PROTECTION OF AIRCRAFT STRUCTURES AGAINST HIGH TEMPERATURES

By Wilfred H. Dukes

Chief of Structures, Aero-Space Rockets,
Bell Aerosystems Company, Buffalo 5, New York, U.S.A.

1. INTRODUCTION

In 1945, over 40 years after the first manned flight, the X-1 became the first airplane to exceed the speed of sound. In the short span of 15 years since that time, the development of power plants has been so rapid that our velocity potential has increased thirtyfold and orbital and escape speeds are now possible. This capability has brought with it frictional or kinetic heating, an airframe structural problem of the first magnitude.

In the development of airframes to sustain these conditions, two general approaches have been followed. With the so-called "hot structure" approach, the requirements of increasing speeds have met been by the substitution of materials of higher and higher temperature capability into comparatively conventional airframes so that the primary load carrying members operate at high temperature. The alternate approach maintains the load carrying structure at some moderate temperature by providing some form of thermal protection system between the structure and the hot boundary layer. For the more severely heated airframes, protection offers the only practical approach to airframe construction. In other cases where the heating is less severe, it offers an interesting and advantageous alternate to the "hot" structure.

This paper will review the present position with respect to the development of protection systems of various types and will show the performance characteristics of each. It will also indicate the areas in which further development of protection systems is urgently required.

It is believed that the figures presented in this paper to show the performance capabilities of various protection systems, are sufficiently accurate for direct use in preliminary design, despite the simplifying assumptions which have been necessary in the interests of generalization. References to any particular vehicle or vehicle requirements have been avoided to minimize security problems.

2. CLASSIFICATION OF PROTECTION SYSTEMS

Airframe thermal protection systems can be classified, as shown in Figure 1, into two broad groups comprised of absorptive systems, in which most of the aerodynamic heat is absorbed by material carried aboard the aircraft, and radiative systems, in which most of the heat is dissipated to the atmosphere by radiation.

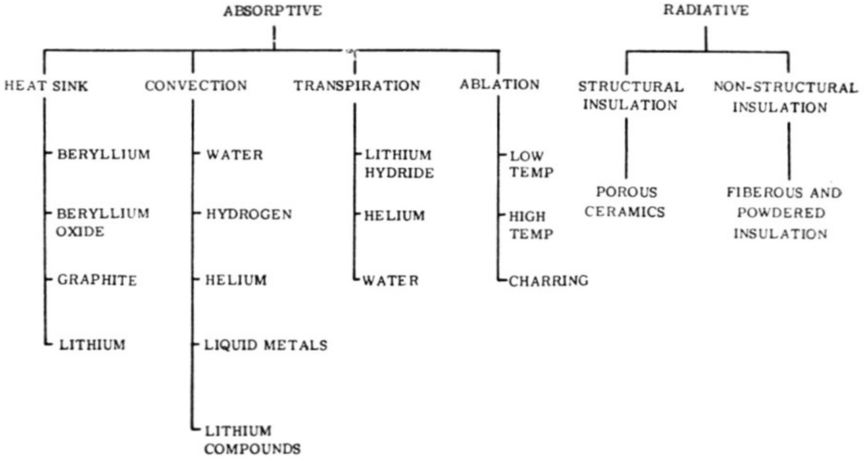

FIG. 1. Classification of protection systems.

Absorptive systems depend upon material heat capacity, including sensible heat due to temperature rise in the solid, liquid and gaseous phases, the latent heats of phase change and also the heat absorption capabilities due to chemical breakdown. Airframe and material temperatures achieved with absorptive systems depend upon the characteristics of the heat absorbing material rather than the aerodynamics of the vehicle, so that such systems are suitable for use under conditions of severe heating. On the other hand, due to the limited heat capacity of most materials, these systems are comparatively heavy and are consequently limited to short flight times.

Radiative systems dissipate heat by radiation from a high temperature surface and are, therefore, limited in heat flux capability by the temperature resistance of available outer surface materials. Since these systems do not involve a significant amount of heat absorption, however, they are comparatively light in weight and, therefore, suitable for long flight times.

As shown in the figure, there are a number of forms of absorptive systems. We begin with the simple heat sink in which the aerodynamic heat is absorbed by temperature rise in the solid material without phase change or chemical reaction. The primary consideration for the choice of material for a heat sink is the product of specific heat and permissible temperature rise. However, depending on the thickness of material required and on the intensity of heat flux and the flight time, the average temperature rise which can be achieved without exceeding the melting temperature at the surface will depend upon material diffusivity. Studies have shown that beryllium and beryllium oxide are the most promising heat sink materials. Graphite has also been suggested but its efficiency is based on achieving high surface temperatures, which are actually impractical due to oxidation. Some consideration has also been given to the use of composite materials in an attempt to obtain an optimum combination of capacity and diffusivity for particular applications. So far as is known, however, such developments have not been carried very far. As will be shown later, the solid heat sink is a comparatively inefficient protection system, but it has been used because of its simplicity, reliability and relative freedom from development requirements.

A more efficient but more complex form of heat sink exploits, in addition, the heat of fusion and the sensible heat of the liquid phase. For this purpose the heat sink material is contained in a metallic shell forming the structural surface. The permissible temperature rise in such a system is therefore limited by the temperature capability of the containing metal shell which, with presently available materials, is about 2400°F. Seeking the material with the greatest heat capacity within this temperature limitation and without vaporizing leads to the metal lithium, which will absorb 2800 BTU/lb.

Further improvements in absorptive efficiency can be obtained at the cost of greater complexity by exploiting also the heat of vaporization. This is done with the convective cooling system. A suitable coolant is circulated through passages in the external surface, picking up heat by temperature rise and transporting it to a centralized container where, through the medium of a heat exchanger, it is absorbed by the primary coolant. The vapor is expended overboard to dissipate the heat and the container is refilled with coolant after each flight. For convective cooling, therefore, we seek the coolant having the maximum heat capacity when sensible heat, fusion, and vaporization is included. In addition to the coolant, however, the system weight must include the surface structure with its cooling passages, the circulating fluid, the heat exchanger, coolant tank, pump and the fuel required to generate pumping power.

Examination of potential coolants for convection systems shows that materials of interest are limited to water, hydrogen, helium and the liquid metals. Heat capacities range from 1000 BTU/lb for water to about 10,000 BTU/lb for lithium. Other characteristics of these materials, however, such as density, storage temperature, vaporization temperature, etc. are vastly different, so that no one material is best for all applications. Water, for instance, has a comparatively low heat capacity but the associated cooling system is simple and light so that for short time applications where the cooling system weight may be as important as the weight of coolant, water shows promise. Hydrogen is a very efficient heat absorbing material but its low density creates serious storage problems, particularly since it must be stored as a cryogenic. Consequently, for long flight times a point is reached where the volume required cannot be contained within the vehicle being protected.

There are also a number of compounds which undergo chemical change with the absorption of heat at certain temperatures. Such compounds can also be utilized as a coolant, with a heat transport system to bring the heat from the vehicle surface to a central reservoir. Compounds offering heat capacity values of interest can be located from a study of the periodic table of the elements, and it turns out that the material with the greatest endothermic capacity is lithium hydride. This material is particularly attractive since the chemical reaction occurs at temperatures within the range of conventional structural materials. Furthermore, the material has a large specific heat value in the solid phase due to the hydrogen component. Finally, the chemical breakdown, which consists of driving off the hydrogen, leaves liquid lithium, the material with the greatest heat of vaporization. The total capacity is 17,000 BTU/lb if the heat absorption includes both chemical breakdown and lithium vaporization.

The next step in coaxing greater heat capacity from available materials is by heating the gas or vapor. This is done with transpiration cooling in which the gas is forced through a porous external surface of the vehicle. Heating to much higher temperatures occurs by mixture with the boundary layer, and in the process the boundary layer is cooled and the heat transferred to the vehicle surface is correspondingly reduced. The ideal coolant for this application would probably be lithium hydride since the maximum heat capacity is required for producing the transpired gas, and this gas in turn is principally hydrogen which has the maximum of specific heat of all known materials. This possibility has evidently not been studied at the present time, possibly due to the question of ignition of the hydrogen in the boundary layer. Consideration on the basis of potential heat capacity is then limited to water and helium, and pumping and circulating systems are required to distribute properly the fluids at the surface. A limited amount of work has also been done with other chemical compounds, such as $NaHCO_3$, which absorb heat by chemical breakdown and produce a gas which can be used for transpiration cooling.

Such materials are distributed over the vehicle surface inside the porous skin and are suitable only for one-flight vehicles. The heat capacities realized are not particularly high, although the system simplicity is attractive.

The final step in absorptive systems is ablation, in which absorption by sensible heat, phase change, chemical breakdown, and gas transpiration are combined. Furthermore the material is distributed over the vehicle surface as a solid, in the quantities required, and mechanical transport systems are unnecessary.

Three types of ablation have been developed. Low temperature ablation, characterized by a low phase change temperature of the material, leading to relatively low surface temperatures. Teflon is presently the most popular of this class with an ablation temperature of about 800–1000°F which simplifies the task of insulating the substructure.

Next are the high temperature ablation materials, represented by quartz which vaporizes at about 3000°F. Insulation of the substructure is more difficult, due to the higher surface temperature, but this high temperature increases efficiency by increasing the heat dissipation by radiation.

Finally, there are the charring ablators, represented by inorganic fibers in a resinous matrix. Heat is absorbed and gas is formed both by vaporization of the fibers and by polymerizing of the resin. The resin, however, is not completely destroyed, but leaves a surface char, which is principally carbon. This char, being very refractory, develops high surface temperatures, and dissipates a significant quantity of heat by radiation.

Radiative systems utilize insulating material between the external vehicle surface and the load carrying structure so that the high surface temperatures necessary for heat dissipation can be generated. The insulating efficiency of available materials covers a very wide range of values, some three to four orders of magnitude. The most efficient insulators, however, have negligible strength while the strong materials are poor insulators.

These characteristics give rise to two distinct types of protection systems; first, the so-called "structural" insulation, in which the airframe is surrounded by a material or material composite having sufficient mechanical strength to resist aerodynamic forces and thermal gradients, but usually of mediocre insulating performance. Development work on this type of system has been quite limited so far, and it is not easy to select the best example. Fiberglas reinforced phenolic is excellent for this purpose except that its temperature capability is quite limited. For higher temperatures some form of ceramic material is used; with porosity to decrease conductivity and a dense surface layer to provide surface smoothness and erosion resistance. Because of limited strain capabilities, and the presence of temperature gradients and thermal stresses, ceramic materials cannot be successfully applied in the thicknesses required for insulation purposes, as a continuous layer over an aluminum load carrying structure. Consequently, it is usual to find these materials either with metallic reinforcements, or embedded in a metallic matrix. The metallic elements increase the structural integrity of the material but at some cost in conductivity increase.

The second type of radiative protection system is called "non-structural" since the insulating material has no mechanical strength. These systems are based on the use of very efficient powdered or fibrous insulation located externally around the load carrying structure and which require a separate surface structure to form the vehicle contour and to sustain aerodynamic forces. Typically, this surface structure consists of individual small panels of temperature resistant material, either metallic or nonmetallic, each panel mounted from the load carrying structure in a manner permitting freedom for thermal expansion.

3. PERFORMANCE OF PROTECTION SYSTEMS

To show the capabilities and the usefulness of protection systems,Figures 2 through 7 have been prepared. These figures show performance as the weight per unit area for the entire protection system. To form a proper comparison, the systems have each been designed to protect an aluminum load carrying structure operating at 250°F. System weights are expressed in terms of a heat flux intensity and an equivalent time. Where the vehicle flight conditions involve a varying heat flux, the maximum

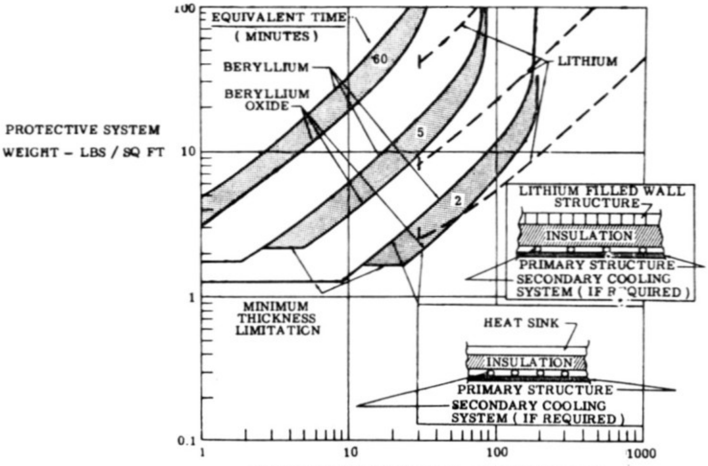

FIG. 2. Performance of heat sink systems.

value is used. It is then possible to show, on the same charts, the flux limitations of the various systems. The equivalent time is defined such that when multiplied by the maximum heat flux, the product is equal to the area under the actual heat flux-time curve. Where other flight path parameters are involved, as is the case with ablation and transpiration, suitable correction factors, which will be explained later, are introduced. Three time values have been selected; 2 minutes, typical of ballistic unmanned re-entry, exit boost and air-to-air missiles; 10 minutes, typical of manned ballistic and lifting body re-entry and ground-to-air missiles; and 60 minutes, typical of lifting re-entry and long range cruise vehicles.

Depending on the heating intensity and the type of protection system, the maintenance of a 250°F load carrying structure generally requires some insulation between the external surface and the aluminum. The weight of this insulation is included in the figures which follow.

As the flight time increases it is found that a point is soon reached where it is lighter to use less insulation but to add a secondary cooling system to the aluminum structure to absorb the low intensity heat which penetrates the insulation. For the present paper water cooling is used and the weights include the water required for secondary heat absorption, the weight of cooling lines, manifolds, residual water, a heat exchanger, storage tank and pump, and also the fuel to generate pumping power. In each case the proportions of insulation and water cooling are also selected to give the minimum total weight.

The accuracy of these charts is considered adequate for preliminary design studies. They apply principally where significant areas of surface are involved and although they can be used for local areas such as leading edges of wings, other schemes, which exploit the local variations of heat intensity over the surface and the local geometry, may also have advantages. Such schemes are not included in the present study. This work, in other words, is limited to one dimensional heat flow.

Figure 2 shows unit weights of the best solid and liquid heat sink systems for various values of maximum heating intensities and equivalent flight times. Due to the significance of heat intensity and material diffusivity on the useful heat capacity of the various materials used, the effect of the variable conditions along the flight path cannot be completely represented by an equivalent time; thus the figure is approximate, depending on the type of vehicle. Fibrous insulation has been assumed between the heat absorbing shield and the aluminum load carrying structure. Notice that the solid heat sink has a definite maximum heat flux, depending on flight time and material diffusivity, which cannot be exceeded regardless of the weight of material provided.

Figure 3 shows similar weight data for the more interesting convective cooling systems. The weights include all coolants, lines and manifolds and contained fluids, pumps, heat exchangers, etc., and where necessary supplemental insulation and cooling of the aluminum structure. The weight of the cooled surface structure is also included, where this is not the load carrying aluminum. In other words, any weight additional to the aluminum structure as designed for the applied loads, is considered as protection system weight.

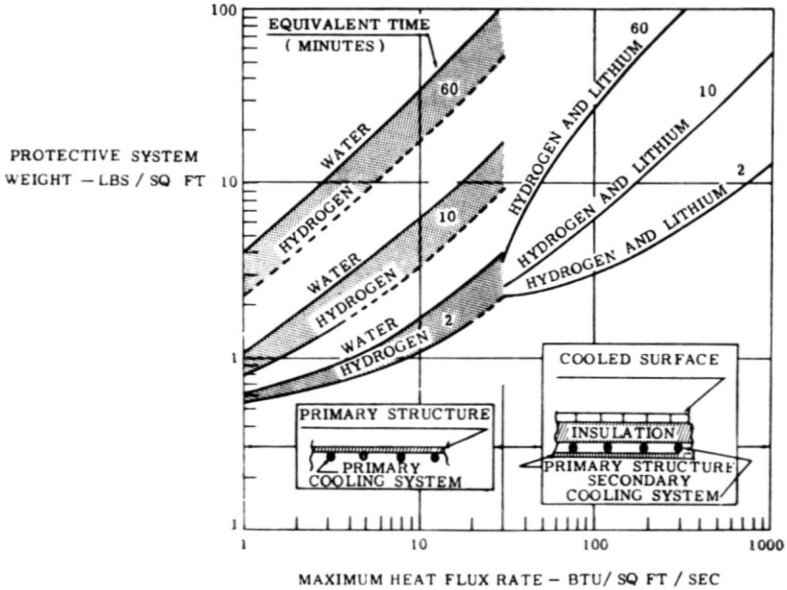

FIG. 3. Performance of convective cooling systems.

Figure 4 shows weight curves for transpiration cooling systems based on helium, which gives the lightest system if hydrogen is excluded. Account has been taken, in computing the weights of transpired gas, of the effect of variations in the stream enthalpy, and other boundary layer characteristics during the flight, using the methods of reference(1). By approximating as constants those parameters which vary only slightly for a wide range of conditions, it has been possible to express the effective heat capacity, for a given coolant, as a linear function of stream enthalpy and therefore as a function only of vehicle velocity. The weight of coolant can then be expressed in terms of maximum heat flux, maximum velocity, equivalent time, and a time integral which expresses the variation of velocity and heat flux along the vehicle flight path. This integral has been evaluated for a wide range of vehicle types and flight paths, and for a number of coolants and it is found that the result varies only between 1.0 and

1.4. Consequently an average value of 1.2 has been used in preparing Fig. 4.

Figure 5, which shows ablative system weights, is based on similar assumptions so far as the transpiration effects are concerned except that the effective heat capacity of the material as a function of enthalpy, has been based on experimental data. Materials representative of each of the three classes, low temperature ablation, high temperature ablation and ablation with charring, have been considered. Again the effect of variable heat flux and velocity (enthalpy) with time, has been evaluated for many vehicles and materials and is found always to result in a factor between 1.0 and 1.5. Representative average values, for the various materials, have therefore been used.

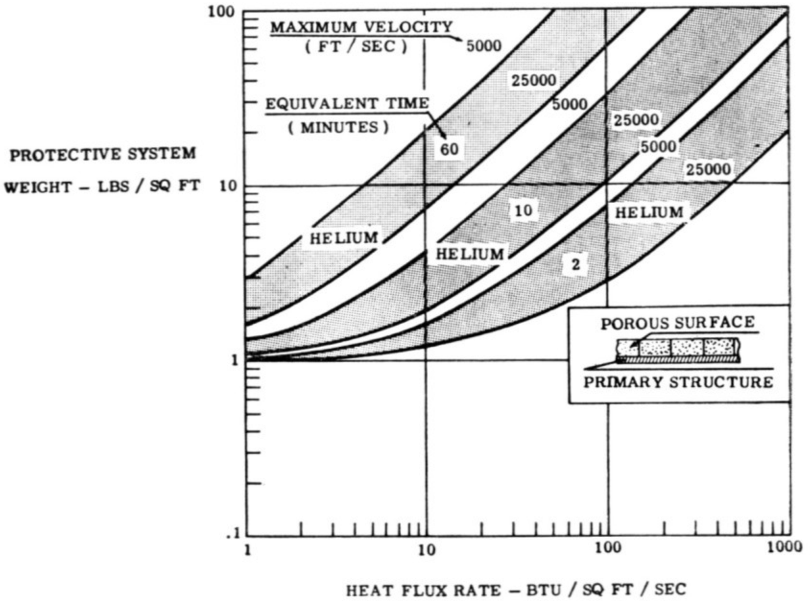

FIG. 4. Performance of transpiration cooling systems.

The figure is an envelope curve in which only the lightest weight system, for any heat flux and equivalent time, is included, and again the weights include additional insulation and cooling for the aluminum structure, when necessary.

Depending on the material, some ablative systems have a minimum heat flux value below which they will not operate properly. At low heat fluxes the heat can penetrate into the body of the material and soften and melt it before the surface layers have vaporized, so that material is lost in bulk and its heat capacity is not realized. This limitation has been

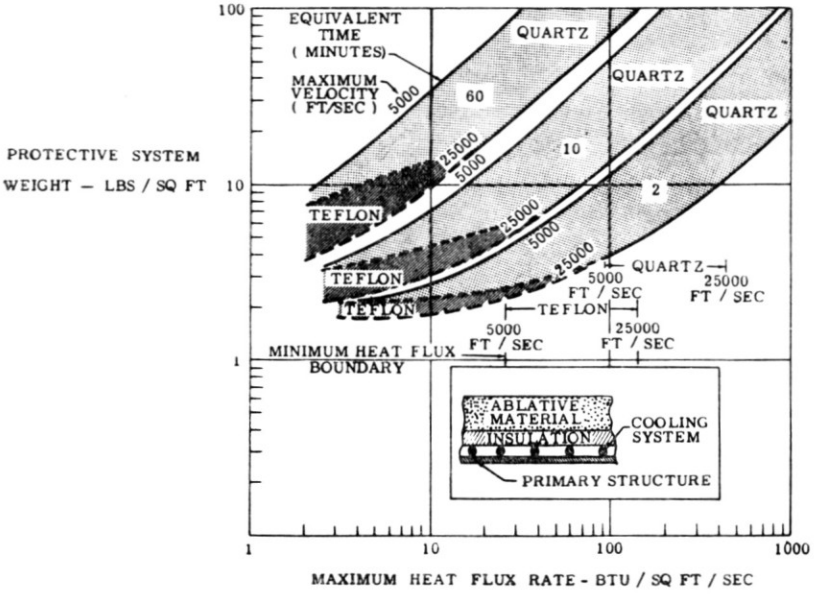

FIG. 5. Performance of ablation systems.

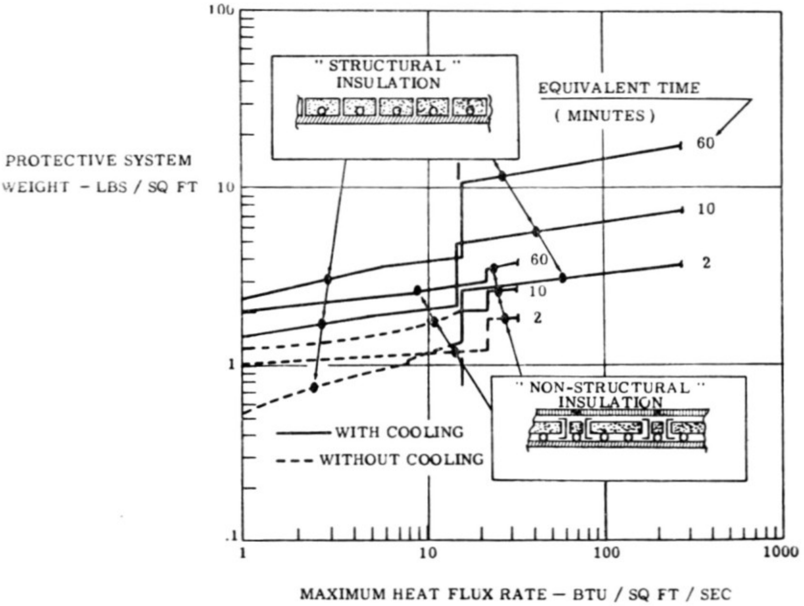

FIG. 6. Performance of radiative systems.

included approximately in the present study, by setting up an arbitrary limit to the thickness of the layer of material which is permitted to exceed the softening temperature.

Figure 6 shows weight data for the two types of radiative system, and, since radiative systems are quite limited in flux capability such limitations are shown on these curves. Material changes, usually at a cost in weight, and which are necessary to obtain greater temperature, and therefore heat flux capabilities, account for the abrupt jumps in the curves. The "structural" insulation is based on the use of porous ceramics with a hard surface layer of dense zirconium oxide.

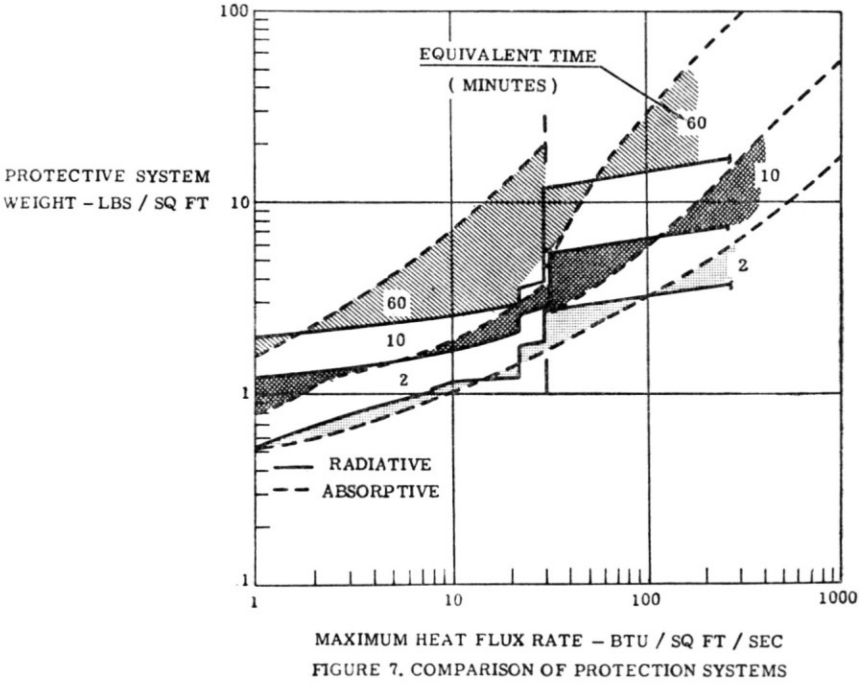

FIG. 7. Comparison of protection systems.

The non-structural insulation is based on the use of powdered insulation, since significant reductions in conductivity can be produced in material of very small particle size, when the vehicle experiences the low pressures of extreme altitudes. The powder is contained in metal foil packages, similar to those used around jet engine tail pipes. These packages are surrounded, in turn, by the outside shell of small metal panels which form the vehicle contour and protect the insulation from the air stream. These panels are necessarily of temperature resistant material and it is principally this material which imposes the heat flux limit of the system. Superalloys are used to 2200°F and refractory metals to 2500°F. Here again water cooling is applied to the aluminum structure beneath the insulation, where the flight time is long enough that this arrangement gives minimum weight.

Figure 7 is the result of superimposing all of the previous curves to show the minimum weight protection system for any combination of maximum heat flux and equivalent time. The picture is too complex to show all of the data in detail, and therefore the figure shows only how the best absorptive systems compare with the best radiative systems.

From this figure a number of interesting features are apparent. At 2 minutes, for instance, both radiative and absorptive systems are comparable to a heat flux of 300 BTU/ft^{2}sec, after which only absorptive systems may be used. Convective, transpirative and ablative cooling are all comparable in weight provided that the vehicle velocity is very high, but at low velocities convective cooling is decidedly superior. Either hydrogen or lithium cooling is required, however, and both represent extensive, though feasable, developments. There is, therefore, promise even for these short times, and particularly for lower velocity vehicles in extending the temperature capability of "non-structural" insulation systems. The chief requirement here is an external surface panel structure of 3000°–4000°F capability implying probably graphitic or oxide materials.

Also of interest is the fact that direct cooling of the aluminum structure with water, with no other protective device, is a very promising and very simple system for low heat flux conditions; say below 10 BTU/ft^{2}sec.

Notice that the heat sinks do not come into the picture, on a weight basis, although their simplicity and reliability continues to make them attractive for short time applications.

At 10 minutes the comparisons are essentially similar, but numerically the differences are more important. For instance, the "structural" insulation is very heavy over the range of heat fluxes from 30 to 300 BTU/ft^{2}sec, so that higher temperature capability in "non-structural" insulation is badly needed. The weight cost for using ablation or transpiration, rather than convection, at low velocities is enormous, 30–40 1b/ft^2, so that the development of the more efficient convective cooling systems for this application, is an urgent requirement.

At 60 minutes the radiative systems have a large numerical weight advantage except for the heat flux range from 30 to 70 BTU/ft^{2}sec. Here again is an important requirement for higher temperature "non-structural" insulation. Where the absorptive systems must be used, say above a heat flux of about 200 BTU/ft^{2}sec, the more efficient convective systems have large weight advantages over transpiration and ablative systems.

4. PROTECTION SYSTEM DEVELOPMENT REQUIREMENTS

From the previous analysis, the following conclusions can be drawn, regarding the direction in which thermal protection system development should proceed:

1. A most urgent requirement is for the introduction of refractory surface panels, particularly in the non-metallic materials, into the "non-structural" insulative system to increase temperature capability at least to 3000°F and preferably to 4000°F.

2. Because of the difficulties of the development just described, "structural" insulation should also be fully developed, at least to the capability shown on the previous curves. This emphasizes the need to find methods for suitably applying the higher melting point oxides to the vehicle surface, and these must be used in the porous form to obtain sufficiently low conductivities. The oxides are believed necessary to obtain the required oxidation resistance reliably, and this introduces problems of thermal shock resistance and brittleness.

3. Next it should be noted that there is no application for heat sinks on a weight basis; however, these systems are still of interest because of simplicity, reliability and status of development. Thus they have a temporary application in the heat flux range above the developed capability of radiative systems, and below the values where ablation works well, and they should therefore be a short term development.

4. Convective cooling with hydrogen or lithium is desirable to get above a heat flux of 200 BTU/ft^{2}sec, which is probably the ultimate limit of any radiative system, with good weight efficiency at low maximum velocities. These systems are likely to be complex; the materials problems are difficult, and development will probably be slow. This type of system is particularly interesting for small, intensely heated areas of vehicles of long flight time where it is superior to ablation because of the lack of large dimensional changes. It is also adaptable to low heat fluxes which may be present over portions of the flight of a long range vehicle, whereas ablative materials will simply be destroyed.

5. Transpiration cooling with helium is also a desirable development to achieve higher weight efficiencies above a heat flux of 200 BTU/ft^{2}sec, but at high velocities. For use with an aluminum structure the surface temperature can be limited to 200°F and hence avoid any other insulation or supplemental cooling requirements.

Development work on transpiration cooling seems to have been neglected in recent years, probably due to difficulties with blocking of surface pores due to contaminated cooling liquids, and also due to the difficulty of achieving vaporization of liquid, with the consequent large volume change, within the thickness of the porous surface material. It would seem that both of these problems are overcome by using a gas coolant such as helium.

There is still, however, the important problem of controlling coolant distribution to match heat flux variation over the surface and during the flight. In this respect the curves are optimistic since they assume a perfect coolant distribution which, in fact, is achieved automatically with ablation.

6. With respect to ablation there is the obvious need to increase the effective heat capacity as much as possible by proper selection and combination of materials. The sublimation of graphite is frequently discussed as the ultimate solution, but this solution is probably suitable only for very limited areas of the low drag, ballistic nose cones. For all other applications the graphite would act as a radiation shield, because of its very high sublimation temperature. It would not even be a very good radiation shield because of the oxidation problem, and the present difficulty of finding reliable oxidation resistant coatings for temperatures above 3000° F or heat fluxes above 60 BTU/ft^{2}sec.

Another promising line of development for ablation materials, and one which has been given only a little attention so far, is to seek materials with low ablation temperatures, preferably as low as 250° F for use with aluminum. This approach does not take advantage of heat loss by radiation from the surface, but it avoids the need for supplemental insulation and cooling of an aluminum structure. It would therefore be of interest for longer flight times, say up to 10 minutes, if good effective heat capacities can be achieved.

7. Finally, there is the need to consider direct water cooling of the aluminum structure, for low heat fluxes and short times. This is a very simple system which offers an interesting low cost alternate to the titanium or brazed stainless steel hot structure which is usually specified for such conditions.

REFERENCE

1. ROBERTS, L., Mass Transfer Cooling Near the Stagnation Point. NASA Technical Report R-8, 1959.

DISCUSSION

N. J. HOFF: Mr. Dukes presented information on protective systems from the standpoint of the engineer who has to make use of all the advanced knowledge available at the present time in the design of vehicles that will be in the drafting board stage very soon. For this reason he had to use material presently available and rule out hypothetical ones that may be developed in the future. It seems to me that the greatest advance in structural design will result from the improvements in materials which our friends in metallurgy and the physics of the solid state are going to bring about. These improvements are likely to extend the usefulness of the radiation shield solution of the aerodynamic heating problem.

As a structural engineer of long standing I am very fond of structures which do not require complex mechanical systems for their proper functioning. For this reason I find cooling by radiation very attractive. Mechanical engineers may feel differently; according to another speaker, they are, for instance, in favour of variable sweep wings. This goes to show that personal preferences should be excluded from the selection of the system to be used in a new vehicle. The selection should be based on an objective evaluation of the efficiencies of the various possible solutions of the design problem, just as Mr. Dukes has done in his paper.

W. H. DUKES: I too would like to use only non-active airframe structures but I do not believe that we can wait for major improvements in materials since experience has shown that these take long periods of time. We must, therefore, take an objective view and at least evaluate also mechanical or active systems as an integral part of our airframes. Present day aircraft rely heavily upon mechanical and electrical systems, and this will be even more true for the applications that I have in mind. Furthermore, we have accepted ablation systems where the structure is literally vaporizing as it operates, and oxidizing or burning structural elements are also being studied. With the long available background in mechanical design it seems to me that mechanical systems are actually less adventurous than the two concepts just mentioned.

D. J. JOHNS: The writer would like to confirm the existence of the difficulties mentioned with transpiration cooling 4(5) and would like to ask whether there would be any significant change in the relative merits of the various protection systems at higher primary structure temperatures e.g. if steel were used. It would then be possible to have a porous primary structure rather than the composite porous surface/primary structure considered in the paper (Fig. 4).

W. H. DUKES: The combination of load carrying structures of materials other than aluminum and operating at temperatures other than 250°F in conjunction with various protection systems is, of course, another series of trade-off studies which were not attempted in the present paper. With specific reference to transpiration cooling, I believe it will be more advantageous to continue with an aluminum structure and make the surface porous and cooled directly by transpiration. This is because with transpiration cooling the efficiency is principally dependent upon the final temperautre of the transpired gas and this depends more on the boundary layer temperatures and the degree of diffusion of the gas into the boundary layer than it does on the surface temperature. The only loss by using a lower surface temperature is heat dissipation by radiation. The heat that can be dissipated by radiation for the steel structure is negligible compared with the total heat flux that must exist to justify transpiration cooling. Therefore, I think that the penalty paid for a steel structure would be much greater.