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STRUCTURES FOR REENTRY HEATING

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SUMMARY

The basic structural approaches for dealing with reentry heating of manned vehicles are summarized. The weight and development status of both radiative and ablative shields are given and the application of these shields to various vehicles is indicated.

INTRODUCTION

Feasibility for lightweight structure is one of the major considerations in selection of a configuration for a manned vehicle capable of executing an atmospheric entry at orbital speeds. The major uncertainty in structure arises from the severity of the heating environment, which not only demands that familiar methods of construction be exploited to the fullest but that investigation be made of new materials and associated construction methods. Progress is being made in these investigations as may be seen from references 1 and 2.

The purpose of the present investigation is to review in rather broad outline the heating encountered by manned vehicles during reentry and to summarize some of the basic structural approaches for dealing with the problem. Both radiative- and ablative-cooling systems are described and compared. Research and development work has proceeded with these systems to the extent that weight estimates can be given and an appraisal made of the probable application of these systems to certain types of manned vehicles.

SYMBOLS

C	heat capacity, Btu/lb
Δh	heat of vaporization (or other phase change), Btu/lb
H_{eff}	effective heat of ablation, Btu/lb

k	thermal conductivity, Btu/(hr)(ft)(°F)
q	heating rate, Btu/(sq ft)(sec)
Q	total aerodynamic heat input, Btu/sq ft
L/D	lift-drag ratio
S	surface area
t	time during which heating occurs, hr
T	absolute temperature, °R (unless denoted in °F)
V	velocity
W	weight
ΔW	weight of heat-protection system per unit area, lb/sq ft
α	constant of proportionality (eq. (1))
ϵ	emissivity
ρ	density, lb/cu ft
σ	Stefan-Boltzmann constant, Btu/(hr)(sq ft)$(^{\circ}R)^4$

Subscripts:

A	ablation
B	final value at inner surface
e	radiation-equilibrium value
i	initial value at inner surface
m	mean value
max	maximum
o	outer surface

HEATING ENVIRONMENT

The heating inputs to manned reentry vehicles are shown in figure 1. Maximum heating rate has been plotted against total heat load per unit area and a band of combinations of these two quantities encountered by manned vehicles has been defined. This band is based on an analysis of the heating histories experienced by vehicles having large variations in wing loading and lift-drag ratio. The range of heat rates and heat loads at various points on these vehicles is reflected in the range of the vertical and horizontal scales, whereas heating time is reflected in the width of the "manned-vehicle band." The left edge of the band corresponds to about 4 minutes of heating and the right edge to about 70 minutes. This variation in heating time is associated with changes in average lift-drag ratio during reentry from 0 to about 2.5.

Similarly, the height of the band in figure 1 is associated with changes in wing or area loading and with changes in entry velocity. Very lightly loaded vehicles fall at the lower end of the band, while vehicles of comparable lift-drag ratio but with heavier loadings per unit area are shifted upwards along a constant time line. The most severe heating conditions are encountered by vehicles which combine a high L/D with a high W/S.

Some vehicles with wing or area loadings varying from about 25 to 75 lb/sq ft have been placed on the band in the vicinity of the maximum heat rate and heat load for which an important area of their structure is designed. For example, the Project Mercury capsule is shown near the design point for its front-face heat shield. (See fig. 1.) In actuality, a considerable range in heating conditions is encountered from the front face to the rearward areas of the capsule as indicated by the length of the line extending from the capsule. A similar line drawn through the reentry glider gives the range of heating conditions encountered from the nose stagnation point to the rearward areas. When variations in L/D, W/S, and vehicle shape are considered, it is apparent that structures must be provided to handle heating inputs varying from about 1,000 to over 100,000 Btu/sq ft and to survive heating rates of less than 10 to more than 100 Btu/(sq ft)(sec). Radiation-equilibrium temperatures associated with these heat rates are shown on the scale at the right in figure 1. As noted, they are computed with the assumption that a material emissivity of 0.8 is achieved.

A conservative evaluation of the current status of structural design for this operating environment is indicated in figure 2. Established areas for designs based on radiation and absorption of heat are indicated. As shown, radiative structures can handle large total heat loads but have temperature or heating-rate limitations. Up to a temperature level of a little over 2,000° F, a capability for constructing metallic surfaces using nickel and cobalt-base materials has been demonstrated, but at higher temperatures rather serious material problems arise. The arrow at the metallic-surface boundary in figure 2 indicates that current research efforts are devoted to raising this boundary up to about 3,000° F through use of the refractory metals.

Although not indicated in figure 2, a capability currently exists for constructing smaller structural components, such as nose caps, for temperatures above 3,000° F by using ceramic materials. Similarly, recent work with inflatable structures of metal fabric indicates a capability for use at about the 1,500° F level.

In contrast to the area for structures which dissipate heat by radiation, an area for structural design based largely on heat absorption is also shown in figure 2. The absorptive designs include liquid and metal heat sinks and ablative shields. Absorption of heat by ablation of surface material has proven to be an efficient and practical means for achieving self-regulated transpiration cooling for missile nose cones and has recently been extended to the design of the Mercury capsule heat shield. The edge of the absorption area in figure 2 represents an approximate boundary of present test experience with ablative cooling. Use of this cooling concept for longer reentry times and larger heat loads should be possible but poses a challenge in weight reduction which will be discussed later in this paper. The arrow at the ablative surface boundary indicates that present research efforts are devoted to ablative systems which can operate for flight times associated with lifting vehicles and to systems which combine absorption with radiative cooling.

RADIATIVE SYSTEMS

The principal types of radiative structures that have been investigated are indicated in figure 3. They may be classified according to whether the structure and its internal contents are unprotected, partially protected, or fully protected from high temperatures. In each case 95 percent or more of the heating input is dissipated by radiation, with the remainder being absorbed by a temperature rise in the structure or by an internal cooling system.

The unprotected structure applies to lightly loaded vehicles with large lifting or drag surfaces. Small, but structurally important, reductions in operating temperature are achieved by internal radiation of heat from the highly heated surfaces on the windward side of the component to the surfaces of lesser heating on the leeward side. Special construction techniques which use corrugated metal and expansion joints have been developed; these techniques alleviate thermal stresses and permit use of thin sheet metal in the presence of large temperature gradients as is demonstrated in reference 1. Corresponding weights are in the range of 1 to 3 lb/sq ft of wetted area depending upon vehicle type and external load conditions.

The partially protected structure (fig. 3) is designed to cope with a more severe heating environment. It uses an arrangement of insulating shields to block the inward flow of heat at the highly heated windward surfaces. The temperature of the structure behind the shields is thereby reduced to values which lie close to the radiation-equilibrium value for the leeward side of the component. This means in some cases that a load-bearing structure operates at temperatures that are 60 percent or less of those on the shield surfaces.

The fully protected structure is designed to obtain the degree of internal-temperature control necessary for cargo areas and requires the addition of a cooling system to absorb heat that passes through the insulating shields. Cooling systems using gases and water as expendable coolants have been investigated. When consideration is given to the large storage-volume requirements for gaseous coolants, it becomes clear that water-boiling systems are the most practical choice. They are capable of maintaining desired interior-wall temperatures of 150° F or less by boiling at reduced pressures.

The price to be paid for obtaining a cool interior with a radiation-cooled vehicle can be assessed in terms of weight. In the remaining discussion, therefore, attention is given to the weight of radiation shields with back-surface cooling and to the weight of the alternate device, the ablative shield.

The characteristics of two types of radiative-shield designs undergoing investigation are shown in figure 4. One of these designs uses a metallic wall as the hot radiating surface; the other uses ceramic materials. The corrugated outer wall shown in figure 4 is but one of several lightweight metallic outer walls that have been investigated. This work has indicated that superalloy surfaces can be operated successfully at temperatures up to 2,200° F. Special problems encountered in the design of such surfaces are discussed in reference 2. Through the use of refractory metals in place of superalloys, a potential for operating temperatures up to 3,000° F exists.

The ceramic shield is being investigated for surface temperatures in excess of 3,000° F. The materials required are foamed ceramics of low thermal conductivity which also have enough mechanical integrity to serve as the vehicle surface. With these shields, provision of a reliable attachment of a thick layer of low-density ceramic to the load-bearing structure is a problem. A possible solution indicated in figure 4 is the use of a corrugated-metallic-honeycomb attachment. The proximity of the water-cooling system confines melting of the honeycomb to a short distance beneath the surface.

At the present time, there is a rather important difference in the insulating capability of these two types of radiative-shield designs which has a large effect on the amount of water required for back-surface cooling. This weight difference is shown in figure 5 where the weight per unit area ΔW of shields and water required to maintain a 150° F environment is plotted as a function of external heat load. The weight ΔW does not include the load-bearing structure.

The lowest curve in figure 5 gives the weight achieved with insulating shields which utilize superalloys for the external surface. The next higher curve is a conservative estimate of the weight penalty involved in substituting a refractory metal surface for the superalloy surface in order to achieve a higher operating temperature. The highest curve applies to the ceramic shield. It is based on the insulating properties of materials such as foamed quartz, aluminum oxide, and zirconia. The derivation of these curves is indicated in the appendix. The comparison shows that the weight penalty associated with higher maximum surface temperatures becomes increasingly severe, particularly for the larger heat loads.

An important characteristic of these radiative-cooling systems is that although weight increases with total heat load, system efficiency is greater at higher heat loads. Thus, the lower curve in figure 5 shows that in the heat-load range of 10,000 to 20,000 Btu/sq ft, corresponding to design values for body areas of vehicles, each pound of system weight handles 6,000 to 7,000 Btu, while at the larger heat loads well over 20,000 Btu can be handled by each pound. Even with the foamed-ceramic shield, a system efficiency of 10,000 Btu/lb and higher can be achieved when the total heat load exceeds 100,000 Btu/sq ft. Heat loads of this magnitude are encountered at the stagnation areas of lifting vehicles. These high weight efficiencies for radiative-cooling systems at large heat loads may be compared with the efficiency of ablative shields, which provide a practical method for handling high heat rates, but which encounter difficulty in maintaining a high weight efficiency as heating time is increased. Two approaches for alleviating this difficulty are discussed in the next section.

ABLATIVE SYSTEMS

Cross sections of two ablative heat shields are shown in figure 6. The shield material may be thought of as being composed of an ablation layer and a self-insulation layer. The latter layer protects the structure by acting as a sink for heat which is conducted from the hot surface. The weight of the self-insulation layer depends on flight time and can become very substantial for lifting vehicles if the temperature rise at the back surface must be restricted. One way to reduce this weight is to find a suitable shield material which ablates at a low temperature and which is also a poor heat conductor. An alternate method, which permits use of presently developed shield materials, is to provide the back surface with a water-cooling system. This method is indicated by the lower sketch in figure 6. The use of water as a back-surface heat sink will reduce the thickness of the insulation layer, and it may be expected that the combined weight of water and insulation will be less than the weight of the self-insulation layer in the shield without a water-cooling system.

Calculations illustrating the effect of a back-surface water-cooling system on the weight of an ablating shield are shown in figure 7. Calculations were performed for a typical heat load of 20,000 Btu/sq ft with the assumption that the ablating material yields an average effective heat of ablation of 4,000 Btu/lb during reentry. Details of these calculations are given in the appendix. The resulting weight ΔW is plotted as a function of the temperature for ablation, or vaporization, of an idealized shield material which does not leave a char residue.

Increases in vaporization temperature mean increased heat conduction toward the back surface as well as increased radiation from the heated face. The interaction of these two trends with increasing surface temperature leads to a weight for uncooled shields that first increases rapidly due to heat conduction toward the back surface and then levels off due to increased radiation cooling at the front face. The weight of uncooled shields for a given total heat load is also seen to be influenced significantly by increases in heating time. In order to obtain a weight of 5 lb/sq ft, which is the minimum that can be achieved with this combination of heat load and H_{eff}, the ablation temperature must approach the allowable temperature for the back surface of the shield. A system efficiency of 4,000 Btu/lb is then approached.

The curves for the water-cooled shield show that the weight of these shields (including water weight) is relatively insensitive to variations in ablation temperature and heating time. (See fig. 7.) Significant weight reductions over that for uncooled shields are achieved even in the temperature range around 1,000° F associated with a low-temperature ablator such as Teflon. The downward trend of the curves at the higher temperatures indicates that a substantial fraction of the heat load is being dissipated at the surface by radiation. It would appear from this comparison that the use of a back-surface water-cooling system permits the selection of the ablating material on grounds other than its ablating temperature and makes possible the achievement of a weight efficiency for the system equal to or greater than the material H_{eff}, even for long heating times.

RADIATIVE SYSTEMS WITH TRANSIENT ABSORPTION

An entry maneuver which presents a challenge in structural design is that initiated at steep angles with a subsequent pull-up to an equilibrium flight path. The type of heating history encountered is shown in figure 8. During the initial dip into the atmosphere, heating rates and surface temperatures are encountered which are difficult to handle with radiation systems, but the principal part of the heat load occurs at heating rates that are compatible with radiation cooling. Modification of radiation-shield systems to provide transient heat absorption is therefore desirable.

The sketches in figure 8 show how the ceramic-wall and metallic-wall designs described previously (fig. 4) can be modified to provide a transient period of absorption followed by radiation. One modification consists of impregnating the porous-ceramic shield with a vaporizing material which when heated will generate gas for a period of transpiration cooling. Analysis of such a system indicates that materials with decomposition or vaporization temperatures below 1,000° F should generate gas at a sufficient rate to reduce surface temperatures to 70 percent or less of the radiation-equilibrium value. Such reductions would permit a surface designed for a temperature of 3,000° F to operate under a transient condition that would ordinarily produce a 4,000° F temperature at the surface. Calculated weights of vaporizing material required to produce the necessary surface cooling during a steep-angle reentry at orbital velocity are of the order of 1 lb/sq ft. A limited number of hot-gas-jet tests of such systems have been made with porous ceramics impregnated with various organic and inorganic materials.

Possible modifications to an insulating shield with a metallic wall are indicated by the remaining two sketches in figure 8. One possibility is to apply a thin layer of ablating material directly to the external surface of the solid shield. This layer would appear to provide a positive method of temperature control, but the risk is run that a thin layer may be lost during the heating of the boost phase and the subsequent exposure to the vacuum of space. An alternative is to impregnate the insulating material beneath the shield with a vaporizing material and to substitute a porous metallic shield for the solid one. The degree of temperature reduction of the metallic surface again depends upon the rate of gas generation beneath the surface. Although all of these approaches appear promising, system development is in an early stage, and much experimental work will be required to prove their reliability.

THERMAL-PROTECTION SUMMARY

A summary of the weight of protection systems is given in figures 9 and 10. Radiative systems are shown in figure 9; their weight, in lb/sq ft of vehicle surface, is shown superimposed on the vehicle-heating environment. The weights given are those required to step down from the external environment to a low-temperature interior. With each system, a gradual weight increase occurs as the total heat load increases but, more importantly, step increases in weight take place at certain temperature limits for design of the outer surface.

Of these systems, the superalloy shields may be placed in the category of being well-developed and ready for application to those areas of reentry vehicles where maximum temperatures do not exceed 2,200° F. Vehicle areas exposed to higher temperatures require refractory-metal shields. The construction of such shields is perhaps more art than science at the present time, but current work indicates that present technology should permit design of shields that would be serviceable for at least 2 hours at high temperature. This lifetime should be sufficient for one or more flights before shield replacement.

At higher heat rates the area for application of foamed-ceramic shields is encountered. It is difficult to assess the development status of shields based on these new materials because of the proprietary nature of much of the work. The exploratory tests that have been accomplished, however, indicate that there should be no technical barrier in achieving designs of the weight shown in figure 9.

The ablative-system summary given in figure 10 shows that through the use of a back-surface cooling system, ablative shields of reasonable weight extend well into the manned-vehicle band. Near the low L/D edge of the band, shield weights are encountered in the range 3 to 8 lb/sq ft. Considerable experience has already been accumulated in the design of shields of these weights for ballistic vehicles. Even though these weights are somewhat heavier than those indicated for the ceramic shields in figure 9, they provide a current solution for heavily loaded reentry vehicles of compact design which fall in this area of the band. They also provide the only currently available solution for entries at the higher heating rates associated with return from lunar missions.

CONCLUDING REMARKS

Practical structural approaches are available for a substantial area of the manned-reentry-vehicle band. The choice between radiative and ablative structures is seen to depend mainly on vehicle wing or area loading and lift-drag ratio. Radiative structures appear to be the logical choice for lightly loaded vehicles independent of their lift-drag ratio. Similarly, it appears that the ablative approach could be readily extended to the design of compact vehicles developing a moderate amount of lift during reentry.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 12, 1960.

APPENDIX

WEIGHT ANALYSIS OF THERMAL PROTECTION SYSTEMS

Radiative System Weight Analysis

In the weight analysis of radiative systems, the heat capacity of the insulation layer was neglected and the conductivity-density product was assumed to vary with the cube of the mean temperature of the insulation. Thus,

$$k\rho = \alpha T_m^3 \tag{1}$$

where

$$T_m^3 = \frac{1}{T_o - T_i} \int_{T_i}^{T_o} T^3 \, dT = \frac{\left(T_o^2 + T_i^2\right)\left(T_o + T_i\right)}{4} \tag{2}$$

The value of α depends upon the type of insulation required for tolerance of the maximum value of T_o during a flight.

With these simplifications the minimum weight of insulation and back-surface coolant can be expressed as

$$\sqrt{\frac{\alpha Q}{\sigma \epsilon_o \, \Delta h}\left[1 - \left(\frac{T_i}{T_e}\right)^4\right]} - \frac{\alpha}{4\sigma\epsilon_o}$$

To obtain the weights shown in figure 5, the value of Δh was taken to be 1,000 Btu/lb corresponding to boiling water, and the values of the remaining parameters are given in the following table as a function of the maximum outer-surface temperature:

$(T_o)_{max}$, $^{\circ}F$	Type of insulation	α, $\frac{(Btu)(lb)}{(ft)^4(hr)(^{\circ}R)^4}$	Type of outer shield	ϵ_o	Weight of outer shield, lb/sq ft
2,200	Fibrous	0.1×10^{-9}	Superalloy	0.9	1.0
3,000	Fibrous	$.1 \times 10^{-9}$	Refractory metal	.9	1.5
4,000	Foamed-ceramic	1.0×10^{-9}	Foamed-ceramic	.5	---

Ablative Shield Weight Analysis

For the purpose of a weight analysis of ablation shields the initial temperature of the shield outer surface was assumed to be the ablation temperature. The distribution of temperature through the shield thickness was assumed to be linear and the heat conducted to the back surface was assumed to be negligible insofar as its effect on the heat balance at the outer surface was concerned.

For a constant outer-surface heating rate, the weight required for an ablating shield having an initial back-surface temperature T_i and a final back-surface temperature T_B was calculated from the following equation:

$$\frac{\Delta W H_{eff}}{Q\left[1-\left(\frac{T_A}{T_e}\right)^4\right]} = \frac{1}{2}\left(1+\sqrt{1+\frac{8k\rho t}{C}\left(\log_e\frac{T_A-T_i}{T_A-T_B}\right)^{-1}\left\{\frac{H_{eff}}{Q\left[1-\left(\frac{T_A}{T_e}\right)^4\right]}\right\}^2}\right) \qquad (3)$$

It may be noted that the value of H_{eff} used in this equation should not include a radiation-cooling contribution, inasmuch as radiation at the outer surface is accounted for by the factor $\left[1-\left(\frac{T_A}{T_e}\right)^4\right]$. The values of $k\rho$ and C used to obtain the weights given in figure 7 were $15\ \frac{(\text{Btu})(\text{lb})}{(\text{ft})^4(\text{hr})(^\circ\text{F})}$ and 0.25 Btu/lb, respectively.

For the shield whose back surface is maintained at the initial temperature by a water-cooling system, the optimum weight combination of ablation layer, insulation layer, and coolant can be obtained from the following equation:

$$\frac{\Delta W H_{eff}}{Q\left[1 - \left(\frac{T_A}{T_e}\right)^4\right]} = \frac{1}{2}\left\{1 + \sqrt{1 + \frac{4k\rho t\left(T_A - T_i\right)}{\Delta h\left[1 - \left(\frac{T_A}{T_e}\right)^4\right]^2}\left(\frac{H_{eff}}{Q}\right)^2}\right\}$$

$$- \frac{k\rho t\left(T_A - T_i\right)}{\Delta h\left[1 - \left(\frac{T_A}{T_e}\right)^4\right]^2}\left(\frac{H_{eff}}{Q}\right)^2 \log_e\left\{\frac{\sqrt{1 + \frac{4k\rho t\left(T_A - T_i\right)}{\Delta h\left[1 - \left(\frac{T_A}{T_e}\right)^4\right]^2}\left(\frac{H_{eff}}{Q}\right)^2} - 1}{\sqrt{1 + \frac{4k\rho t\left(T_A - T_i\right)}{\Delta h\left[1 - \left(\frac{T_A}{T_e}\right)^4\right]^2}\left(\frac{H_{eff}}{Q}\right)^2} + 1}\right\} \qquad (4)$$

In order to determine the validity of the constant heating-rate approximation, triangular heat pulses of various shapes but having the same heating time and heat input were investigated. These calculations indicated that the weight for a more realistic heat pulse should not differ from that calculated by equation (4) by more than 5 percent.

A more refined analysis was also made without the restriction of a linear gradient throughout the shield thickness. Numerical results from an IBM type 650 electronic data processing machine indicate that the weight obtained with the linear temperature gradient is conservative by 5 to 10 percent.

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1. Pride, Richard A., Royster, Dick M., and Helms, Bobbie F.: Experimental Study of a Hot Structure for a Reentry Vehicle. NASA TM X-314, 1960.

2. Anderson, Melvin S., Trussell, Donald H., and Stroud, C. W.: Research on Radiation Heat Shields for Bodies and Leading Edges. NASA TM X-312, 1960.

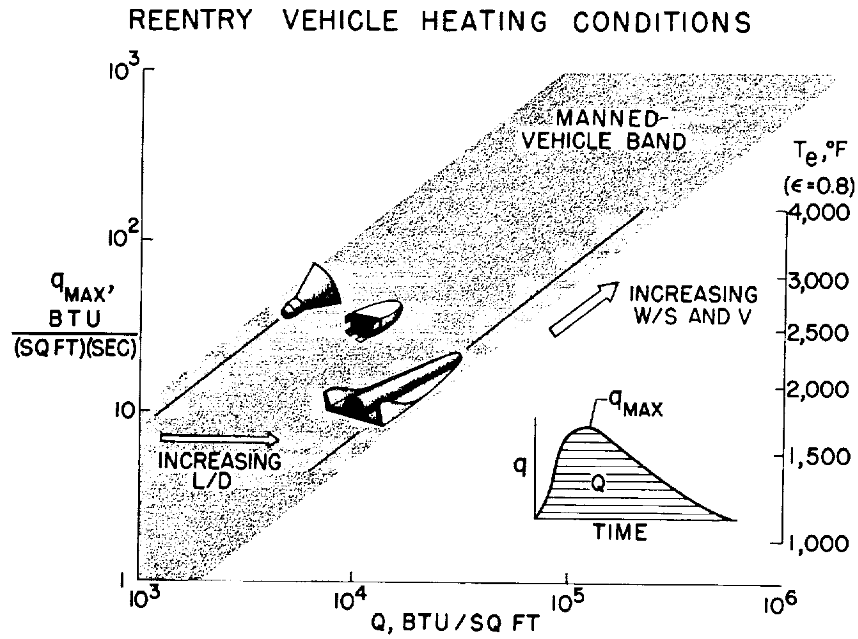

Figure 1

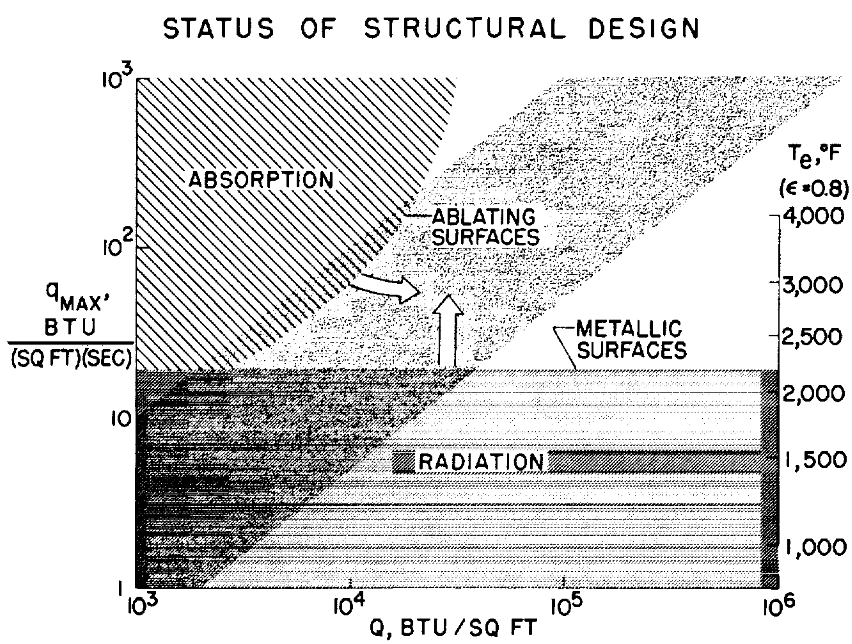

Figure 2

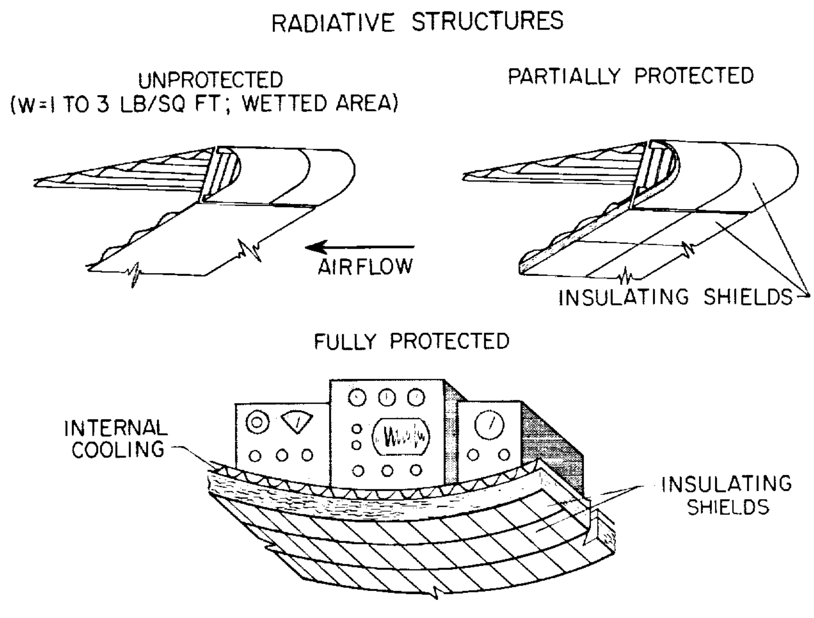

Figure 3

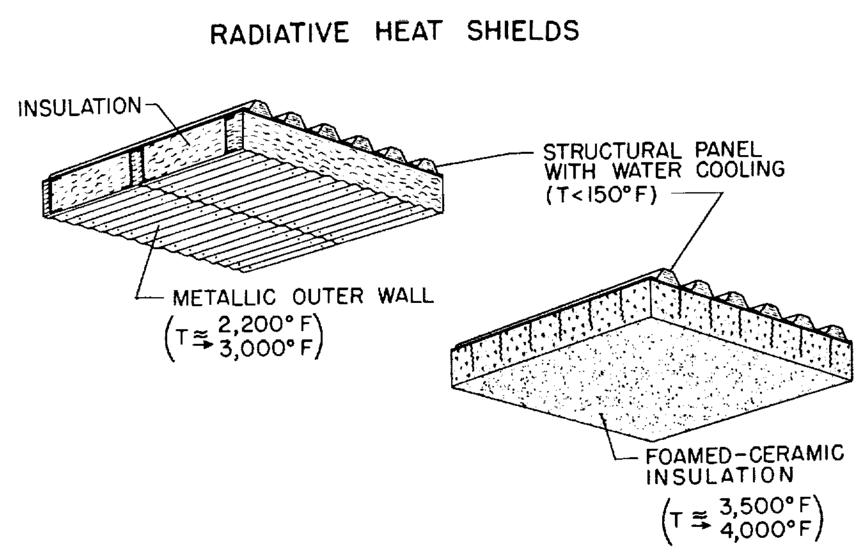

Figure 4

RADIATIVE COOLING SYSTEM WEIGHTS

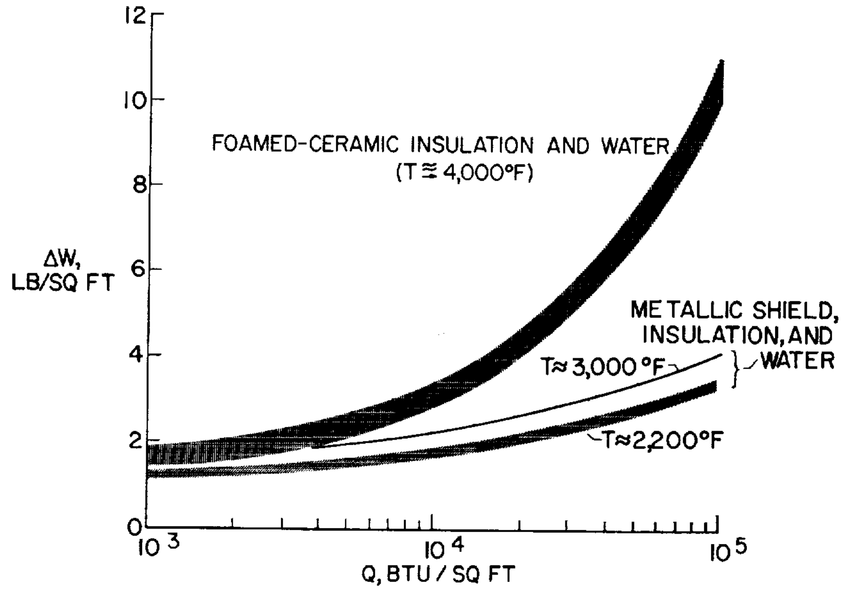

Figure 5

ABLATIVE HEAT SHIELDS

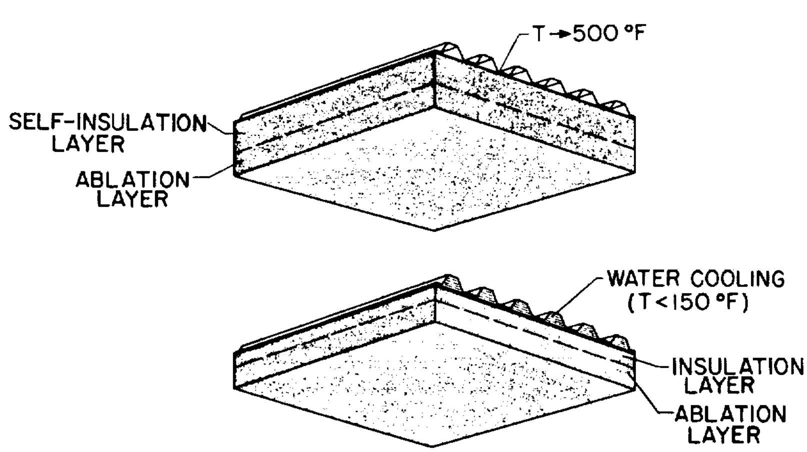

Figure 6

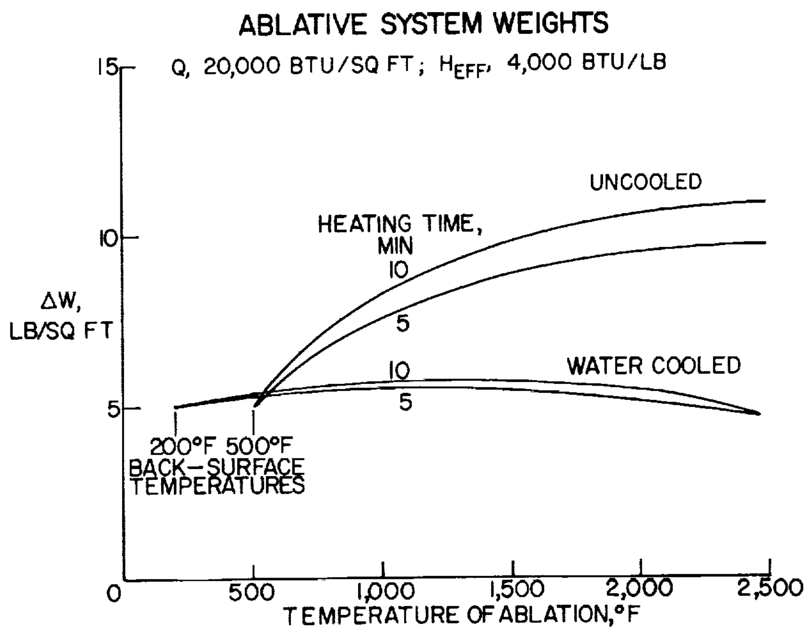

Figure 7

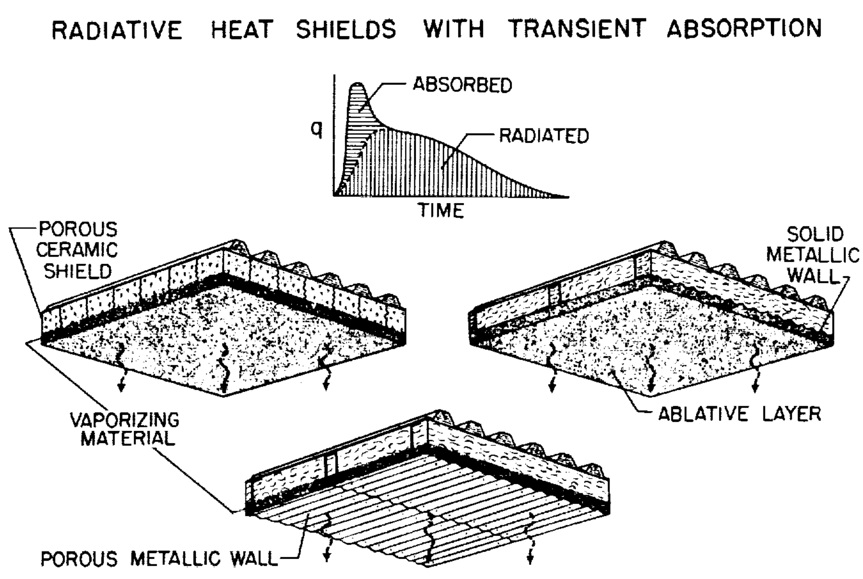

Figure 8

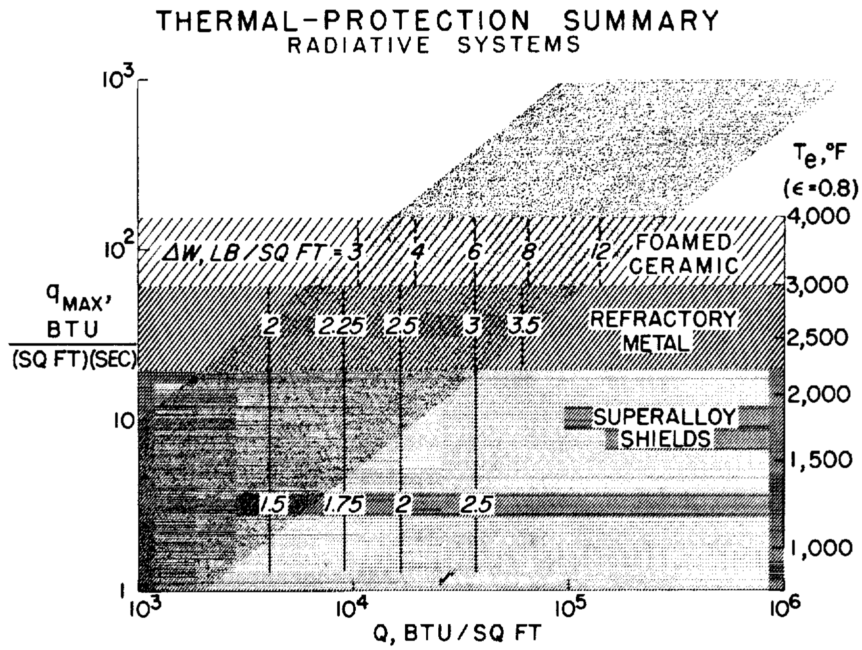

Figure 9

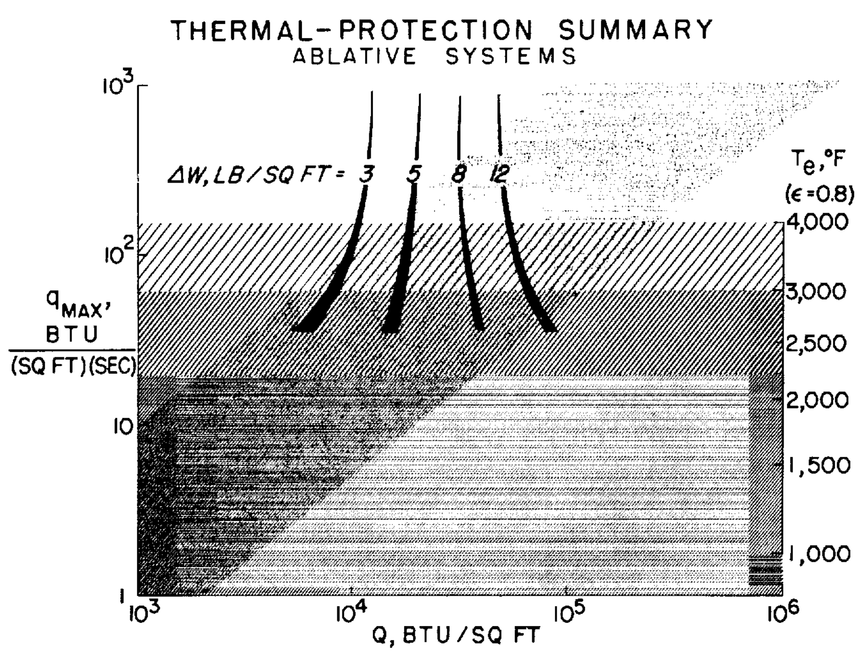

Figure 10