THERMAL PROTECTION

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Recent advances in space technology have necessitated consideration of a large number of hypervelocity vehicles which are expected to operate over a wide band of flight conditions. Each of these vehicles requires thermal protection to withstand the environments created by the flight trajectories. We shall endeavor to describe several passive thermal protection systems, with the aid of tables and figures, and to provide some guidance for fruitful areas of investigation. We shall also present a method for the judicious selection of a particular protection phenomenon for a specific application.

The selection of a thermal protection system becomes particularly important for those mission profiles which expose structures to relatively low heat transfer rates for long time periods and those which couple low heat rates with intermittent high heat transfer rates typical of controlled re-entry.

If all the heat acquired by the material were retained, the material might undergo changes which would impair or destroy its usefulness. However, there are many ways by which the material can utilize, dissipate, or be shielded from the heat. These modes of transference and protection are listed in table 1.

Heat may be transferred from an environment to a material by (a) convection —the transportation and exchange of heat by moving masses of matter (usually a liquid or a gas) in the vicinity of the material (b) conduction — the exchange of heat through matter in direct contact with the material (c) radiation — the exchange of heat between the material and some other body of material or mass of hot gas not in direct contact, where the energy is transmitted through the intervening medium in the form of electromagnetic waves without warming of the medium; and (d) chemical heating — heat resulting from exothermic chemical reactions within, on, or adjacent to the surface of the material.

The material may be protected from acquiring excessive heat by the following methods:

1. Sensible Heating (heat storage): Retention of heat by the material, resulting in an increase in its temperature.

2. Change of Phase: The transfer of heat resulting from a change in the material from one phase to another. There is a specific amount of heat which must be transferred to produce each change of phase. For example, when a material changes from a solid to a liquid, a quantity of heat called the latent heat of fusion must have been transferred to the material.

3. Liquid Film: The liquid phase of a material which forms on the surface and reduces the heat which is transferred to the material by increasing its own sensible heat. The behavior of the liquid film (in contrast to the solid phase) involves fluid mechanics in addition to simple heat storage.

4. Mass Transfer Cooling: A highly effective shielding mechanism which may result from the ejection of gases from the material's surface. The gases reduce the convection rate to the solid surface by reducing the temperature and velocity gradients in the fluid

boundary layer adjacent to the material's surface and by acting as a thermal sink in the boundary layer. Some mass transfer cooling is achieved by surface liquid formation transport.

5. Magnetohydrodynamic Effects: The effect of a magnetic field upon an ionized fluid stream adjacent to a material. The magnetic field deflects the fluid from its normal path, reducing the heat transfer by thickening the boundary layer and consequently reducing the velocity and temperature gradients adjacent to the surface.

6. Thermoelectric Effects: Heat transfer between two materials by means of an electric current through a junction of dissimilar metals or by electron emission. The junction phenomenon is known as the Peltier effect, and can be used with an external power source to construct a refrigeration machine consisting of an electrical circuit, without moving parts, which absorbs heat at one junction and rejects it at the other. In the use of other phenomena, electrons emitted from a hot source, as in the cathode of a vacuum tube, are carried away and deposited in the cooler region, which is connected electrically to the hotter region, completing the circuit and replenishing the cathode with electrons and redistributing the heat over a larger region. Both of these methods are reversible under certain conditions.

The basic heat balance relationship is predicated on the axiomatic principle that the total of the heat supplied must be equal to the total of the heat utilized, shielded, and dissipated (the radiated and chemical heat terms may be combined as single net terms) as indicated in table 2.

Since the major emphasis has been placed on those systems which provide passive protection, that is, radiation, heat storage, and mass transfer cooling, my remarks will be directed along these lines. We are not going to be concerned with ablation at this time since the subject of mass transfer cooling by ablation is covered by another panel. These three phenomena display entirely different thermal protection characteristics and these are summarized in table 3 with regard to heat flux rates, heat fluxes, and heat absorbed per unit weight. These three characteristics are the primary features of a given thermal environment and protection problem.

The only limitation on the use of thermal radiation as a protective phenomenon is in the rate at which heat can be emitted. This limitation is dependent upon maximum allowable material surface temperatures and, to a lesser extent, on surface emissivity. Radiation cooling is independent of the duration of heat flux and is not directly associated with any weight penalty.

The characteristics of heat storage as a protective phenomenon are intimately related to the transient behavior of materials exposed to heating. Analysis of a simple representative problem, wherein a material is subjected to a constant one-dimensional heat flux rate, q, at an exposed surface for a period of time, t, shows that there is a maximum value of the parameter $q\sqrt{t}$ which may be employed for nondestructive use of the material. The value of this parameter is directly related to maximum allowable material surface temperature and, to a lesser extent, upon thermal conductivity. Since the parameter $q\sqrt{t}$ is limited, both the heat flux rates and heat fluxes in a given application problem must be considered simultaneously. Heat storage functions as a protection phenomenon through stored sensible heat in the material; therefore, the heat absorbed per unit weight is limited by the permissible temperature rise and specific heat of the material.

Mass transfer cooling operates as a protection phenomenon against convective heat inputs. In high speed flight applications, the phenomenon is utilized most efficiently if the mass transfer coolant is in the gaseous phase throughout the boundary layer adjacent to the surface of the flight vehicle. Under these conditions, the effective heat absorbed per unit weight by the mass transfer coolant is directly proportional to the enthalpy or temperature difference causing heat transfer as well as being inversely related to the molecular weight of the coolant. Hence, the effective heat absorbed per unit weight depends upon both the environmental and coolant characteristics. At present there seems to be no known limitations on the use of this phenomenon with respect to heat flux rates or heat fluxes present in a particular application problem.

The characteristics of the thermal protection phenomena discussed above are quantitatively depicted in figure 1. The two coordinates employed represent the thermal environment. The abscissa corresponds to the heat flux rate and the ordinate represents the heat flux, which is the time integral of the heat flux rate and therefore represents the total heat input per unit area.

The vertical lines shown in figure 1 pertain to the use of radiation cooling as a protective phenomenon. Each vertical line represents constant values for the heat flux rate emitted from the surface of a material. Along each line is indicated the corresponding value of the product of the absolute surface temperature, Tw, and the fourth root of surface emissivity, ε, as determined from the Stefan-Boltzmann law applied to gray surfaces. For a given heat flux rate and surface emissivity, the corresponding surface temperature requirement can consequently be determined from the appropriate vertical line. Since the lines are vertical, it is apparent that this form of thermal protection is not dependent on heat flux, Q, or material weight.

Two sets of lines pertaining to the use of heat storage appear in figure 1. The diagonal lines correspond to constant values of the parameter $q\sqrt{t}$ (where q is a constant heat flux rate). The horizontal lines denoted by ϕH_{av} correspond to the total heat flux, Q, which is the sensible heat stored. The quantity ϕ represents the weight per unit surface area of the heat-absorbing element, and the quantity H_{av} represents the average heat stored in this element per unit weight. The use of heat storage as a protective phenomenon may therefore be dictated by either material limitations, as represented by the diagonal lines, or by weight limitations, as represented by the horizontal lines.

The horizontal lines in figure 1 denoted by the symbol κH_{eff} are related to the use of mass transfer cooling. Each of these lines corresponds to a particular value of the total heat flux as determined for heat transfer in the absence of mass transfer action and at the same surface temperatures. A similar qualification applies to interpretation of the heat flux rate coordinate in this case. The quantity κ represents the weight injected (or ablated) per unit surface area, and the quantity H_{eff} represents the effective heat of ablation of the mass transfer coolant employed. For a given situation, with known thermal environmental conditions and a particular coolant, the quantity H_{eff} can be evaluated. The horizontal lines would then permit determination of coolant weight requirements.

The thermal environment existing in a given application can be represented by a region. The characteristic regions associated with several severe thermal environments are depicted in figure 2. The information contained in this figure relative to both the thermal environments and the modes of thermal protection aids in delineating those modes which may be most advantageously employed in a given environment. For example, consider the ballistic missile thermal environment. A cursory examination of the vertical lines passing through this region shows that over much of this region, surface temperature requirements are prohibitive for consideration of radiation as a primary means of thermal protection. This leads to examination of relative merits of heat storage and mass transfer. For known heat storage materials applicable for flight vehicles, the most promising have maximum values of the $q\sqrt{t}$ parameter of less than 4000 Btu/ft^2/sec$^{1/2}$ with an associated H_{av} of approximately 1000 Btu/lb. However, mass transfer coolants in this application might realize values of H_{eff} between 4000 and 12,000 Btu/lb for laminar flow conditions at the flight velocities associated with the aerodynamic heating. Correlation of the above information with the ballistic missile thermal environment shows that:

a. Heat storage protection is not adequate over a major portion of the environmental region because of excessive requirements for the $q\sqrt{t}$ parameter.

b. In those portions of the environmental region where heat storage protection is feasible, a comparison of H_{av} of the heat storage material with H_{eff} for mass transfer coolants shows that the mass transfer cooling system would afford a significant weight-saving possibility. On this basis, the most promising primary thermal protection phenomenon for use on ballistic missiles is mass transfer cooling. In addition, if materials are used which form high temperature surfaces during re-entry, radiation cooling can be an important secondary form of thermal protection which does not introduce any penalty in the form of weight.

The preceding discussion demonstrates that the process of selecting a suitable form of thermal protection involves several steps. The results of this step-by-step procedure, for other thermal environments depicted in figure 2 as well as for the ballistic missile case, are schematically represented in table 4. Some of the salient factors in arriving at the results indicated for the other thermal environments are briefly discussed.

For the glide vehicle thermal environment, the feasibility of employment of radiation cooling is improved over that existing in the ballistic missile environment because of the lower heat flux rates with attendant lower surface temperature requirements. Furthermore, the expected heat inputs per unit area preclude primary dependence upon either heat storage or mass transfer cooling systems because the associated weights would be prohibitive on a flight vehicle. Consequently, radiation is the most suitable primary protection phenomenon in this application. For secondary protection at local hot spots, mass transfer cooling would provide a weight-saving advantage over a heat storage system, since the values of the effective heat of ablation of the mass transfer coolant, H_{eff}, and the average heat stored per unit weight of heat storage material, H_{av}, are similar to those encountered in the ballistic missile application. Consideration of the effect of changes in geometry on vehicle flight performance might require that the mass transfer cooling system be of a gas-injection rather than an ablation type.

The region indicated for thermal radiation from nuclear explosions corresponds to nonattenuated radiation from explosions in the 100 to 200 kiloton yield range at distances down to 2000 feet from the explosion. For these selected conditions, total heat fluxes resulting from the explosions do not appear to be a serious problem for either the glide vehicle or the ballistic missile. However, the peak heat flux rates from such an explosion may be significant enough to cause local overheating if glide vehicles were constructed with thin-skinned surfaces lacking heat storage capabilities. The mass transfer phenomenon is not applicable to protect against radiative heat inputs of this type. Thermal damage could be avoided by providing additional sufficient heat storage capacity in the skin. Reradiation following the input from the nuclear explosion could be used as a secondary protection to re-establish equilibrium conditions.

The thermal environment in a rocket motor constitutes a unique thermal protection problem. Turbulent flow conditions prevail, and the geometry of the nozzle must be preserved within prescribed limits during operation. Because of the internal cylindrical geometry, radiation protection at the critical nozzle throat region is not applicable. The combination of turbulent flow conditions and temperature differences across the boundary layer, which are significantly lower than in the external environment of hypersonic flight, tend to markedly reduce the effectiveness of mass transfer cooling. Simultaneous consideration of geometry requirements and the limited effectiveness of the mass transfer cooling phenomenon under the prevailing conditions appears to preclude the direct application of an ablation form of mass transfer cooling, at least in the critical throat region. A gas injection form of mass transfer cooling may still be a promising system. Conventional modes of protection have utilized heat storage or, in some liquid-fueled rockets, heat transfer through the nozzle wall to a flowing fluid coolant.

There are other passive protective phenomenon which were not touched upon because of time considerations. The subjects of radiation heat shields and thermal insulations have not been discussed for the same reason. We recognize these as potential systems as well as some of the absorptive variety such as convective cooling and transpiration cooling. Transpiration cooling has received considerably more attention than convective cooling since it is a form of mass transfer cooling, and because of the inherent problems associated with circulating cooling systems of the liquid metal variety. This is not to say that transpiration cooling is free of problems. The most difficult problem peculiar to this system is the fabrication and maintenance of porous surfaces.

The current state of the art for thermal protection systems leaves a great deal to be desired. The capabilities we possess today are relative only to first generation developments which are considerably removed from the anticipated goals with respect to efficiency and reliability. It is clearly evident that the heat storage system is inherently limited to short time exposures of five minutes or less because of heat penetration and structural decomposition. Perhaps increased consideration is indicated here for absorptive systems based on liquid cooling for long-time applications, with development of reliable, lightweight pumping systems. The need for increased R & D activities in the development of radiation cooled systems is evident for advanced glide re-entry vehicles subject to high radiative equilibrium temperatures and high cumulative heat input characteristics. Radiative heat shield systems would bear further investigation in this system. The solid propellant rocket nozzle presents a serious challenge to thermal protection. It is conceivable that a solution may be found in an unusual combination of several thermal protection systems. This is not the end; only the beginning.

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Table 1

MODES of HEAT TRANSFER and MATERIAL PROTECTION

HEAT MAY BE TRANSFERRED FROM AN ENVIRONMENT TO A MATERIAL BY:	THE MATERIAL MAY BE PROTECTED FROM ACQUIRING EXCESSIVE HEAT BY:
Convection	Sensible Heating
Conduction	Change Of Phase
Radiation	Reradiation
Chemical Heating	Chemical Cooling
	Liquid Film Formation
	Mass Transfer Cooling
	MHD Effects
	Thermoelectric Effects

Table 2

BASIC HEAT BALANCE RELATIONSHIP

	HEAT (Sensible)
	+ HEAT (Phase Change)
HEAT (Convected)	+ HEAT (Liquid Film)
+ HEAT (Conducted)	+ HEAT (Mass Transfer)
+ HEAT (Net Radiated)	+ HEAT (MHD)
+ HEAT (Net Chemical)	+ HEAT (Thermoelectric)
TOTAL HEAT (Supplied)	= TOTAL HEAT (Utilized + Dissipated + Shielded)

Table 3

CHARACTERISTICS of THERMAL PROTECTION PHENOMENA

Thermal Protection Phenomena	Permissible Heat Flux Rates BTU/FT^2 –Sec	Permissible Heat Fluxes BTU/FT^2	Permissible Heat Absorbed Per Unit Weight, BTU/LB
Radiation	Limited By Maximum Material Surface Temperatures	No Limitations	No Limitations
Heat Storage	Limited By Material Surface Temperatures And Thermal Conductivity		Limited By Maximum Material Temperature Rise And Specific Heat
Mass Transfer	No Limitations	No Limitations	Limited By Combination of Environmental And Coolant Characteristics

Table 4

RELATIVE COMPARISON of MODES of THERMAL PROTECTION IN SELECTED THERMAL ENVIRONMENTS

THERMAL PROTECTION PHENOMENON / THERMAL ENVIRONMENT	HEAT FLUX RATES ENCOUNTERED (BTU/FT^2 –SEC)			HEAT FLUXES ENCOUNTERED (BTU/FT^2)			WEIGHT of THERMAL PROTECTION SYSTEM REQUIRED (LB/FT^2)			OVER-ALL RATING: PRIMARY PROTECTIVE PHENOMENON			OVER-ALL RATING: SECONDARY PROTECTIVE PHENOMENON		
	Radiation	Heat Storage	Mass Transfer	Radiation	Heat Storage	Mass Transfer	Radiation	Heat Storage	Mass Transfer	Radiation	Heat Storage	Mass Transfer	Radiation	Heat Storage	Mass Transfer
Hypersonic Flight Applications															
Ballistic Missile	Poor	Fair	Excellent	Good	Fair	Excellent	Excellent	Fair	Good	Poor	Fair	Excellent	Excellent	Fair	Primary basis for secondary selection
Glide Vehicle	Good	Good	Good	Excellent	Fair	Fair	Excellent	Poor	Fair	Excellent	Fair	Fair	Primary basis for secondary selection	Fair	Good
Rocket Motor Nozzle	N/A	Fair	Good	N/A	Fair	Fair	N/A	Fair	Fair	Excellent	Fair	Fair	Excellent	Fair	Fair
Thermal Radiation From Nuclear Explosions (On Flight Vehicles)	Poor	Good	N/A	Good	Good	N/A	Excellent	Fair	N/A	Poor	Good	N/A	Good	Primary basis for secondary selection	N/A

Relative Ratings of Protection Phenomena for Selected Application Characteristic

- Excellent (white)
- Good (diagonal hatching)
- Fair (grey shading)
- Poor (black)

Protection Phenomenon Not Applicable to Thermal Environment (dotted) = N/A

Primary Protection Phenomenon Used for Basis of Secondary Phenomenon Selection (cross-hatching)

THERMAL RADIATION HEAT FLUX AS A FUNCTION OF SURFACE TEMPERATURE & EMISSIVITY

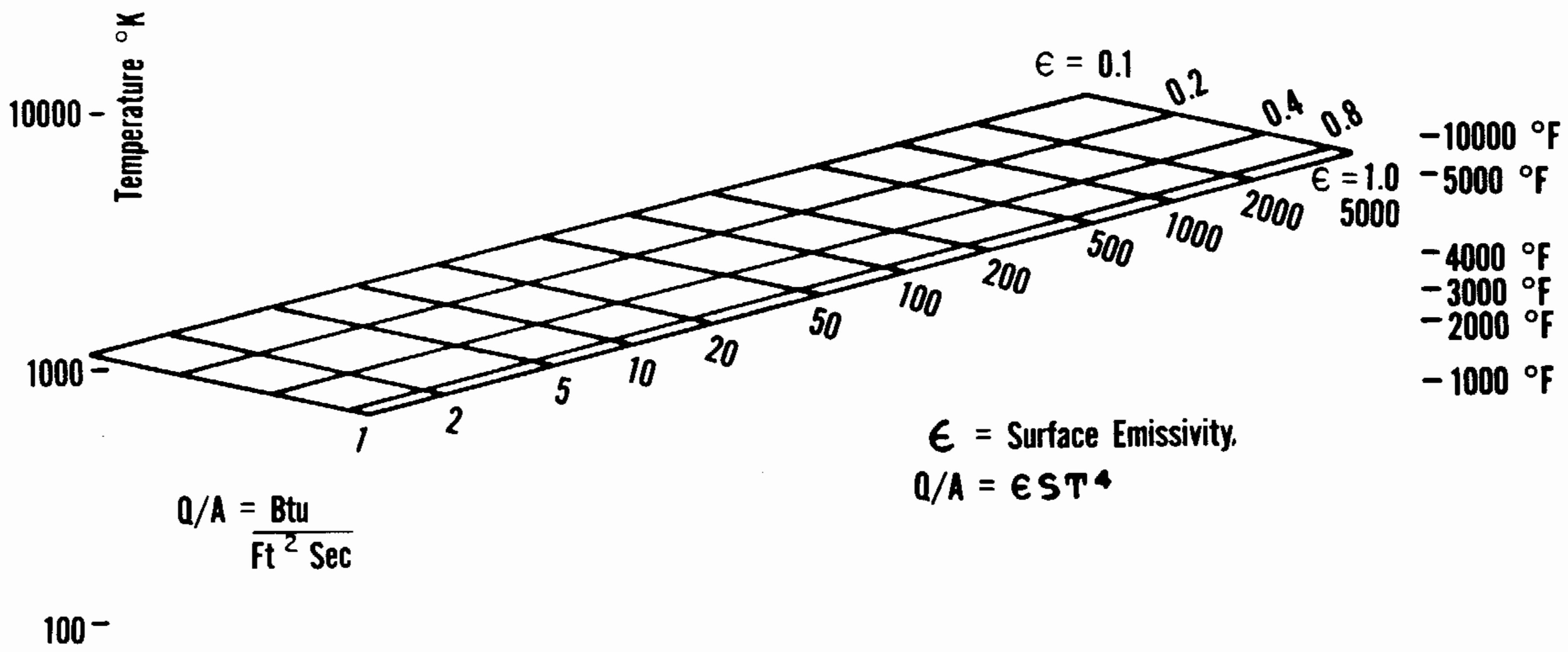

Figure 1.

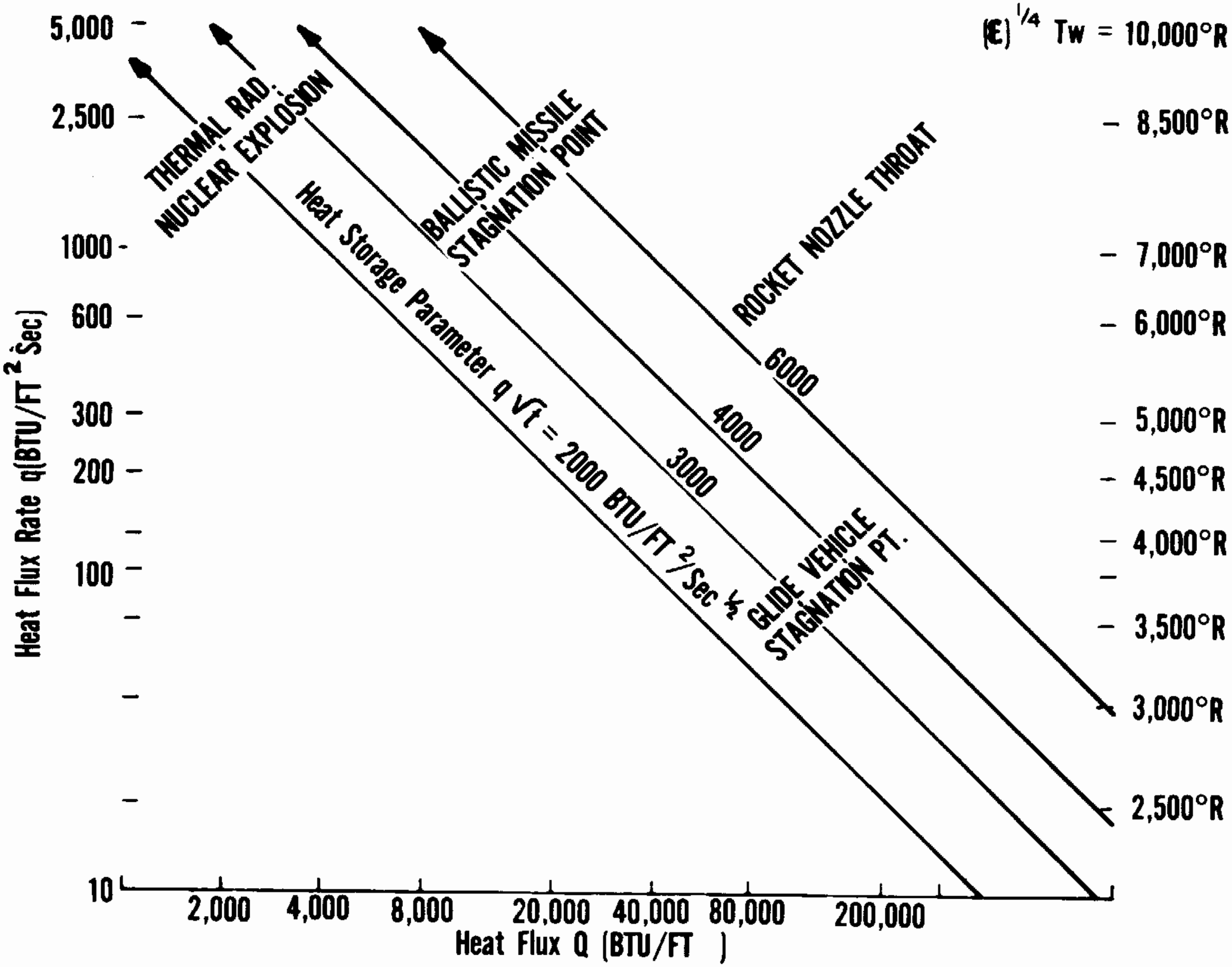

Figure 2. Comparison of Thermal Environments and Modes of Thermal Protection