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PROBLEMS RELATING TO THE NEED FOR HEAT
TOLERANT MATERIALS IN AERODYNAMIC APPLICATIONS

by

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HEAT TOLERANT METALS

FOR AERODYNAMIC APPLICATIONS

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PROBLEMS RELATING TO THE NEED FOR HEAT-TOLERANT
MATERIALS IN AERODYNAMIC APPLICATIONS

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ABSTRACT

The need for heat-tolerant materials in aerodynamic applications is discussed on the basis of the temperatures attainable in high-speed flight, the effects of these temperatures upon structural materials, and the problems encountered by the airframe designer as a result of the changes in these structural properties.

INTRODUCTION

Man's inherent desire to provide for himself locomotion at speeds and in environments other than he is basically capable of obtaining with only his own muscular power has consistently provided for him a wealth of problems. Conquest of the air has given him the capability of motion at speeds in excess of those obtained in any other environment, but not without obstacles that must have seemed, initially at least, nearly insurmountable. Within the past 20 years, two major impediments to increasing flight speeds have been encountered. The first was the existence of a large drag rise as flight Mach numbers of unity were approached. As flight speeds approached this magical Mach number, the rate of drag increase was so large that some felt that a Mach number of one would never be exceeded. Thus, the term "sonic barrier" was applied to the phenomenon. In retrospect, the problem posed by the sonic barrier was not so formidable as it may have seemed when first observed.

Once the sonic barrier was broached and flight speeds increased, another phenomenon of flight at high speeds became apparent. This phenomenon manifests itself as an increase in the temperature of structures flying at these velocities and has been tagged with the rather appropriate nom-de-plume, "thermal thicket". As with the "sonic barrier", the "thermal thicket" appears rather formidable, and much effort will be expended on methods to allow man to penetrate further into the thicket. The thermal problems of flight have existed, at least in the minds of man, for a considerable time. Greek mythology tells of one early flight by two humans, Icarus and Daedalus, which ended in disaster when the younger of the pair, heedless of his father's warning, flew too near the sun. This imprudent venture resulted in the melting of wax used to apply feathers to the wings, and a subsequent fatal drop into the ocean. More recently, the 5th Volta Congress convening a score of years ago, considered the problems expected to become associated with high-speed flight. That august group of conferees was more concerned with the low ambient temperatures encountered at high altitudes, however, than it was with the thermal thicket as we know it today.

The thermal problems associated with high-speed flight are many and varied. They affect the design of aircraft, missiles, power plants and the experimental tools of the trade. Let us consider, then, the thermal problems associated with high-speed flight, first by examining the thermal phenomenon, and secondly by discussing how high temperatures influence the design of aerodynamic structures.

THE PHENOMENON OF AERODYNAMIC HEATING

The flow of air under conditions where pressures or temperatures are not extreme is well behaved and well predicted by developed theory. One of these theories states that the total energy of a particle of air flowing in a stream wherein there is no work done nor heat added from an outside source is a constant. The energy of this air particle is composed of kinetic energy due to directed (as opposed to random) motion and intrinsic or potential energy due to the temperature of the particle. This theorem may be simply stated algebraically as:

$$C_P T + \frac{U^2}{2} = C_P T_0 \quad (1)$$

where

C_P = Specific heat at constant pressure

T = Temperature of particle having a velocity U

U = Directed velocity of particle

T_0 = Temperature of particle if its velocity is slowed to zero

If the particle velocity is re-expressed in terms of its Mach number, M ,

where

$$M = \frac{U}{a} \quad (2)$$

a = The velocity of sound corresponding to the temperature T

and the ratio of specific heats for air is taken as 1.4, then the energy equation may be rewritten as

$$T_0 = T (1 + 0.2M^2) \quad (3)$$

Eq. 3 may also be used to ascertain the effect of changes in Mach number on the particle temperature. Thus,

$$\frac{T_2}{T_1} = \frac{1 + 0.2M_1^2}{1 + 0.2M_2^2} \quad (4)$$

from which it may be seen that the particle has a high temperature if its velocity is small and a low temperature when its velocity is large. The maximum air temperature is attained at points of zero velocity. (It should be noted that Eq. 4 reduces to Eq. 3 if either velocity decays to zero,)

A body immersed in a flow of air creates a disturbance to the air flow such that the velocity of the air in the vicinity of the body varies from zero to values larger than the free-stream velocity. The temperature of the air, if it is nonviscous and nonheat-conducting, will vary with the velocity according to Eqs. 3 and 4. Thus, the velocity of the air will be zero at positions near both the leading and the trailing edge of the body,

and the velocity will be a maximum near the thickest region of the body. From Eq. 4 it appears that the air will be hottest near the front and rear, and the coolest near the thickest portion of the body. If the Mach number of the air stream is large, the air temperature at the points where the velocity is small will be large, and vice versa. Since the temperature of the air at the zero velocity, or stagnation points is a function of the free-stream Mach number squared, the stagnation temperature is seen to increase rapidly with the flight Mach number. These stagnation temperatures are illustrated in Fig. 1 for flights in the lower stratosphere where the ambient air temperature is -67°F . At a Mach number of 10, the stagnation temperature is sufficiently large to vaporize diamonds.

Air is, of course, both viscous and heat-conducting and the simplified description of the flow of air over a body outlined above is not realized. The viscosity of the air creates a thin region about a body in which the relative velocity between the air and the body rapidly increases from a value of zero at the body boundary to a value nearly that which it would have obtained had the flow been inviscous. This thin layer of air near the body in which the flow is affected by viscosity is known as the boundary layer. Except for heat conduction of the air and the work done by shearing stresses due to viscosity and the difference of air velocity in adjacent strata in the boundary layer, the temperature of the air within this layer would vary with the velocity as expressed by Eq. 4. Thus, the temperature of the air next to the body would be equal to the stagnation temperature. The heat conduction of the air modifies this hypothesis, however, since heat will be conducted from the hot regions to the cooler ones. If the boundary is insulated so that it conducts no heat to or from the air, the actual temperature of the air at the boundary will be somewhat less than the stagnation temperature. This temperature of the air at the insulated boundary is known as the adiabatic wall temperature, and may be simply expressed as

$$T_{aw} = T (1 + 0.2 r M^2) \quad (5)$$

where

T_{aw} = Adiabatic wall temperature

r = Recovery factor

A typical variation of temperature within the boundary layer for an "actual" flow of air is depicted in Fig. 2, where the effects of the heat conduction and viscosity of the gas within the boundary layer are easily seen.

The recovery factor appearing in Eq. 5 is a means for accounting for the difference between the "ideal" stagnation temperature that might be expected at the inside of the boundary layer on the basis of Eq. 3, and that which actually occurs assuming an insulated boundary. The value of the recovery factor is generally less than unity and is dependent upon the type of boundary layer that exists. If the flow of air within the boundary layer is steady and smooth, the boundary layer is called laminar. If, however, the flow within the boundary layer is unsteady and rough, the boundary layer is turbulent. The recovery factor varies from a value of about 0.85 for a laminar boundary layer to a value of nearly 0.90 for a turbulent boundary layer. Thus it is seen that, all other things being equal, the temperature of the air at the air-body interface is larger for a turbulent boundary layer than for the laminar boundary layer.

No true boundary in an aerodynamic configuration is perfectly insulated and in general, heat will flow from the air to the body or vice versa. The temperature achieved by the body is a function not only of the temperature of the air at the surface of the body, but also of the rate at which heat is transferred between the body and the air, the heat

MAXIMUM TEMPERATURE ATTAINABLE IN SUSTAINED FLIGHT IN
THE LOWER STRATOSPHERE

Fig. I

DISTRIBUTION OF STATIC AND TOTAL TEMPERATURE NEAR
AN INSULATED BOUNDARY

Fig. 2

capacity and conduction of the body structure, and radiation between the body and its surroundings. Neglecting for the moment the effects of radiation, the rate at which heat is conducted between the body and the air can be simply, and aptly, described by Newton's law of cooling. In algebraic form this may be written as

$$q = h (T_{aw} - T_w) \quad (6)$$

where

q = Rate of heat transfer

h = Heat transfer coefficient

T_w = Temperature of the body surface

It can be seen from this expression that heat transfer between the body and air ceases when the temperature of the body surface becomes equal to the adiabatic wall temperature, as might have been expected.

The rate of heat transfer is seen from Eq. 6 to be a function of the temperature differential between the adiabatic wall temperature and the body surface temperature, and the heat transfer coefficient. The heat transfer coefficient is a function of many variables, including density. As density increases, so does the heat transfer coefficient so that the heat transfer coefficient will vary with altitude. Because of this effect the rate of heat transfer will decrease with altitude, all other things being equal. The value of the heat transfer coefficient is also a sensitive function of the condition of the boundary layer. It may be an order of magnitude larger for a turbulent boundary layer than for a laminar one, and the condition of the boundary layer may well define whether a particular configuration may be operated for more than very brief periods at high Mach numbers. Because of the sensitivity of the heat transfer coefficient to boundary layer condition, extraordinary steps to insure preservation of a laminar boundary layer may be justified. Since very smooth surfaces promote the existence of a laminar layer, surface finishes on bodies immersed in high Mach number flows may be expected to have a surface of extreme smoothness.

To illustrate the rate at which heat may be conducted from the air to the body surface, Fig. 3 has been prepared. This figure shows the maximum heating rate to be expected for a fully developed turbulent boundary layer and for body surface temperatures equal to the ambient air temperatures. The rather tremendous heat potential available is well illustrated by this plot.

Although the heat flux expressed by Eq. 6 is the basic source of large temperatures within aircraft structures, heat may be added to the structure from internal components such as the propulsion system and electronic equipment. The structure may also radiate to its environment and/or receive radiation from its surroundings. Typical heat transfer rates due to body radiation and solar irradiation are shown in Fig. 4. As indicated by this figure, radiation of the body to its environment proceeds at low heat transfer rates unless the structure temperatures are large, and solar irradiation is small at the lower altitudes. On the other hand, sustained operation of a typical contemporary fighter-type aircraft with a full complement of electronic gear may raise the temperature of the airframe 20-40°F due to the heat generated by the electronic equipment and the power plant.

The considerations of the previous paragraphs serve to indicate the tremendous heat potential existing about a body immersed in a high-speed flow of air. As a further example of this heat potential, if a ballistic missile re-enters the atmosphere at a Mach number of about 20, it has sufficient potential energy which, if it were converted to heat,

MAXIMUM HEATING RATE AS A FUNCTION OF ALTITUDE
AND MACH NUMBER

Fig. 3

RADIATION EFFECTS ON BODY HEATING

Fig. 4

would be sufficient to vaporize the missile some 20 times over. Although manned aircraft will not be expected to fly at these extreme Mach numbers in the very near future, contemporary designs for manned aircraft might well be expected to operate at Mach numbers approaching 4.0 in the next several years. As an illustration of the heating problem for such an aircraft, the adiabatic wall temperature for a hypothetical Mach 3.5 fighter-type aircraft operating at moderate altitudes is presented in Fig. 5. Since the heat transfer coefficient decreases with decreasing air density, the hypothetical fighter could remain cooler by flying at higher altitudes. At higher altitudes, the heat transfer rates become so small that even small radiation rates from the aircraft can maintain low-equilibrium body temperatures. At extreme altitudes, the solar (or nocturnal) and body radiation determine the body temperature.

DESIGN PROBLEMS GENERATED BY AERODYNAMIC HEATING

To the designer of aeronautical equipment such as airframes, propulsion units, experimental tools of the trade, and miscellaneous components, the tremendous heat potential supplied by high Mach number airflow creates a series of problems. The magnitude of the thermal design problems encountered by the designer is a function of the n-dimensional time dependent environment in which the design must operate. The magnitude of the problem is also a function of the primary purpose of the configuration, e.g., whether it is to be used as a one-shot device, such as a missile, or an aircraft designed for repeated missions. It is also a function of whether the device will be manned or automatically operated. Each of these possibilities will, in general, create entirely different design requirements. To attempt a complete discussion of all the design problems engendered by the large heat potential is beyond the scope of this discussion. As a result, this discussion shall be primarily limited to the general effects upon the design of aircraft structures, although certain of the comments may also be applicable to other components.

It is perhaps unfortunate, but true nevertheless, that the component most susceptible to the temperature effects of high-speed flight is the crew member who flies in a manned aircraft. The earliest temperature problems encountered in airframe design arose because human beings were required inside the airframe. This human had, first of all, to be kept comfortable, and although almost any aircraft structure will withstand temperatures of the order of 150°F, man cannot operate efficiently in an environment this warm. Even at low supersonic Mach numbers a cooling system must be provided for crew comfort, and at flight Mach numbers of 3.5 to 5, the power required to keep the crew cool may approach that required to propel the aircraft itself. Other early encounters with the thermal thickets by the designer concerned the problem of keeping the rubber tires and transparent windshield materials cool.

Although these types of problems are interesting and are still current, the primary purpose here is to discuss the design problems arising from the aerodynamic heating of the primary airframe structure. Thus, the effects of heat upon structural properties shall be allied with the resultant problems faced by the designer.

Elongation

Whenever a material is heated, measurable changes of volume occur. In an airframe, these changes of volume of the materials used in the structure will change its shape, and because of differential expansions of the structure due to nonuniform or nonsteady heating or differences in the composition of the materials, thermal stresses will exist. The implication here is that the thermal stresses resulting from the relative elongation of various parts of the structure may add to the stresses resulting from the

ADIABATIC WALL TEMPERATURE FOR HYPOTHETICAL MACH
3.5 FIGHTER MISSION

Fig. 5

aerodynamic load upon the airframe. It is conceivable, of course, that the stress addition, if not properly anticipated, could cause failure of the structure.

Of additional importance is the structural deformation due to these thermal stresses induced by differential expansion. A modern, high-speed wind tunnel is a piece of precision work, and the contour of the nozzle preceding the test section must be maintained to rather close tolerances if the tunnel flow characteristics are to meet design requirements. Small deformations in the nozzle contour due to thermal stresses may well make a useless facility of a rather expensive piece of equipment.

For reasons of a similar nature, deformations of the "ideal" surface contour of an airframe are not desirable. Consider, as an example, a thin, diamond-profile wing section typical of those considered useful for supersonic flight. This airfoil is shown in Fig. 6. If the airfoil is operating at the angle of attack indicated in the figure, the aerodynamic load tends to cause the thin leading and trailing edge of the airfoil to curl up slightly. At the same time, because of differences in recovery factor and heat transfer coefficients, the windward (or under) side of the airfoil is at a higher temperature than the leeward (or upper) side. Differential expansion due to the nonuniform temperature distribution causes further curling, since the warmer under side elongates more than the cooler upper. Although the deformations illustrated in the figure are exaggerated, the "ideal", rigid-structure shape of the airfoil is destroyed, and the deformed shape is less efficient in producing lift and at the same time results in a larger drag. The net result is a loss in aerodynamic performance.

In a built up structure, the differential, thermally induced elongations may result in a buckling of the surface. Since it is highly desirable to maintain a smooth surface to preserve the lowest obtainable heat transfer coefficients, any buckling is undesirable. Conceivably, buckling could result in an increase in the heat transfer rate to the surface, both in the vicinity and downstream of the buckled area, with possible catastrophic results.

Buckling of the surface also results in a reduction of stiffness in the area where buckling occurs. With the loss of stiffness, aerodynamic loads cause larger over-all structural deflections, and a loss of performance which shall be discussed more fully in a section to follow.

Reduction of Strength

Reduction of the yield and ultimate strength of materials in a high-temperature environment has led the airframe designer to search for those materials which retain their strength characteristics at high temperatures. The reduction of strength properties manifests itself in an increase of take-off weight and a structure which may be well overdesigned for the greater portion of its mission.

Contemporary high-speed aircraft are usually required, because of the high rate of fuel consumption typical of flight speeds in excess of Mach 1, to restrict the time at which they operate at maximum speed. Consequently, an attack-type aircraft capable of speeds of Mach 3, say, might cruise out to the target area at a much lower velocity in order to conserve fuel. In the vicinity of the target, the extra power available is released and the aircraft makes its high-speed run and accomplishes its mission. Because the structural temperature is greatest during the high-speed portion of the mission, the designer may find that his critical design condition exists during this phase of the mission and he then designs the airplane for this condition. For the longer, low-speed portion of the mission, the airplane is overdesigned and overweight. If, on the other hand, the airplane is designed for the lower-speed, lengthier portion of the mission, the time to be spent at the maximum speed may become so severely limited that the mission of the aircraft cannot be accomplished.

- SHAPE WITH NO LOAD
- - - SHAPE DUE TO AERODYNAMIC LOAD ONLY
- - - SHAPE DUE TO AERODYNAMIC AND THERMALLY
INDUCED DEFLECTION

EFFECT OF AIR LOAD AND THERMAL STRESS ON
SHAPE OF DIAMOND WEDGE AIRFOIL

Fig. 6

The basic consideration of the above conundrum is the weight of the aircraft. During the preliminary design phase, one pound of weight added to the aircraft will result in a total weight increase of the aircraft to at least an order of magnitude larger than the added weight. This weight penalty is a result of a cyclic process whereby one pound of weight added requires an additional increment of fuel to maintain the mission requirements, which results in an added increment of weight for fuel tank, which requires an added increment of wing area, which requires more weight, more structure, more fuel, etc. For a manned, lunar rocket, this weight penalty may be another order of magnitude larger. An overstrength airframe, therefore, is one which is much more massive than would be required if this growth-factor weight penalty did not exist.

The loss of strength properties at elevated temperatures is not the only concern of the designer. Some alloys regain their strength characteristics when the temperature is reduced after being heated, while others do not. Imagine the plight of the designer of the high-speed attack airplane should he unwittingly construct the airplane of one of the latter type alloys: the aircraft completes the mission without a hitch but upon landing, the large loads imposed cause wings and fuselage to take separate paths down the runway.

Recent experimental evidence indicates that the fatigue strength of a material is reduced in a high-temperature environment. Thus, the operational life of a high Mach number airframe may be reduced while the cost per flight, or required number of an aircraft type, are increased. Since most aircraft will operate in a time-temperature spectrum, the coexistent design problem of predicting the expected life of a structure becomes very complicated.

Reduction of Young's Modulus

The reduction of the modulus of elasticity with increasing temperature is a source of major concern to the designer. The primary result of a decrease in modulus of elasticity is a reduction of the stiffness or rigidity of a structure and an increase of deflection under load. As long as structural deflections are small, they are of little concern to the designer, but when they become large they significantly affect his design procedure and the ultimate performance of the design. Because the aerodynamic loads upon an airplane are a function of the orientation of the airframe with respect to the airstream, gross structural deflections under this load cause a change in the aerodynamic loading. This coupling of elastic and aerodynamic phenomena has become almost a science unto itself and is even named--aeroelasticity.

It has been mentioned previously that it is highly desirable to maintain the ideal geometry of a rigid aircraft structure. Structural deflections tend to alter the geometry of the airframe and the results are generally undesirable. More specifically, structural deformations under aerodynamic loads usually result in loss of lift, increase of drag, reduction of control effectiveness, and loss of stability; all of which can be encompassed in the phrase: "Loss of aircraft effectiveness". The timewise dependent nature of structural temperatures and the change of modulus of elasticity with these changes of temperature makes the aircraft perform differently according to its aerodynamic load and temperature history. Thus, the flying qualities of an aircraft at any given set of conditions may be dependent upon the environment in which it operated before achieving the specified condition, since its time history will have defined the structural temperature and current rigidity. As a net result, two aircraft, otherwise identical, may exhibit quite different flying qualities after a month of operation.

In contemporary, high-speed airframes, reduction of rigidity as a result of an increase in elasticity is a very real problem. Since the really high-speed airframes are basically designed for military purposes, these aircraft must be maneuverable throughout the flight spectrum. One requisite of maneuverability is the preservation of

rolling rate. Unfortunately, aileron control surface deflection, normally used to induce roll, also creates a moment on the wing surface which twists the wing to relieve the effect of aileron deflection and results in a reduced roll rate. As the aircraft velocity is increased at any given altitude, this aeroelastic wing twist due to aileron deflection increases and causes further reduction in the roll rate. This is directly opposite to the increase in roll rate with velocity that would be obtained on rigid wing. The velocity at which the aileron loses its power to produce roll is called the aileron reversal speed, and it is desired to keep this velocity as large as possible. Any reduction in rigidity will, of course, reduce the reversal speed. At velocities in excess of the reversal speed, the structural deformations cause control reversal, and result in an extra burden on an already overburdened pilot.

Flutter is another phenomenon which is a sensitive function of the rigidity of the airframe. Flutter is a result of coupling between the natural frequencies of a structure and the lag in development of aerodynamic forces when the attitude angle of the structure with respect to the airstream is changing. In severe cases, flutter leads to a periodic structural motion in which the amplitude diverges to a point at which the structure fails. Since, for a given geometry, the possibility of flutter usually increases with increasing flight velocity and reducing modulus of elasticity, the designer attempts to build a rigid, stiff airframe. Economical operation of an airframe at high speed requires a thin structure, particularly for the wing, and thin structures are not the most rigid. Consequently, any increase of elasticity of these thin structures due to increasing temperatures of the structure increases the probability that the structure will flutter. Flutter can occur not only in major structural components such as the wings, fuselage, and control surfaces, but also in the small surface panels of a built-up structure. Even if the flutter is not divergent, the repeated stress cycling during flutter may cause fatigue failure.

Creep and Inelasticity

The phenomena of creep and inelasticity arising from operation of an airframe at large temperatures complicates the structural analysis and requires more adroit application of the slide rule than ever before. The designer is now faced with stress-strain relationships which are nonlinear, and nonrepeatable if the structure is temperature-cycled. The designer is further haunted by the specter of airframes whose geometry changes as it "ages" due to the permanent elongations resulting from creep. Permanent elongation due to creep may define, for certain types of aircraft at least, the total useful life of the aircraft and thus replace the fatigue-based life. Since creep is essentially additive, repetitive flights at high Mach numbers will result in continued deformation of the structure. Conceivably, the deformation may reach a value so large that the aircraft is no longer aerodynamically satisfactory even though the structure itself is still reasonably sound. It may be expected that aircraft logs in the future will require an accounting of not only the aircraft flight time, but the time-temperature history of the aircraft.

Since creep introduces permanent deformations, and not all portions of the structure will be subjected to the same temperature-load-time environment, residual stresses will be present in the structure when it cools. These residual stresses may in time reach large magnitude and be destructively additive to the stresses imposed by aerodynamic loading.

Corrosion, Erosion, Melting

These results of high temperatures and high-speed flow of air over hot surfaces are deleterious, not only because they may remove needed structural material from the airframe, but also because of the surface and gross structural deformations they may produce. By themselves, these processes may account for locally weak sections in the structure. The more important consideration, however, is the effect these phenomena may have upon the aerodynamic characteristics of the shape.

Consider, as an example, a rotationally symmetric ballistic missile. Due to aerodynamic heating and a small trim angle of attack, portions on the windward side of the missile are most likely to melt, since the heating rate and recovery factor are larger for this region. If melting takes place, the vehicle configuration becomes changed and the missile will assume a new trim angle of attack. This change in angle of attack will produce a change in the aerodynamic forces acting upon the missile, and the missile may then follow a trajectory different from the one it would have followed had not the melting begun. The actual flow of the melted matter and possible flow and resolidification on downstream sections of the body are difficult to predict. The net result may be a rather random dispersion of the missile about the desired impact point.

In order to prevent melting, the designer of the airframe structure may be required to change the structure geometry from the ideal shape based upon aerodynamic requirements. For example, a wing profile for high-speed flight should be sharp and thin at the leading edge to minimize drag. Since the leading edge of the wing is in a region where a large recovery factor and heat transfer rate exist, it tends to become hot, and heats very quickly because of its thinness. Again, because it is a thin region, heat is conducted away from the leading edge slowly. To reduce the heating problem at this thin section, the designer may have to blunt, or thicken the leading edge and take the aerodynamic penalty resulting from this action.

Corrosion, erosion and melting may also have a large effect upon the recovery factor and heat transfer rate. As noted previously, it is desirable to maintain a very smooth surface in order to preserve, if possible, a laminar boundary layer since the recovery factor and heat transfer rates are then minimized. Corrosion, erosion, or melting destroys the smooth surface and may increase the temperature of the structure as the heating rate subsequently increases. Even a small area which has a small blemish in the surface can "trip" the boundary layer and cause transition from a laminar to turbulent boundary layer in a region downstream of the blemish. Because even small surface blemishes are a problem in this respect, small pits, or bits of matter deposited on the surface as a result of impact with bugs, sand, small pebbles, mud, etc. may cause local "hot" regions to exist and increase the probability of failure in these regions.

Pits are also responsible for another phenomenon arising from the high-speed flow of air. It has been shown experimentally that if one directs a cool stream of air from a tube or nozzle into a small depression drilled in a piece of wood, the bottom of the depression becomes hot enough to char the wood and cause the depression to deepen. The material temperatures experienced in the depression were much larger than one would expect from considerations of normal heat transfer experienced in the flow of air over a surface. It is felt by some that this observed phenomenon is responsible for the rather deep holes and pock-marked appearance of some meteors. If this phenomenon is experienced in high-speed flight, the resulting problems are quite obvious.

SOLUTIONS TO THE DESIGN PROBLEMS

The solutions to the design problems resulting from aerodynamic heating are not difficult to propose--attainment of these solutions is not so simple. From the designer's viewpoint, materials are needed whose physical and structural properties are invariant of temperature, i. e., he wishes his design analysis to be as simple as possible. He requires also large values of strength to weight and modulus of elasticity to weight ratios for the structural materials he uses. These materials must be easy to shape and finish to a high surface quality. Lacking materials with an ideal invariance of physical and structural properties with temperatures, he seeks materials whose properties are least affected by high temperatures. In any case, he requires accurate and complete data on the behavior of these materials at high temperatures and under various loading rates.

Lacking materials which will not withstand a high-temperature environment, use may be made of methods which isolate the structure from the high temperatures. To this end, consideration should be given to methods of insulating primary structural materials from the high temperatures. Insulating matter may be applied to the exterior surfaces, for example, but use of these insulating materials must be tempered by the considerations of weight penalties and preservation of surface smoothness and ease of manufacture. The surface of the structure may be insulated by dynamic rather than static insulation. Transpiration cooling appears very promising, since it reduces the heat transfer rate. To be most effective, it requires a uniformly porous surface through which the coolant can pass. Materials may also be developed which possess nonisotropic heat conduction properties, where the rate of heat transmission through the surface is much lower in one direction than the other. By properly applying a material of this kind, heat may be rapidly conducted from a "hot" spot on the structure to a region where the temperatures are not so large.

Attempting design of materials which are temperature-resistant may not be the best solution to the increasing temperature problems of flight at continually higher speeds. Since the boundary layer is responsible for the thermal problems, consideration should be given to elimination of the boundary layer. This might be accomplished by flight outside the earth's atmosphere. Currently, man is still atmosphere-bound, and other methods might be profitably considered. Causing the structural material on the body surface to move with the air stream at the local stream velocities eliminates the shearing stress between the structural surface and the air stream and eliminates the boundary layer; hence, no heating problem, but maybe a structural one in its place. Recent developments in the field of magneto-hydrodynamics may also allow the thermal and physical characteristics in the boundary layer to be radically altered, although at present this possibility appears to require sizable amounts of electrical energy.

The above solutions are only a partial list of those that could be compiled in answer to the design problems created by high-speed flight. The power-plant designer and the component designer have similar problems for which could be compiled similar lists of remedies. To realize solutions to these problems will require intensive, cooperative effort on the part of the designer and the materials experts. Once these problems have been solved, these scientists can then seek out and explore the next impediment in man's quest for locomotion at higher speeds and further environmental extremes.

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