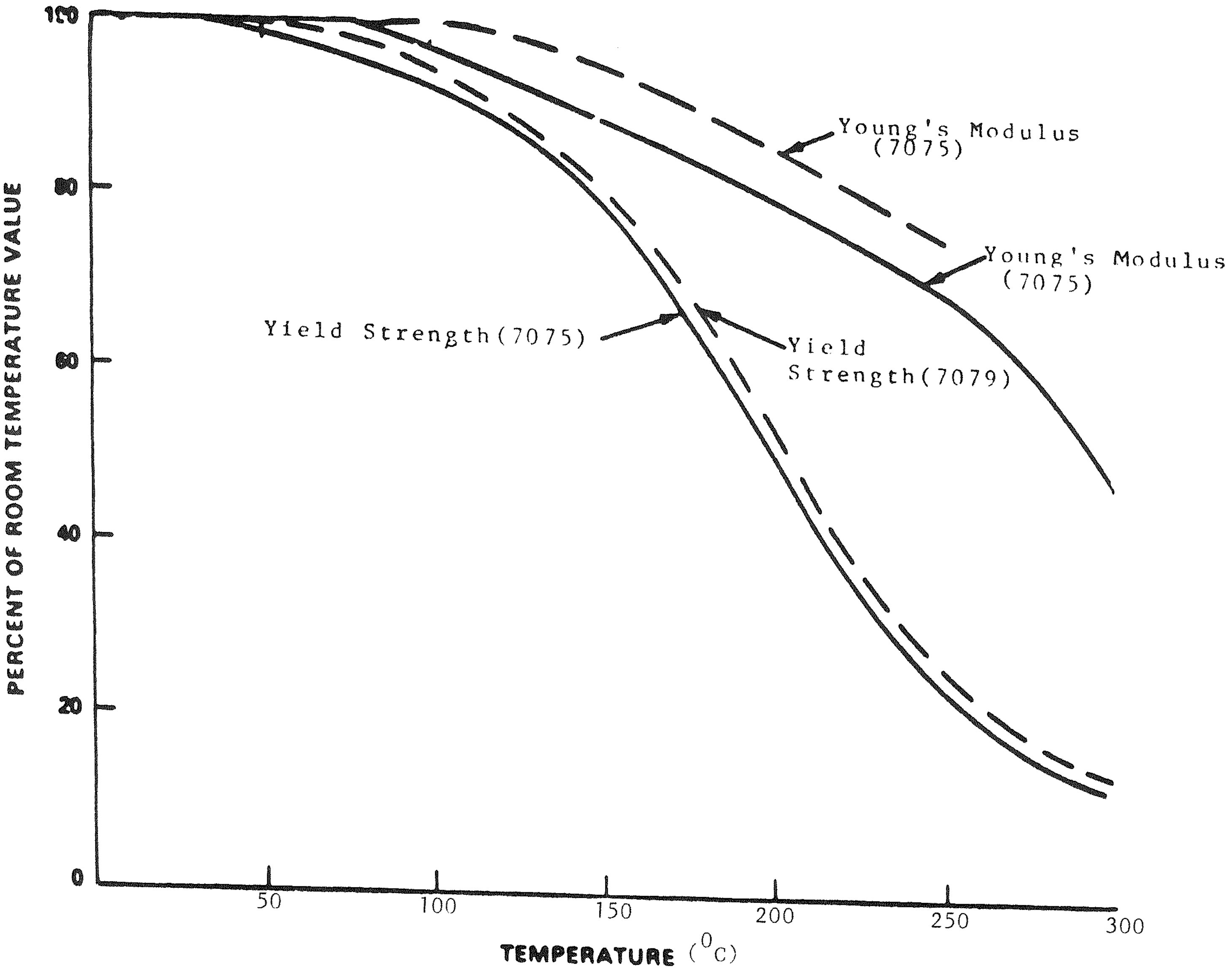
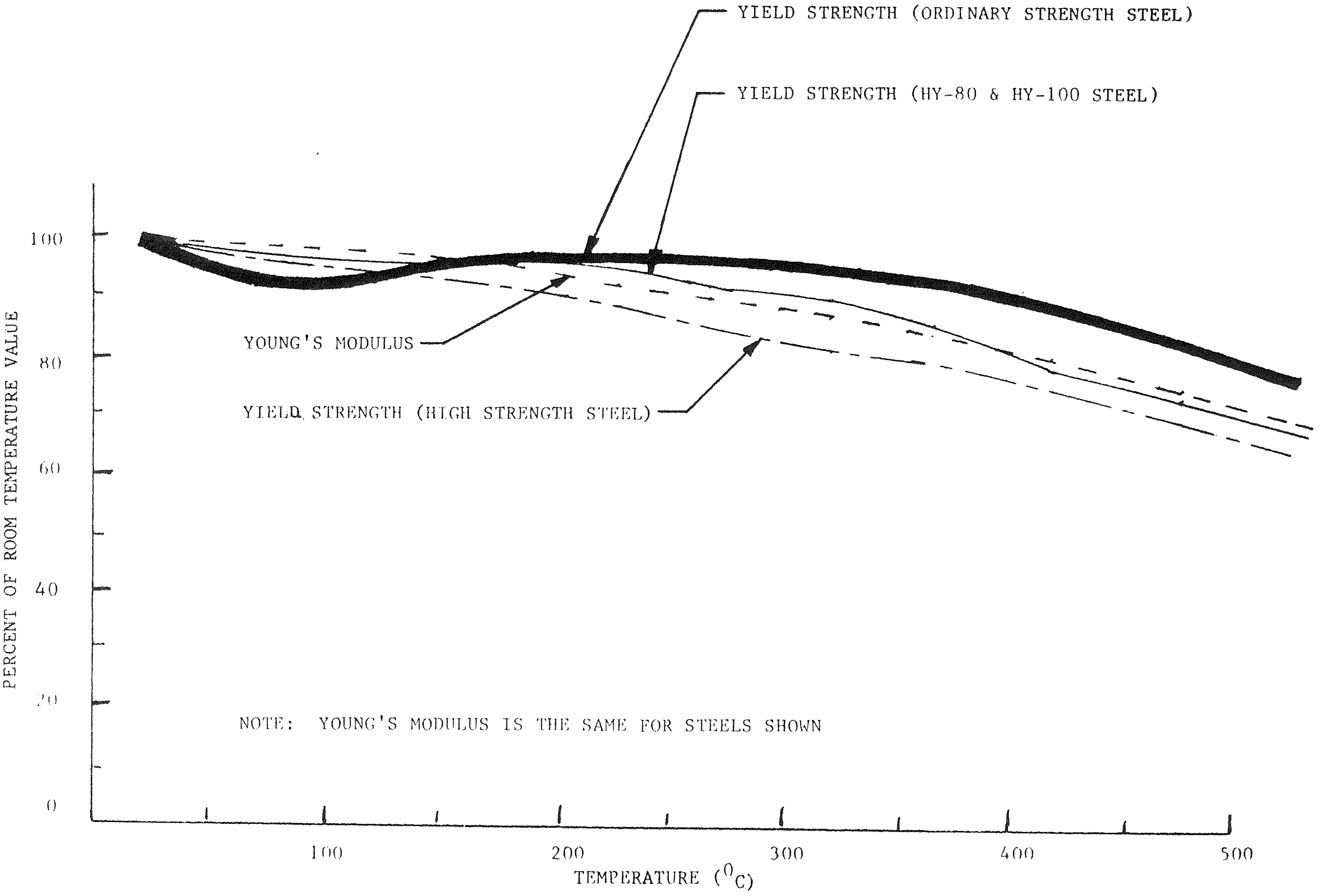


Figure 7 - Temperature Effect on Aluminum Alloy 7075-T6 & 7079-T6 (½ hour soak)



NOTE: YOUNG'S MODULUS IS THE SAME FOR STEELS SHOWN

FIGURE 8 - TEMPERATURE EFFECT ON CARBON STEEL AND ALLOY STEEL

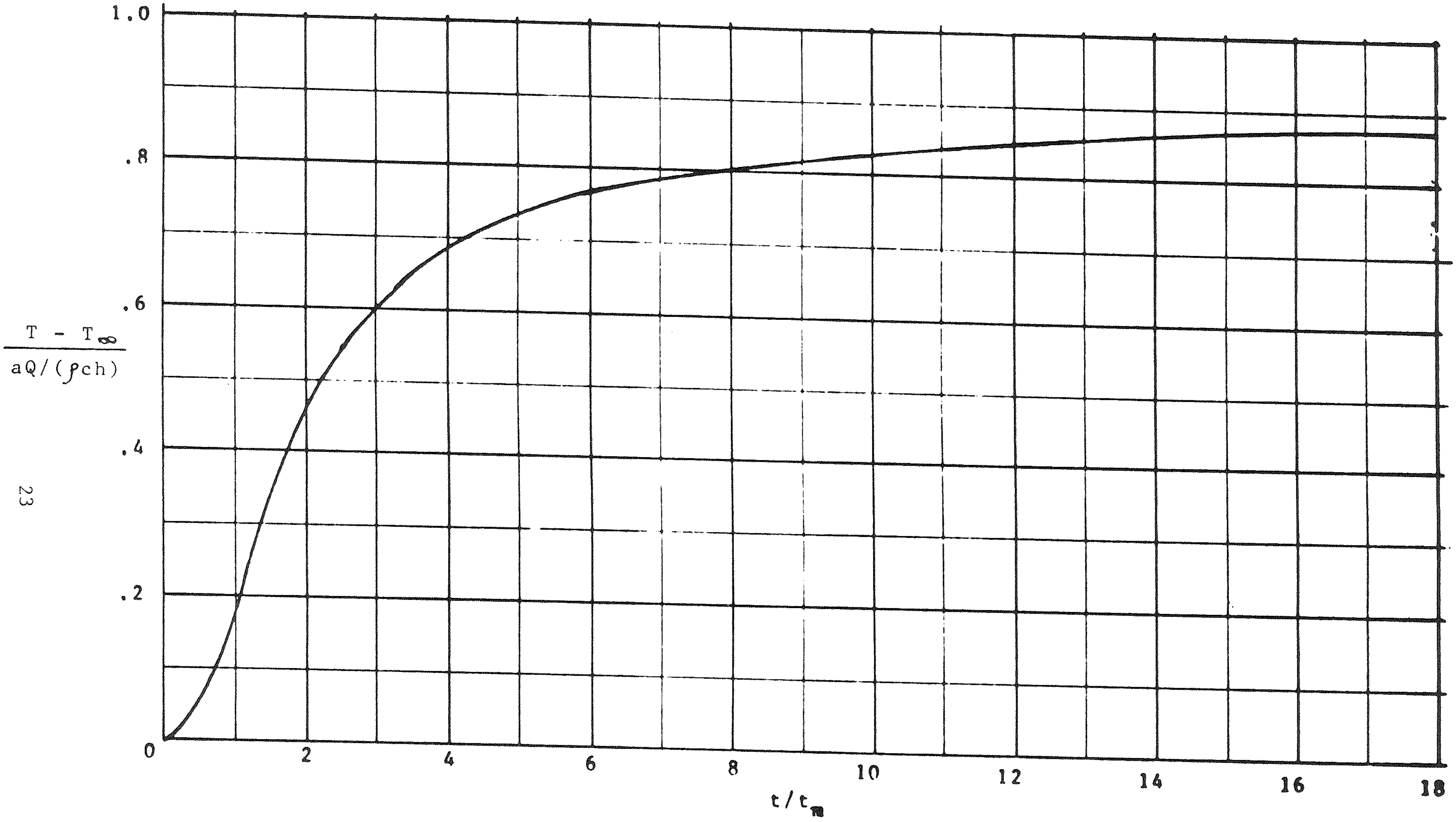


Figure 9 - Temperature Time History on Front Face of a Thermally Thin Plate

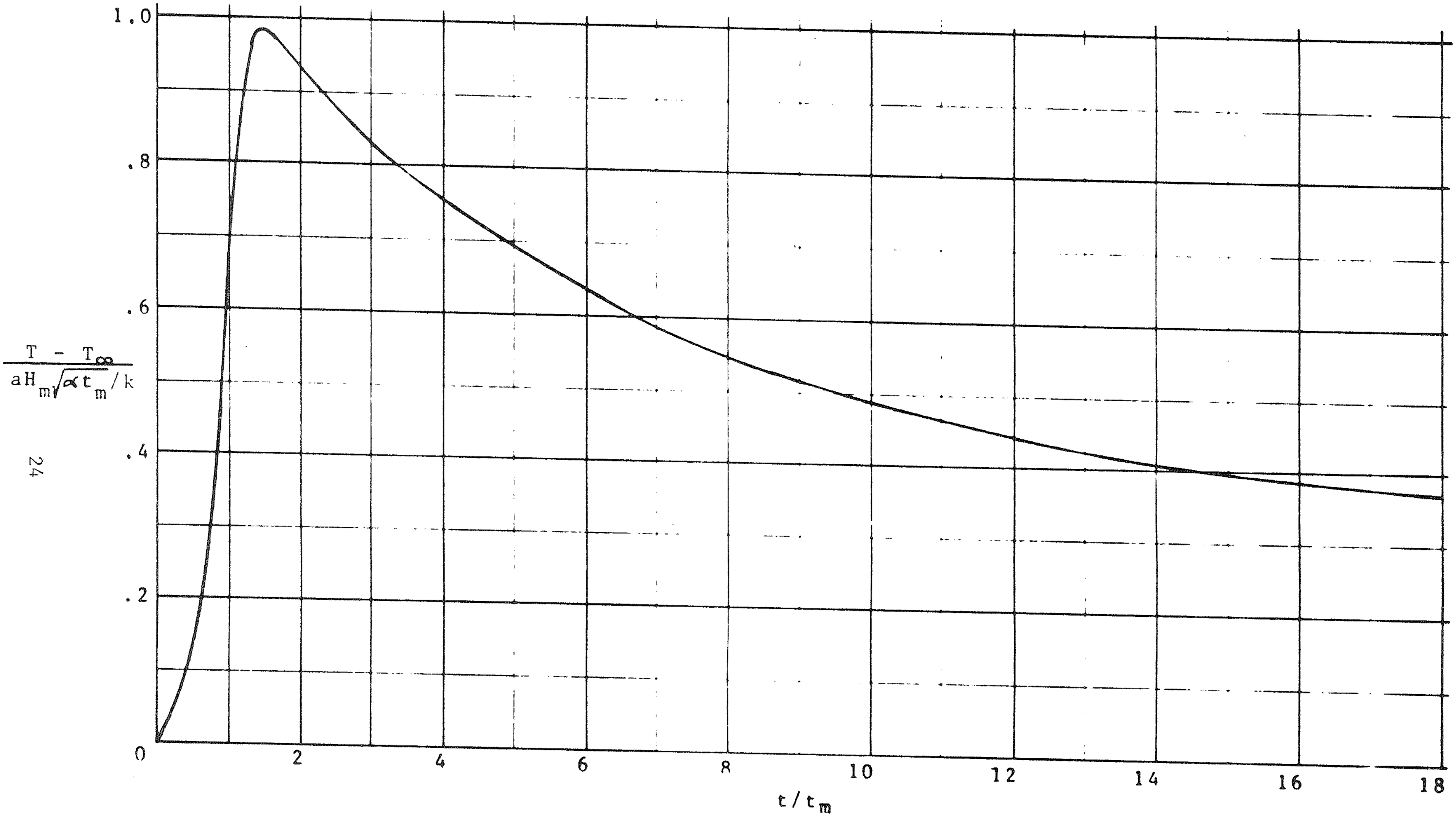


Figure 10 - Temperature Time History on Front Face of a Thermally Thick Plate

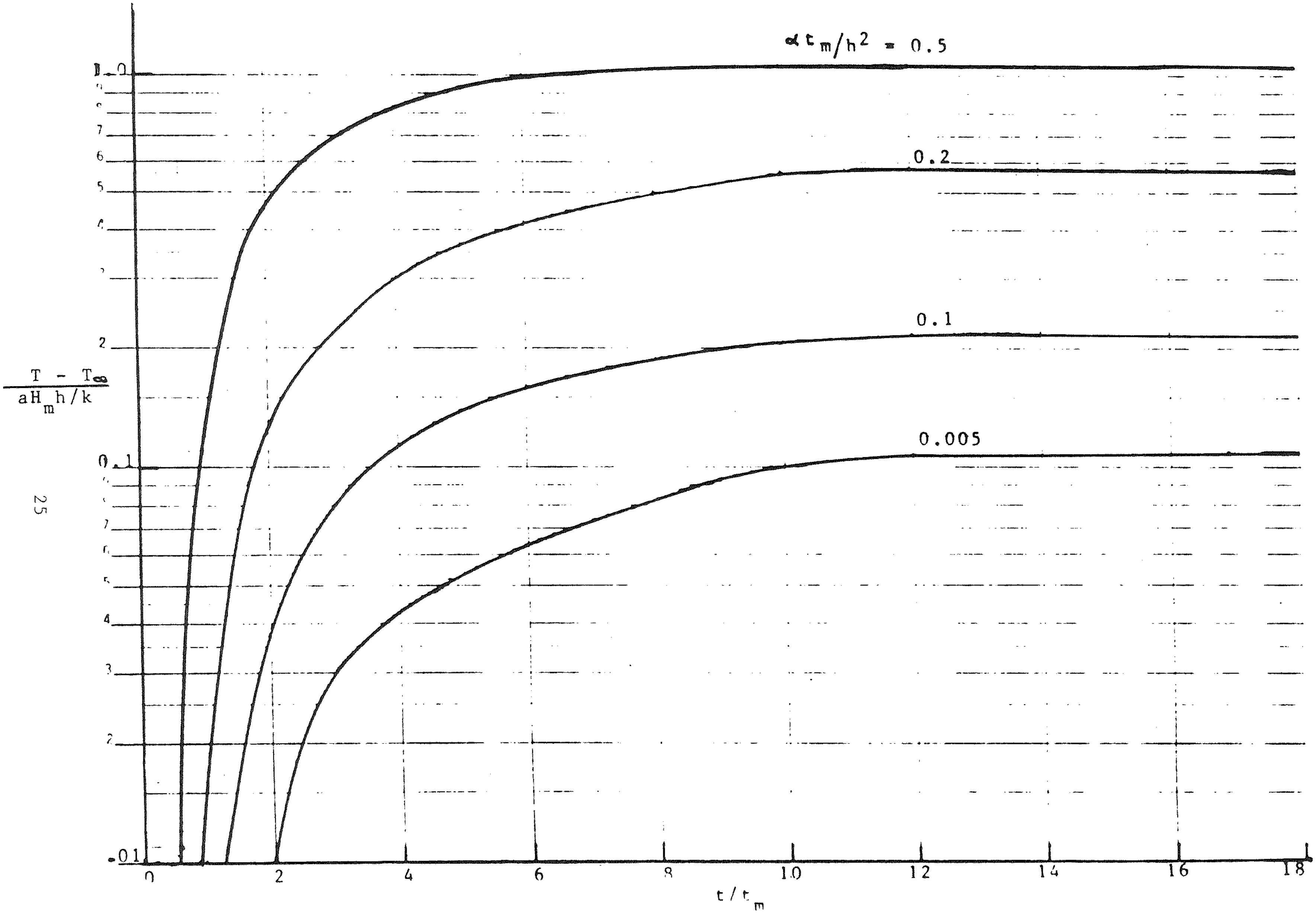


Figure 11 - Temperature Time History on Rear Face of a Thermally Thick Plate

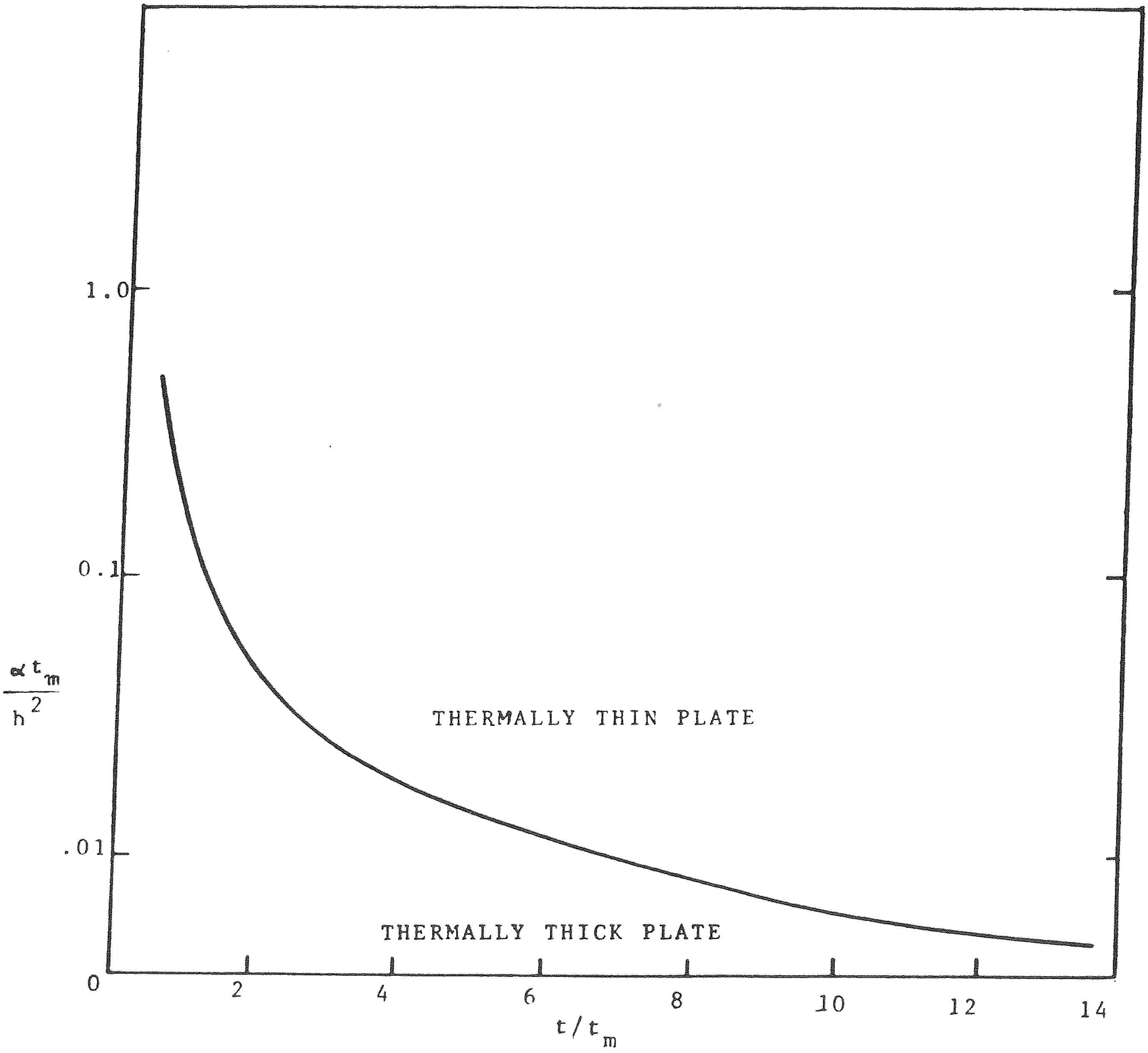


Figure 12 - Map of "Thermally Thin" and "Thermally Thick" Plate Regions

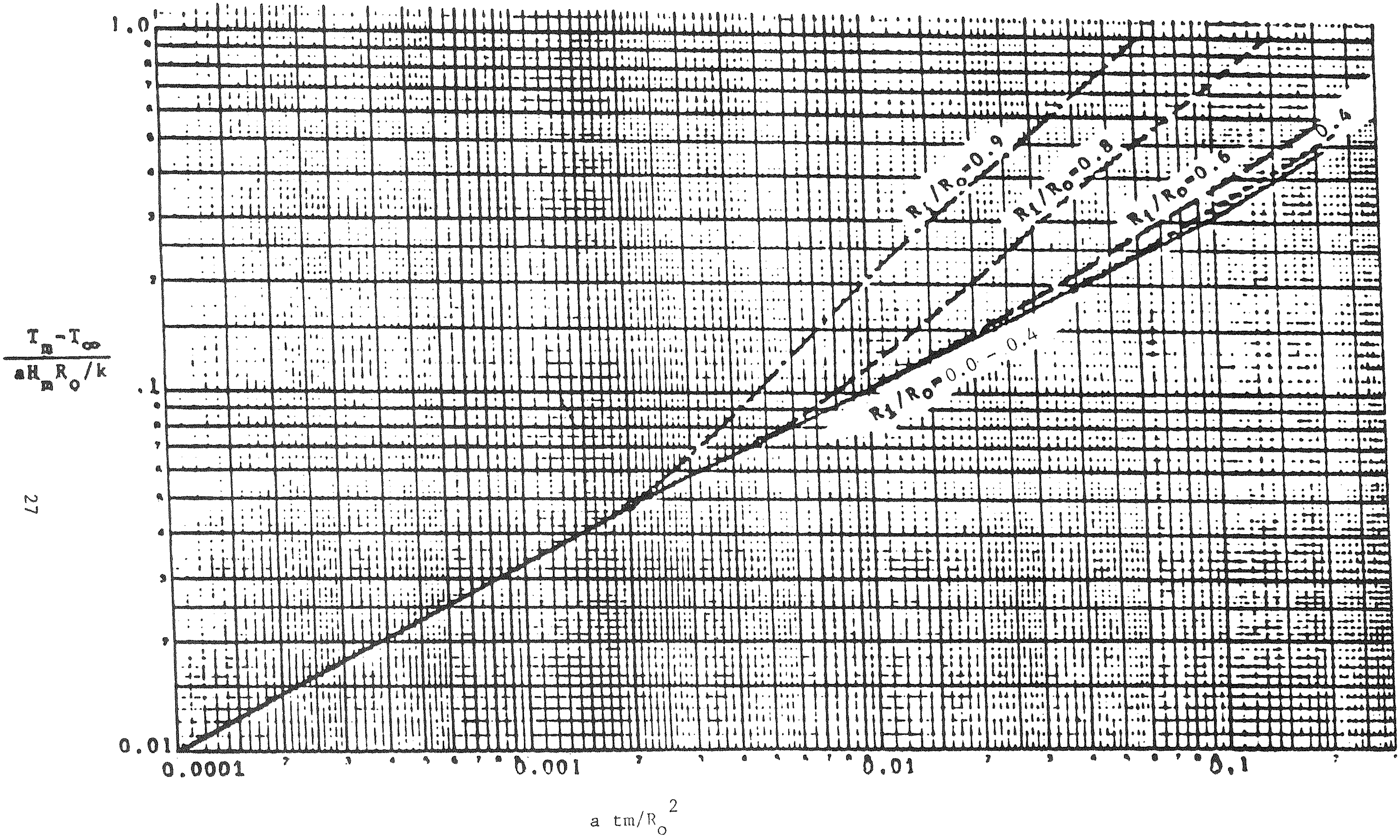


Figure 13 - Maximum Temperature on Front Face of a Cylinder