HYPERSONIC RESEARCH

presented by

Low Density and Heat Transfer Tunnels Branch

10- by 14-Inch Supersonic Wind Tunnel Branch

Supersonic Free-Flight Wind Tunnel Branch

Flight at hypersonic speeds, that is, speeds that are many times the speed of sound, will pose new and severe operational problems; namely, problems involved with guidance and control as well as aerodynamic heating and the associated problem of thermal stress. In view of these rather severe and difficult problems, the question naturally arises as to the advantage to be gained by flying at these tremendous speeds. From the standpoint of military application, a very distinct advantage is the difficulty of intercepting and destroying a very fast moving object, even with one equally as fast. Imagine the analogous problem of shooting to hit a bullet that was fired from another gun. At the speeds that these aircraft may travel (10 - 15,000 miles per hour), it is only a matter of seconds between the time the aircraft could be detected and the time it would reach its destination. Another consideration is that of efficiency, that is, the actual expenditure of fuel (and, consequently, of money) required to carry a given payload a given distance. For distances of 3,000 miles or greater, it appears possible that aircraft may travel at hypersonic speeds with reasonable efficiency. This indicates a possible commercial application for such aircraft, provided they can be made to land safely at their destination. These commercial aspects, however promising, are at the present time somewhat remote.

Having reviewed some of the advantages to be gained by the use of hypersonic aircraft, let us examine the particular types of aircraft that are proposed to fly at these speeds. Two types that are of current interest are the ballistic and glide aircraft. The trajectories of these vehicles are shown in the first chart. Here we show a large segment of the earth's surface and surrounding atmosphere. In order to show the trajectories clearly, the vertical scale has been exaggerated. The true depth of the atmosphere is as indicated at this point.

The flight path of the ballistic vehicle, shown by the upper curve, resembles the trajectory of an artillery shell. This vehicle is brought up to speed in an initial "power phase" which lasts for the first 20 miles or so. The speed at the end of the "power phase," generally in the vicinity of 15,000 miles per hour, is sufficient to carry the vehicle to a height far beyond the atmosphere. It returns to earth under the influence of gravity, entering the atmosphere with about the same speed it had at the end of the powered phase. Atmospheric resistance reduces the speed of the vehicle to about 5,000 miles per hour just before impact at the earth's surface. The vehicle is, of course, expendable. Such a vehicle would not need wings, but might require tail fins, as shown on the chart, to provide some control in the initial and final phases of flight.

The flight path of the glide aircraft is shown by the lower curve. This aircraft is powered to a high altitude, within the atmosphere, and to a speed comparable to that of the ballistic vehicle, about 15,000 miles per hour. At the end of the "power phase" the glide aircraft is oriented in a relatively flat trajectory. It then glides to its destination under the influence of gravity and aerodynamic forces. To achieve long range, the hypersonic glide aircraft would probably have wings in addition to tail-control surfaces. The use of wings suggests the possibility of landing the aircraft at its destination with its consequent use for commercial as well as military purposes.

Long-range, hypersonic vehicles, such as these, may be operated efficiently and are difficult to intercept and destroy. Let us now turn our attention to the problems involved in accomplishing successful flight. Mr. ________ will now discuss these problems.

The previous speaker has pointed out that there are advantages in flying at hypersonic speeds. These advantages, however, cannot be realized without first solving a number of difficult problems relating to guidance and control, power plant efficiency, and aerodynamic heating. The problem of aerodynamic heating appears to be the most difficult of all to solve at the present time. Not only is the air next to the aircraft skin hot enough to melt or even vaporize most metals, but the rate of heat transfer is enormous, that is, the aircraft skin will heat up quickly. For comparison, these rates, depending on flight conditions, can be some 50 to 1000 times greater than those encountered in modern steam boilers.

At supersonic speeds, pointed bodies and wings with sharp leading edges are desirable to minimize drag. At hypersonic speeds, pointed bodies and sharp wing leading edges are still advantageous in reducing drag, but they are undesirable from a heat-transfer viewpoint. Since the pointed shapes have very little material at the tips to absorb the heat transferred into them from the hot boundary layer, they heat up rapidly. The principle involved is one with which you are familiar. If you have ever put a needle into a flame, you have probably noticed that the tip becomes hot first. This characteristic of pointed bodies is clearly demonstrated in a movie we shall see shortly. In the experiment shown, models will be placed in a low-speed stream of hot gas whose temperature corresponds to flight conditions at a Mach number of about 6. First, two bodies such as these will be tested. Both models are similar - except that the one on the bottom has a sharp tip and the one on the top is slightly rounded. The bluntness is slight yet it alters the heat-transfer characteristics of the body at hypersonic speeds.

These bodies are both initially at room temperature. Now the bodies are moved into the hot stream of gas. Note that the tip of the pointed body on the bottom is beginning to glow while the blunt body at the top lags behind in heating. Now, a large area of the nose of the pointed body is incandescent and it can be seen that the blunt body is noticeably cooler.

Sharp-edged wings are also undesirable from a heat-transfer viewpoint. Here you see a body with a sharp leading-edged wing panel on the bottom and a similar but blunt leading-edged wing panel on the top. Now the model is placed in the hot gas stream. Note the tip beginning to heat. Now the sharp wing is beginning to become incandescent near the tip while the blunt wing is still relatively cool.

When a missile flies at hypersonic speeds, the extreme surface temperatures produced by aerodynamic heating may result in destruction of the missile as it passes through the atmosphere due to intense heating and associated loss of material at the missile surface. You have all seen this happen to meteors when they enter the earth's atmosphere and finally burn up and disappear in a shower of sparks.

Research on heating problems associated with hypersonic flight has led to several methods which can be used to alleviate the problem. One of the most promising techniques that can be used to reduce the heat transfer to high-speed missiles is transpiration cooling. This technique is similar to the cooling mechanism used by the human body. In this method, a gas or liquid is forced through a porous skin. The blanketing effect of the gas reduces the amount of heat transferred to the skin from the hot boundary-layer air. If a liquid, such as water, is used, additional cooling is realized from the evaporation of the liquid.

The next chart shows the effectiveness of transpiration cooling. On this chart is shown the temperature of a portion of a wing surface with varying rates of coolant flow for two cooling systems. The first cooling system, which will be referred to as a conventional internal-flow system, is represented by this diagram and consists of cooling fluid circulated under the aircraft skin and discharged overboard. The second cooling system illustrates transpiration cooling and is shown in this diagram. Here, the cooling fluid is passed through the skin. The upper curve shows the temperature that the wing surface will attain if the conventional internal-flow cooling system is used. The lower curve shows the temperature attained by the same wing surface if it is cooled by transpiration.

If we want to keep the wing relatively cool, for example, below the softening point for aluminum, the conventional cooling system requires this coolant flow rate, while the transpiration cooling system requires only this coolant flow rate.

Since the coolant must be carried in the aircraft any reduction in the amount needed to maintain a prescribed surface temperature is an advantage.

We have pointed out that aerodynamic heating is a most important problem at hypersonic speeds. You have been introduced to several of the problems and possible methods of alleviating them that are undergoing study by the NACA at the present time.

The next speaker, Mr.________, will discuss another aspect of the heating problem: Effect of aerodynamic heating on aircraft structure temperatures. Mr.________.

STRUCTURAL AERODYNAMIC HEATING PROBLEMS

A knowledge of the heating of the structures of supersonic airplanes is extremely important if the design is to be efficient from a standpoint of weight and safety. The mathematics involved in the solution of the problem become complex because the structure is usually complicated and because the heating is nonuniform. For example, a thin skin will rise in temperature much faster than a heavy spar which supports it. To speed up the solution of such problems, an electrical analogy is used. To illustrate the use of this analogy, let us look at the next chart. The figure on the left represents a section of skin into which heat is flowing from the hot boundary layer. The inward flow of heat is represented by this arrow on the top. As a result of this inward flow of heat, there will also be an outward flow of heat into adjacent parts of the skin and structure, as represented by these arrows. The electrical equivalent of this problem is represented by the figure on the right. The thermal resistance, in each case, is represented by an electrical resistance. Note that where heat is flowing into the skin, there are two resistances in series. The outer one represents the resistance caused by the thin film of air next to the skin and the inner one is due to the thermal resistance of the metal skin. The ability of the skin to absorb heat is represented by this electrical capacitor. The temperature difference between the skin and the hot boundary layer is simulated by the voltage generated by this battery while the heat flow into the segment is represented by the electrical current flow.

We will next illustrate the importance of studying the transient heating of structures and we will demonstrate the operation of an electrical analog. To illustrate structural heating, we have constructed this model to represent a segment of wing structure consisting of a skin and a bulb-angle stiffener. A heater is mounted on the outer surface of the skin to represent frictional heating from the airstream. Thermocouples for measuring temperature are installed in the skin and in the bulb of the stiffener. The thermocouples are connected through amplifiers to the needles on this dial, the red needle indicating the skin temperature, and the blue needle indicating the bulb temperature. The model is placed in this plastic enclosure to minimize the cooling effects of stray air currents. At the start of heating, the bulb and skin are at the same temperature. As the heater is turned on, you will note that the skin temperature rises rapidly, while the temperature of the bulb hardly changes. At the end of the heating period the thin skin has been heated to about 350° F, while the heavier bulb has reached only about 140° F. This will cause the skin to expand more rapidly than the stiffener, which would result in warpage of this type of wing structure and possible buckling of the skin. Structural temperature differences of this magnitude are characteristic of high-speed aircraft. Even after the heat has been turned off, the bulb temperature continues to rise, illustrating the large thermal lag present in the structure.

We will now demonstrate the operation of an electrical analog. This is an electrical simulation of the thermal circuit of the heat-flow model. This actual circuit is set up on the back of this board. The model is assumed to be divided into several segments. The thermal resistance and capacitance of the model are represented by these resistors and condensers. Current is fed into the circuit at these points to represent the flow of heat into the model. In order to obtain a comparison between the heat-flow model and its electrical analog, voltage is measured at these two points, which correspond to the location of the thermocouples in the skin and the bulb of the stiffener. The voltages are converted into equivalent temperature indications which are now displayed by these needles. When this switch is thrown, current flows into the analog model, and the needles rise in the same manner as for the heat-flow model. Again, note that the skin temperature rises faster than the bulb temperature. The temperatures reach the same values as before, 350° F for the skin and about 140° F for the bulb.

The main advantage of an electrical analog lies in its simplicity and its flexibility. Complex aircraft structures can be simulated by an array of ordinary electrical resistors and condensers. The large temperature differences between the structure and the hot boundary layer can be represented simply by electrical voltages, thus eliminating the need for expensive heating equipment. The combinations of electrical voltage, resistance, and capacity can easily be changed, allowing a great many structures and heating conditions to be studied in a short length of time. Consider, for example, the case of this simple heat-flow model. Although it may appear that this model would be easier to construct than its electrical analog, nevertheless, if we decided to alter, say, the size of the stiffening member in order to investigate the effect of this change on the heating characteristics, we would be forced to construct a second model. On the other hand, a simple change of electrical values in the analog would provide the desired effect. This advantage of the analog is multiplied when a complex structure, such as an entire wing, is being studied.

In order to illustrate a typical practical application of the analog, an analysis was made to determine the temperature distribution over the wing of a supersonic airplane. The conditions assumed for analysis are shown in this next chart. It was assumed that the airplane, flying at 40,000 feet, was accelerated from a Mach number of 0.9 to 3.0 in 3 minutes, after which the speed was held constant. The wing was considered to be flying at an angle of attack of 5°. This figure represents a cross section taken through the wing to show the construction which was that of a supersonic wing 6 feet in chord and 2-1/2 inches thick. The skin was assumed to be titanium 3/16 inch thick. The wing surface temperature distribution was computed on the analog and is shown on this next chart for the upper surface two minutes after the start of acceleration. You can see the severe chordwise variations in temperature occurred at the leading edge where the wing is thin, and where there were large changes in the heating. At this point, a temperature gradient of over 100° F per inch existed. This emphasizes the difficulties associated with sharp leading edges as was shown in the movie we just saw. Temperature differences also occurred at the trailing edge.

As the heating continued, the temperature variations became more pronounced, as shown by this curve. This curve represents the temperature distribution four minutes after the start of acceleration. In the region of transition from laminar to turbulent flow, where the change in heating is high, the change in temperature is very large. The differences in expansion of these areas would tend to cause warpage and perhaps even buckling of the wing.

Another adverse heating condition is indicated by this curve. It represents the temperature distribution for the lower surface four minutes after the start of acceleration. It can be seen that the lower surface is hotter than the upper surface, which would tend to make the wing warp upward. The resulting thermal stresses, of course, are in addition to those imposed by the normal aerodynamic loads.

The severe temperature variations which we have shown are a direct result of the wide variation in heating along the chord of the wing. This emphasizes the need for accurate knowledge of such factors as heat-transfer coefficient and transition location - data which are being supplied by our supersonic wind tunnels, and by flight tests using rocket-powered models. Although the results just shown were for a relatively simple wing, they show the usefulness of an electrical analog in the study of complex heating problems. The analog at Ames is being actively used to investigate the many aerodynamic heating problems confronting airplane and missile designers. Use of the analog, in conjunction with data supplied by our supersonic facilities will permit the structural design of high-speed aircraft to proceed on a rational basis. One of the facilities which is being used to supply quantitative data for the analog is the 10-Inch Heat-Transfer Tunnel, which is here to your right. An unusual feature of this supersonic tunnel is that the air can be heated to a temperature of 1200° F, providing an accurate duplication of flight temperature conditions up to a Mach number of 4. You are invited to inspect the test section of this new tunnel as you leave.

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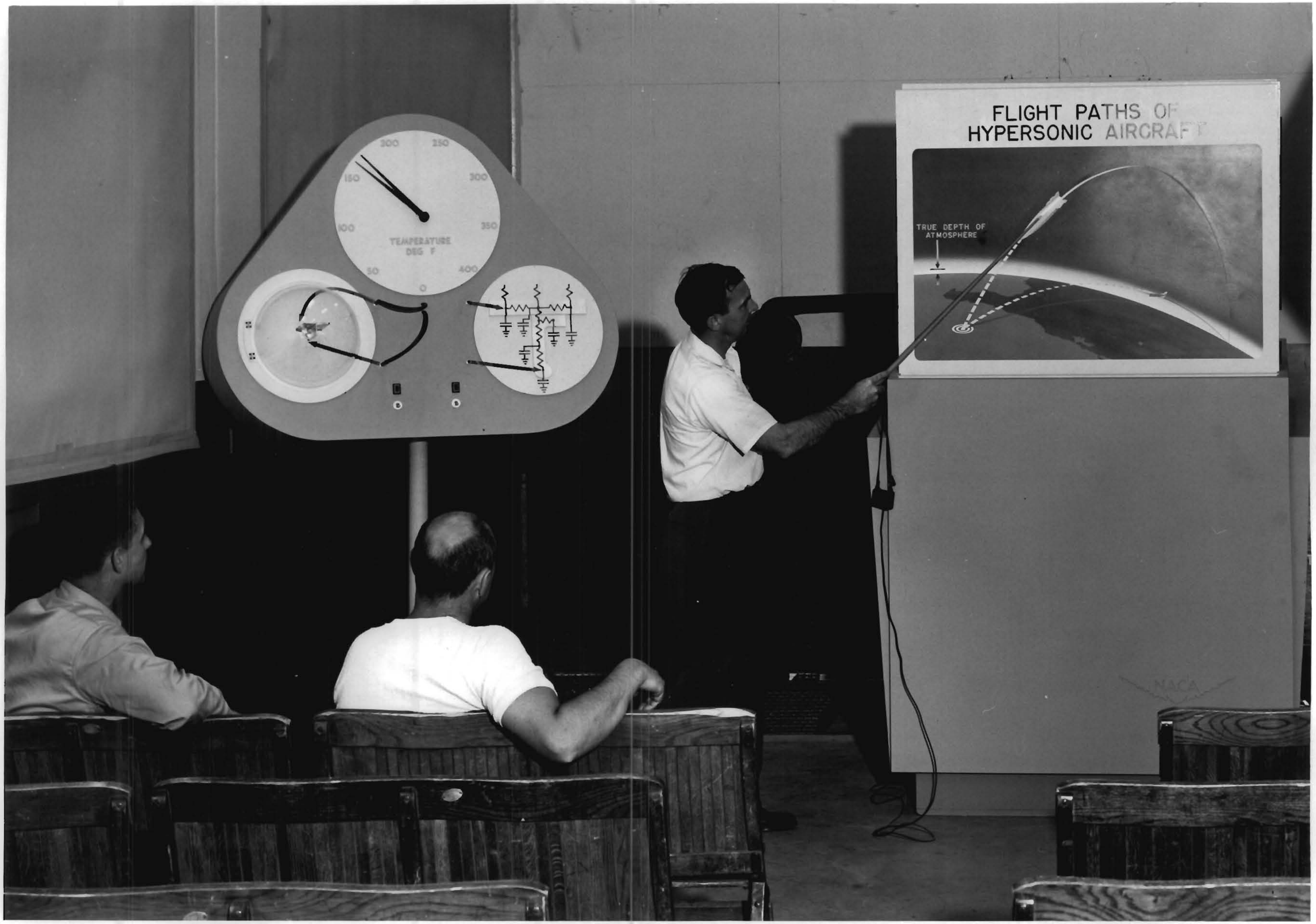

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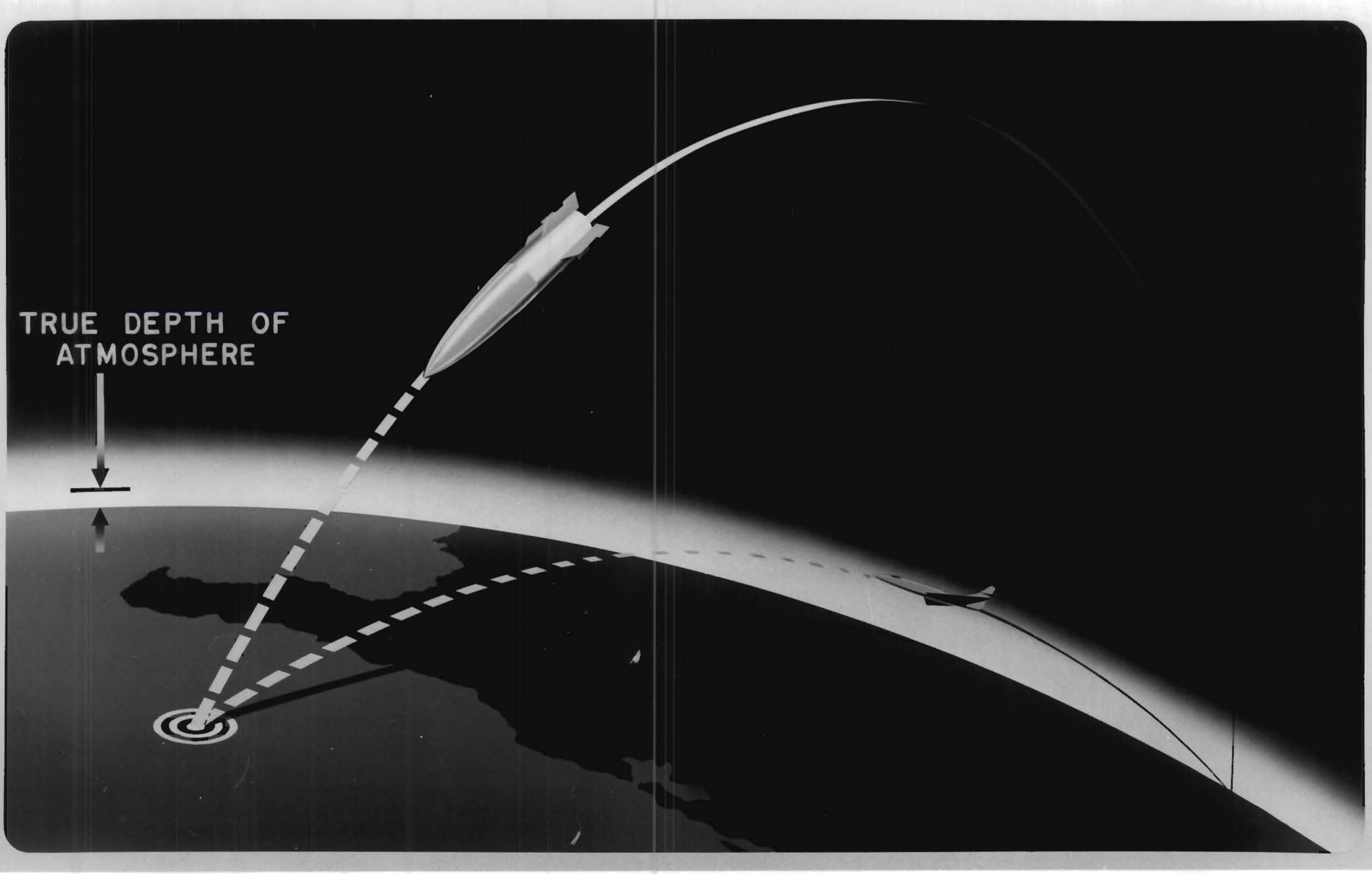
FLIGHT PATHS OF HYPERSONIC AIRCRAFT



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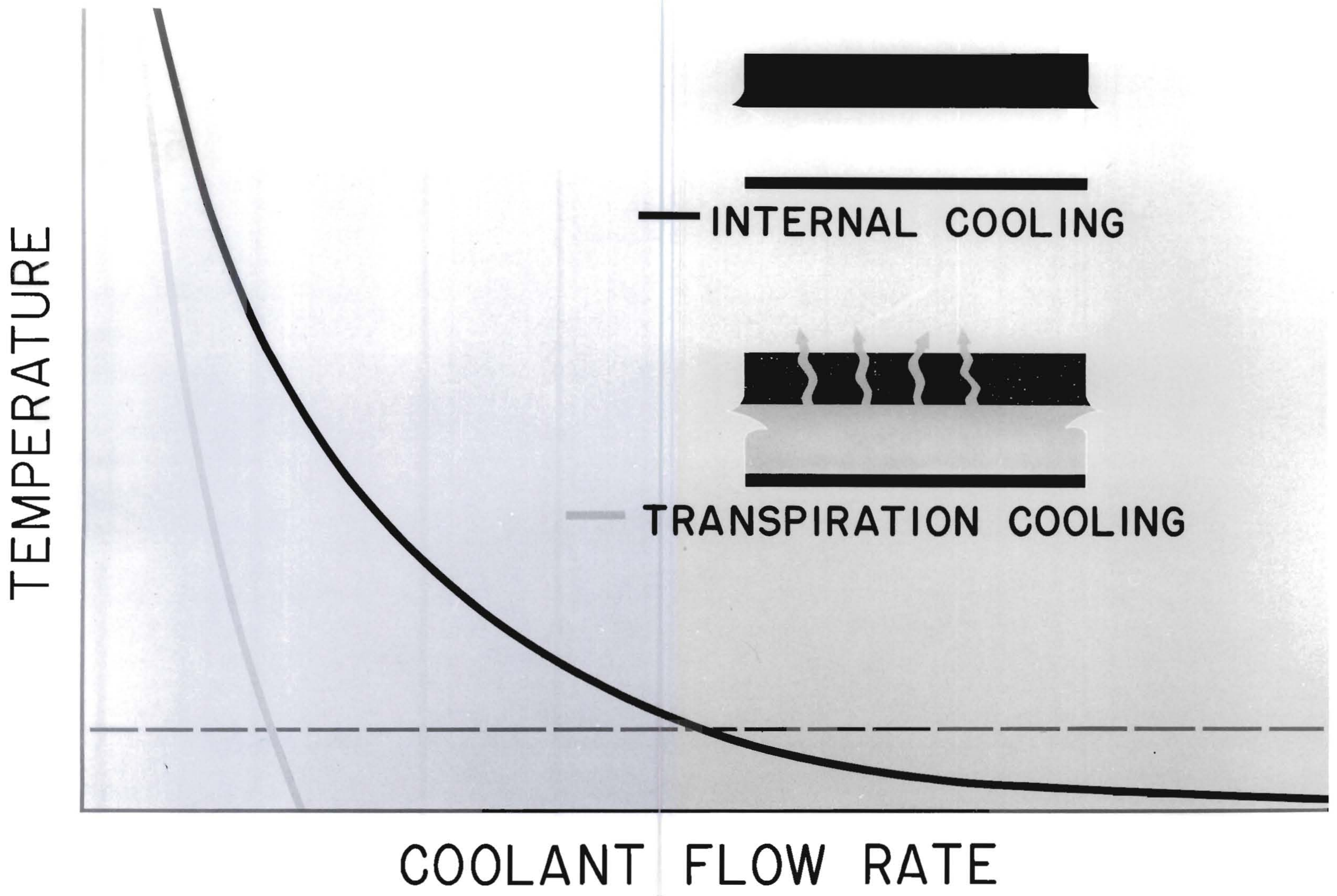
TRANSPIRATION COOLING



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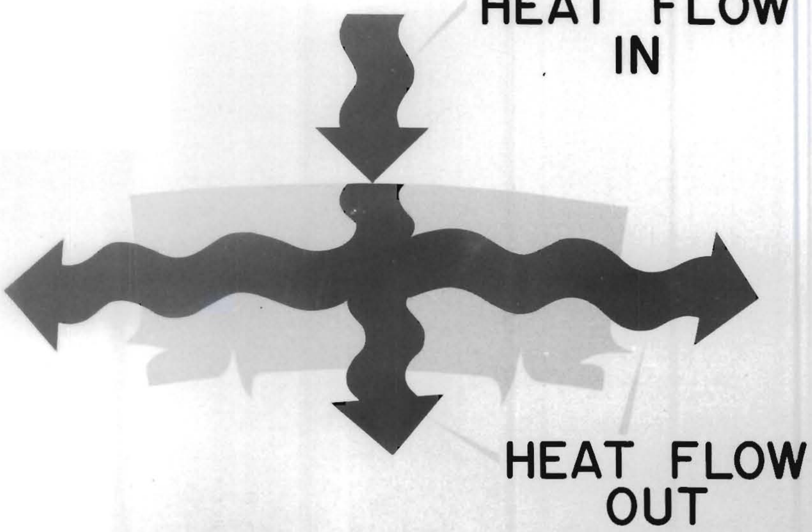
ELECTRICAL ANALOGY OF HEAT FLOW

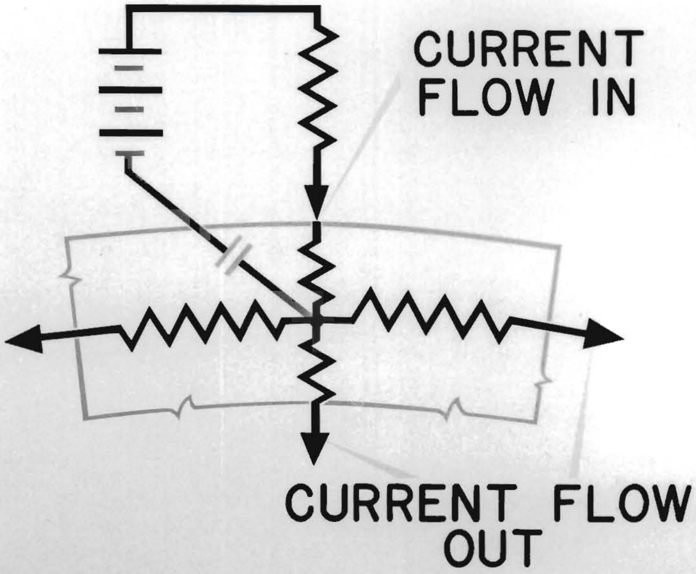
THERMAL CIRCUIT



HEAT FLOW IN

HEAT FLOW OUT

ELECTRICAL CIRCUIT



CURRENT FLOW IN

CURRENT FLOW OUT

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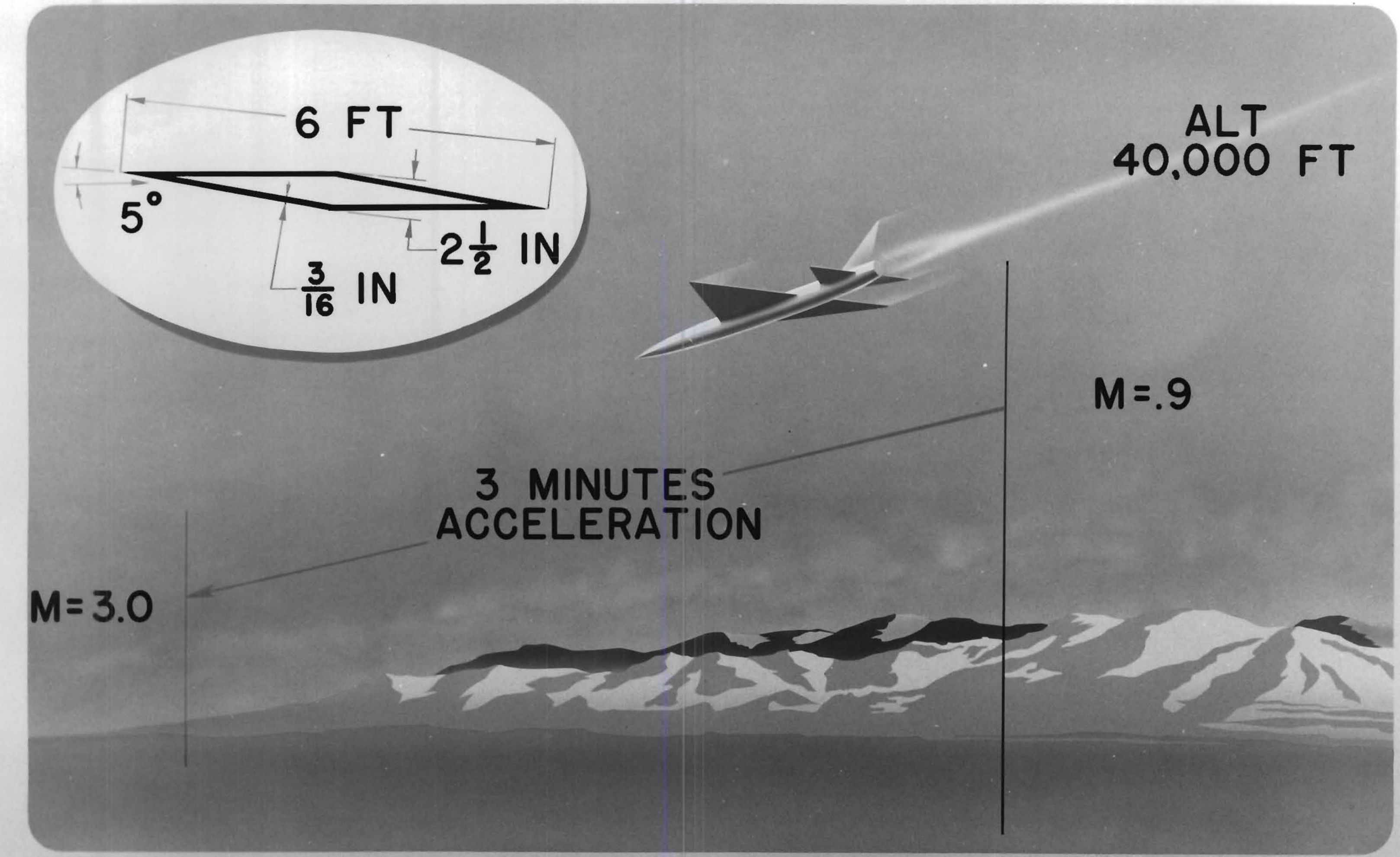
CONDITIONS FOR ANALOG CALCULATIONS



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WING SURFACE TEMPERATURE DISTRIBUTIONS