AERODYNAMIC HEATING

presented by

Low Density and Heat Transfer
Wind Tunnels Branch

You are hearing a lot today about the troublesome aerodynamic heating during flight through the air at very high speeds. We will attempt to show what this heating does to vehicles, and what we are doing about it.

An airplane flying at hypersonic speeds, say 10 to 15,000 miles per hour, will heat the air surrounding it to tens of thousands of degrees. Satellites and ballistic missiles enter the atmosphere even faster, with correspondingly higher temperatures. Unless these vehicles are cooled by some means, the air will heat them to temperatures known materials cannot survive.

In order to get a feeling for the temperatures involved, let us see how they look. This model of a wing section has an electric heater element forming the leading-edge region. We will first heat this element to 1400° F (switch on). This is about the lowest surface temperature that is being considered for these high-speed vehicles. This is well above the melting temperature of aluminum alloys. At this temperature, ordinary structural steel has lost over 90 percent of its strength. Inconel-X, one of the high-temperature alloys, is only half as strong as at room temperature, and stainless steel has lost two-thirds of its strength.

This is 1700° F (control turned on 1700). At this temperature, brass and bronze melt. Inconel-X has less than one-tenth its strength, and stainless steel about one-sixth.

At 2000° F (control turned to 2000) copper melts, magnesium boils, and only a few metals or alloys retain sufficient strength to be useful.

This is realistic surface temperature for hypersonic aircraft and missiles. It is apparent, then, that we must work on the development of high-temperature materials. (Variac off.)

Now that we have a feeling for these temperatures, it is interesting to see how an airplane model heats up in one of our small, high-speed wind tunnels. This is illustrated in the first chart. Now, when air accelerates through a supersonic wind-tunnel nozzle it expands and cools markedly. In order to counterbalance this effect, the air ahead of the nozzle in this tunnel is pre-heated to 2100° F. Then, as it expands and accelerates to 3500 miles per hour, the temperature drops to 0° F. All this is necessary to make the temperature in the test stream the same as in flight at altitude. This tunnel, incidentally, is the pilot model for a larger one now under construction.

When a model is placed in the high-speed stream, compression and friction heat the air next to the model back up to nearly 2100° F, and the model becomes almost this hot. This test has been recorded on a motion picture which we will now see. (Motion picture starts.)

The test model is shown here before its installation in the tunnel. The model is made of stainless steel. The body is hollow, so it will heat in a similar manner to an actual airplane.

Here the model is in the test chamber of the tunnel but to one side of the air stream. Now the model is in the air stream, and is starting to heat up. Notice how the thin wings get hot first. Near the tips, the wings are heating more rapidly than the inner portions. This is caused primarily by the shock wave from the nose of the model. This wave is not visible in these pictures. It sweeps backward from the nose, intersecting the wing about here (trace approximate curve of shock wave on screen with pointer). The part of wing behind the shock wave is shielded somewhat by the wave and the heating is not as rapid in this area.

The nose is becoming the hottest part of the model. Remember when looking at these pictures that the fast-moving air in the test section is cold - about 0° F. It is the compression and friction of the air next to the model surface which heats it. Most of the model has reached about 1700° F, with the nose about 1900° F. This gives a picture of how a high-speed airplane might appear in flight. (End of motion picture.)

During hypersonic flight, and in particular as satellites and ballistic missiles enter the atmosphere, such tremendous heat will be generated that cooling must be provided. Let us look at several of the cooling schemes which the NACA is studying. Incidentally, most of these cooling schemes are not new, but are adaptations and extensions of known methods. Our job is to see how these systems might be used under the extreme heating conditions of high-speed flight, and to provide the necessary basic data to designers.

This model of a satellite will illustrate the various cooling systems. (Model is separated.) Perhaps the most important type of surface cooling is that which takes place automatically by radiation. When a surface is hotter than its surroundings, it loses heat at a rate roughly proportional to the fourth power of its absolute temperature. This means that as the temperature of a body is increased a moderate amount, the heat lost by radiation increases a large amount. For instance, if improvement of materials permits us to raise the temperature of a surface from 1400° F to 2000° F (demonstrate with high-temperature model) the radiant heat loss will be more than tripled. Radiation cooling occurs automatically as the surface is heated, and tends to provide a regulating mechanism for limiting the surface temperature. All hot parts of an aircraft or missile will be cooled to some extent by radiation ragardless of any other cooling system that may be provided. If the surface materials can withstand high enough temperatures, radiation will provide all the cooling needed. Unfortunately, the hot skin radiates heat inward as well as outward so it is necessary to provide an inner skin and insulation, such as this, to protect internal components and occupants. (First lamination removed from model.) The internal-flow cooling system is a familiar one, resembling that used to cool automobile engines. Coolant is stored in a tank and is pumped through passages next to the skin where it absorbs the incoming heat. The used coolant is then ejected overboard. This system has the disadvantage of being heavy, and it suffers from the possibility of disastrous failure through breakdown of the pumping mechanism. (Second lamination removed from model.)

Transpiration cooling is another method that is familiar to us. This is similar to the human cooling system in that coolant is forced through the outer skin, which is porous. During its passage through the skin, the coolant absorbs heat, then it flows back over the surface to form a protective blanket, insulating the surface from the hot layer of air surrounding the vehicle. Like the internal-flow system, a storage tank and pump are required.

In order to illustrate the operation of this cooling system, we have arranged a simple demonstration. We will use a blowtorch in place of aerodynamic heating. (Blowtorch turned on.) This model is hollow and has a nosepiece of stainless-steel mesh. First, the nose is heated red hot. Then it is cooled simply by blowing through the tubing. (Blow through tubing.) Cooling is brought about by the two actions mentioned. First, the skin is cooled by the air passing through it. Second, the same air forms a protective layer of relatively cool air, which prevents the hot gases from the blowtorch from reaching the surface. (Blow through tubing again.) Due to formation of the protective gas layer, a transpiration cooling system can produce a several-fold reduction in heating rate; thus, it is one of the most effective methods of cooling. However, it has the same disadvantages as the internal-flow system: it is fairly heavy and complex. (Third lamination removed from model.)

Another method of cooling is to coat the surface of the vehicle with a material such as a plastic which will progressively change to a gas upon being heated. This is called ablation cooling. The material absorbs heat as it changes to a gas, which then leaves the surface and flows back to form a protective layer in the same manner as the transpiration system. The ablative material would be thickest in the region receiving the most intense heating. A desirable feature of ablation cooling is that it is automatic as long as the material lasts; thus, it is a relatively simple system. Of course, the coating must be renewed for each flight on vehicles which are to be used again. A motion picture illustrating the effectiveness of ablation cooling is being shown at the Langley Laboratory display. (Fourth lamination removed from model.)

The heat-sink method of cooling utilizes the capacity of material to store heat. The method is useful where the duration of intense aerodynamic heating is short enough that the material can absorb and store the heat without exceeding its safe temperature. The heat sink is simply a thick wall of metal which absorbs the heat generated. Notice that the wall is thicker in the region which will experience the most intense heating.

We can demonstrate the heat-sink effect with this second model. (Second model is rotated into blowtorch flame.) This model is constructed of thin stainless steel 1/64 inch thick. Observe how rapidly it heats. Now, when this heavy-walled stainless-steel cap, which is 1/8 inch thick at this point, is placed over the nose of the model, it delays the heating. (Model rotated into flame.)

Simplicity is the main virtue of this system. Its main disadvantage is that it will be quite heavy if it must absorb heat for long periods. Utilizing a material which can hold a lot of heat is one obvious way of minimizing the weight. One of the most promising metals for heat sinks is beryllium, which can absorb nearly five times as much heat as copper. (Cap removed from model.) (Fifth lamination removed from model.)

The last method of cooling we will discuss is conduction. In this system, the skin must be a good conductor of heat, such as copper. The heat from the intensely heated regions flows through the material back into the cooler areas, thus lowering the temperature of the hot spots.

The effect of conduction can be demonstrated with this copper shell. The copper is relatively thin, being less than half the thickness of the heat-sink cap. (Slip copper shell over model and rotate into flame.) Because of the high conductivity of the copper, the heat at the nose is drained back into the cooler regions. This system, like the heat sink, is desirable because it is simple. It has the disadvantage that it is fairly heavy, because sufficient material must be provided to conduct the heat. Of course, during the initial stages of heating, cooling of the surface by conduction will be aided by the heat-sink action of the skin. Even after an extended period of heating, though, notice how the nose of this model remains relatively cool. (Turn off blowtorch.)

In a practical cooling system, several of these methods of cooling are combined. An application of this sort is shown in the next chart. This illustrates the heating and cooling of the wing leading edge of an airplane which reaches a speed of about 5500 miles per hour. The flight is a typical boost-glide trajectory in which the airplane is boosted by rockets to a high-speed, coasts to a high altitude, then drops back into the atmosphere. The wing skin is assumed to be 1/8-inch-thick copper. The leading-edge temperature is plotted as a function of the flight time.

The top curve represents the temperature in the boundary-layer air, close to the wing surface. The peaks result from the changing speed and altitude of the airplane. The first peak comes when the boost rockets burn out; then the speed and temperature start to decrease. The airplane coasts to high altitude, then it drops back into the atmosphere and reaches a high speed at this point. The boundary-layer temperature rises to a peak of nearly 5500° F. This curve shows the temperature the leading edge would reach if it were cooled only by radiation. Notice the large benefit of cooling by radiation. This next curve indicates the additional cooling from the heat-sink action of the small segment of skin at the leading-edge point. Although the copper absorbs considerable heat during the first part of the flight, it gradually gets too hot to be of much further help. Conduction is quite a help, as we see from this curve. Thus, by taking advantage of radiation, heat capacity, and conduction, the maximum temperature can be reduced to about 1000° F, nearly 4500° F below the boundary-layer temperature. Only simple, automatic systems have been assumed in this example.

We have seen the severity of the aerodynamic-heating problem, and how various systems can be used to keep the temperatures within tolerable limits. In order to design an efficient cooling system, however, a designer must be able to calculate accurately the heating rates and temperatures. A great deal of research is required to solve all aspects of the problem. Research must provide data and develop theories to show the designer how to calculate heating of various shapes under widely varying conditions - from low supersonic speeds up to the speeds of satellite and space craft. More must be learned about the air itself and its behavior under extreme heat. This subject is being discussed elsewhere today. We must investigate all possible ways of minimizing temperatures. Materials must be developed and evaluated for these high-temperature applications.

Much progress has already been made along these lines. We are continuing this work in such facilities as the 10-Inch Heat-Transfer Wind Tunnel, directly in front of you, which tests models at 5-1/2 times the speed of sound. Additional facilities are being developed to extend our research. One of these is a wind tunnel using helium so that we can get Mach numbers up to 26, and thus cover the critical range up to satellite speeds. The pilot model for this helium tunnel is being constructed there on your left.

With the help of existing equipment, and with the new facilities, we expect to expand our knowledge of aerodynamic heating, so we can give designers information to help combat the intense heating in hypersonic flight. One of the problems with which we are vitally concerned is the safe return of space craft and satellites. Mr. _______________ will discuss the problems of aerodynamic heating associated with the entry of satellites into the atmosphere.

When space vehicles or ballistic missiles return through the atmosphere, intense aerodynamic heating, such as we have demonstated, will occur. Atmosphere entry is an especially complicated problem, becuase so many factors are involved. Among the most important are the shape of the vehicle and its path through the atmosphere. Shape is important, because it affects the rate of slowing down. For example, these blunt shapes (point to entry models) will slow down much fast than this slender shape (point to boost glider). Now, to understand how this difference affects the heating, we must realize that the energy involved in the tremendous speeds of these vehicles will be changed into heat as they slow down in the atmosphere. This heat is developed in two ways. First, heat is developed ahead of the body where the air molecules cannot get out of each other's way fast enough and they pile up in a shock wave, where much of the heat is dissipated in the surrounding air. Second, heat is developed by compression and friction of the air flowing next to the surface. More of this heat is absorbed by the body. It is desirable, of course, to make the friction heating as small as possible. This is accomplished by making the body blunt. The air is pushed ahead of the blunt body, as shown here, and a strong shock wave is formed. Much of the heat, then, is dissipated in the air, thus reducing the amount of frictional heat absorbed by the vehicle.

The sharper more slender shape, on the other hand, pierces the air, and the shock wave is weaker than for the blunt body. The shock wave lies back near the body, and is less effective in slowing it down. A smaller portion of the heat is dissipated in this weaker shock wave. Most of the heat is generated by friction of the air next to the body, where it heats the surface. Thus, we see that, if the heat absorbed by entering satellites and ballistic missiles is to be minimized, these bodies should be blunt. Analysis of these principles by Mr. Allen of the NACA in 1952 revolutionized the design of ballistic missile nose cones.

Besides its shape, the path of a vehicle through the atmosphere influences its heating. Studies of the complex problems of motion and heating of satellites and missiles returning through the atmosphere have recently been made easier by an analysis by Dr. Chapman of the NACA which greatly simplifies the calculations. Let us review the results of his analysis as they apply to these three possible entry shapes.

The next chart shows the maximum surface temperatures for each of these vehicles plotted as a function of the flight time, with the surface cooled only by radiation. As we would expect, the two blunt shapes would not get as hot as the slender one, which reaches a peak temperature of 4100° F. Notice that the blunt body which is shaped to give a small amount of lift would be cooler than the non-lifting ballistic shape. It would reach about 2200° F, as compared to 2700° F. The reason for this is that the lifting force would keep the craft at a higher altitude longer, so it would slow down more gradually than if it had no lift. Consequently, the heating would not be as intense, and its temperature would remain lower.

Suppose, however, that we decided to use heat-sink cooling in addition to radiation cooling. The next chart shows how this would affect the heating of these same three vehicles. The ballistic shape is now the best, with a maximum temperature of only 1200° F, as compared to a peak temperature of 1800° F for the lifting vehicle. This is because the ballistic body would be slowed down sooner than the lifting body, and, even though the heating of the ballistic body would be more intense, the duration of heating would be much less. Hence, the total heat absorption would be less, and the temperature would be lower.

We can see that the heat sink would lower the peak temperature of the slender vehicle only slightly, from 4100° F to 4000° F. This is because the duration of the flight would be so great that the heat sink could not absorb all of the heat generated, and the temperature would be limited mainly by radiation cooling.

In spite of the adverse heating characteristics of the slender shapes, however, our interest in these vehicles continues because of their higher flight efficiency. Boost-glide airplanes must be slender to obtain long flight range and maneuverability in the atmosphere. Therefore, a more complicated method of cooling may be necessary to make these shapes survive, too.

We have touched on only a few of the problems associated with aerodynamic heating, which will be encountered during descent of vehicles from satellite orbits, and on some of the possible solutions. Through study of satellite entry, we hope to pin-point the critical phases of this important problem, so our research on aerodynamic heating, cooling methods, and high-temperature materials and structures will be guided to produce the most useful results.

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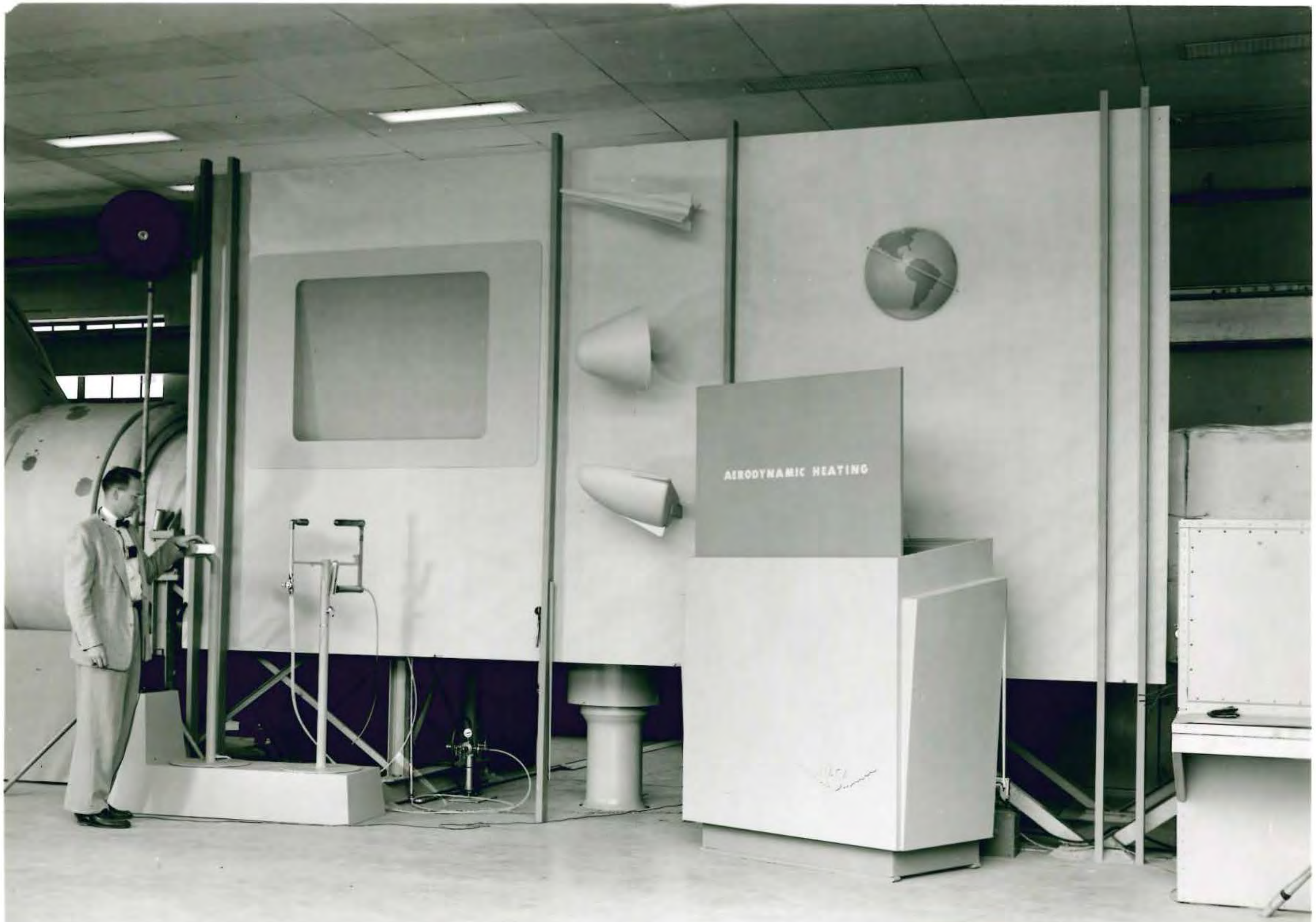

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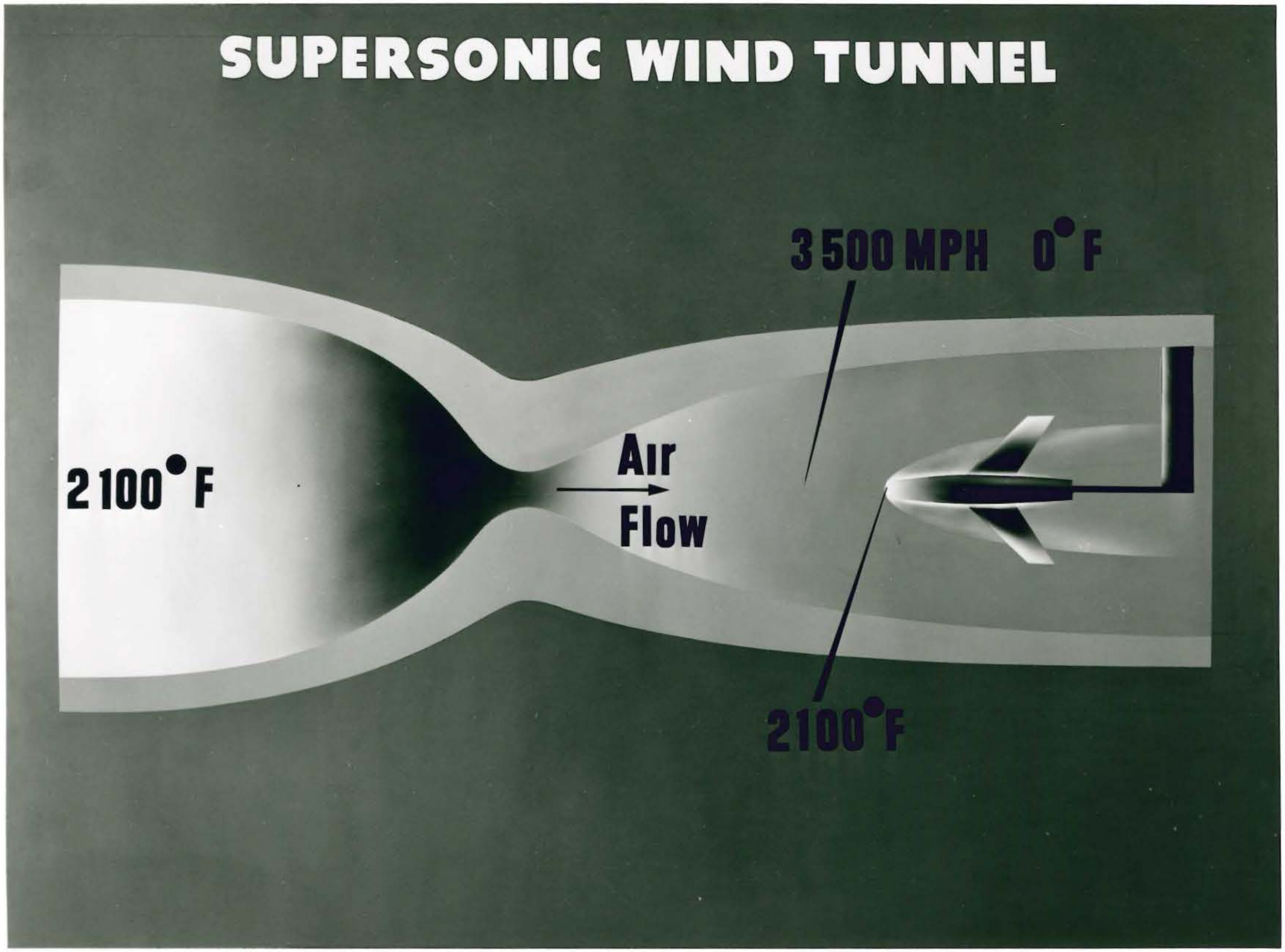

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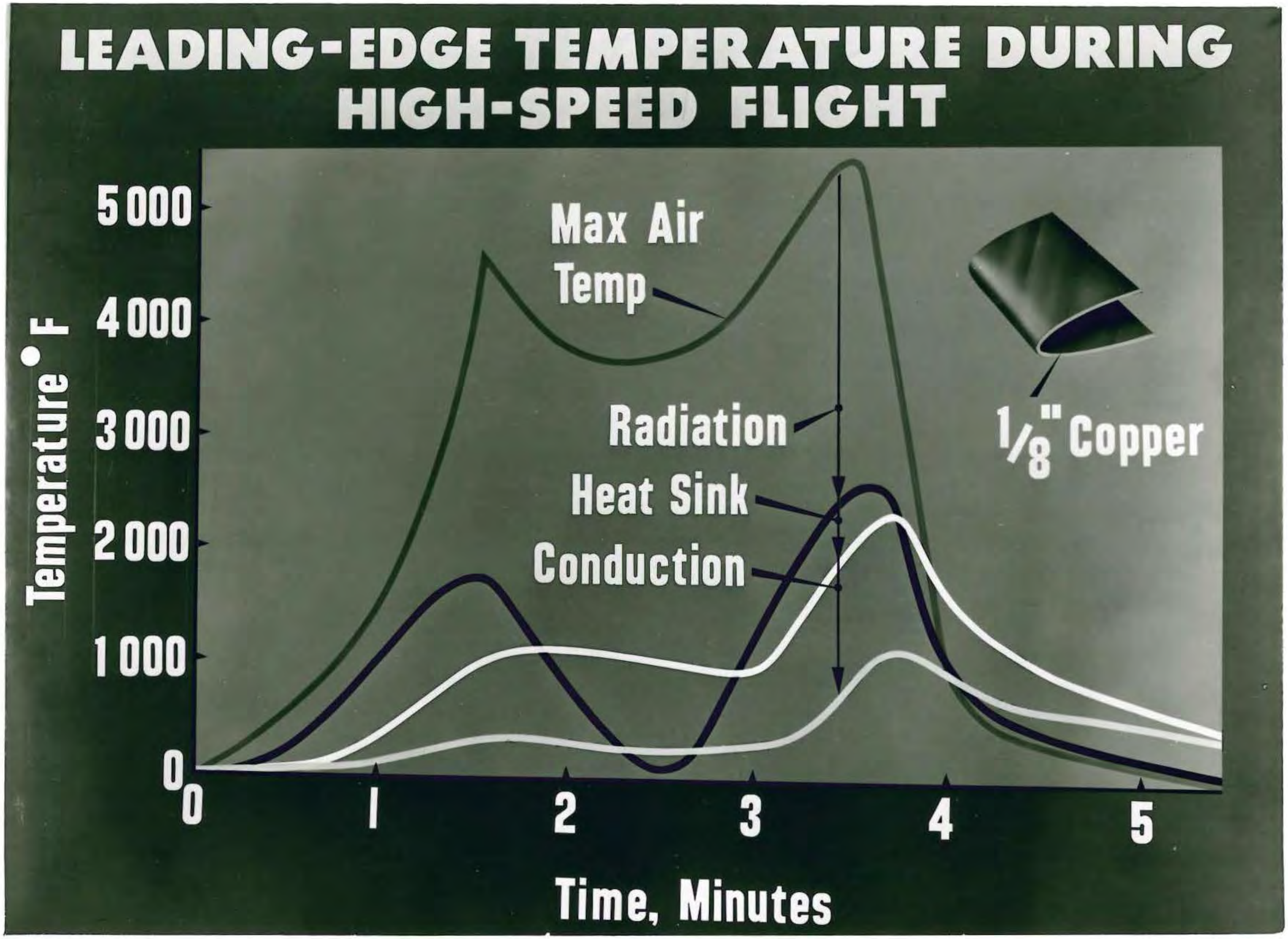

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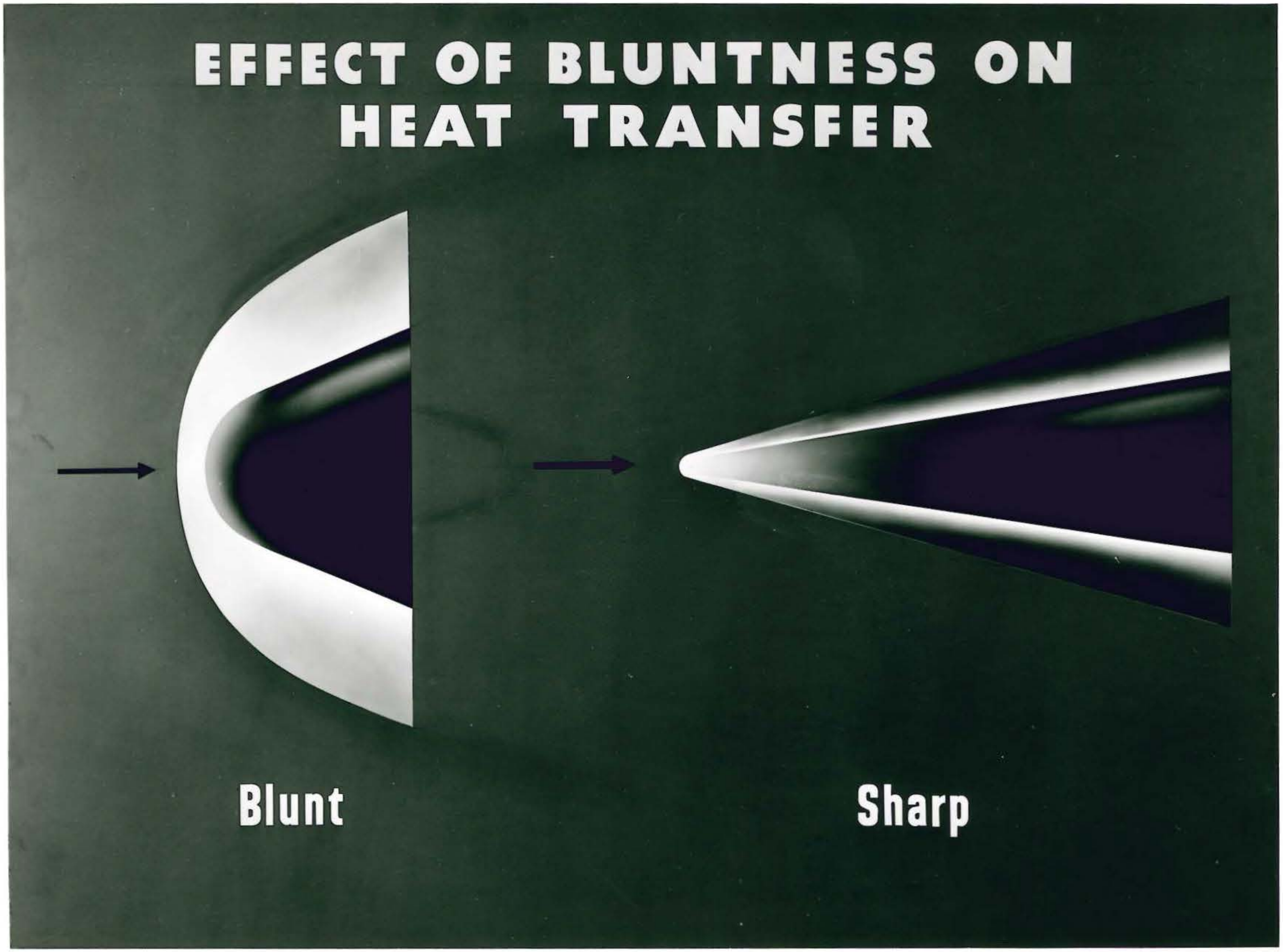

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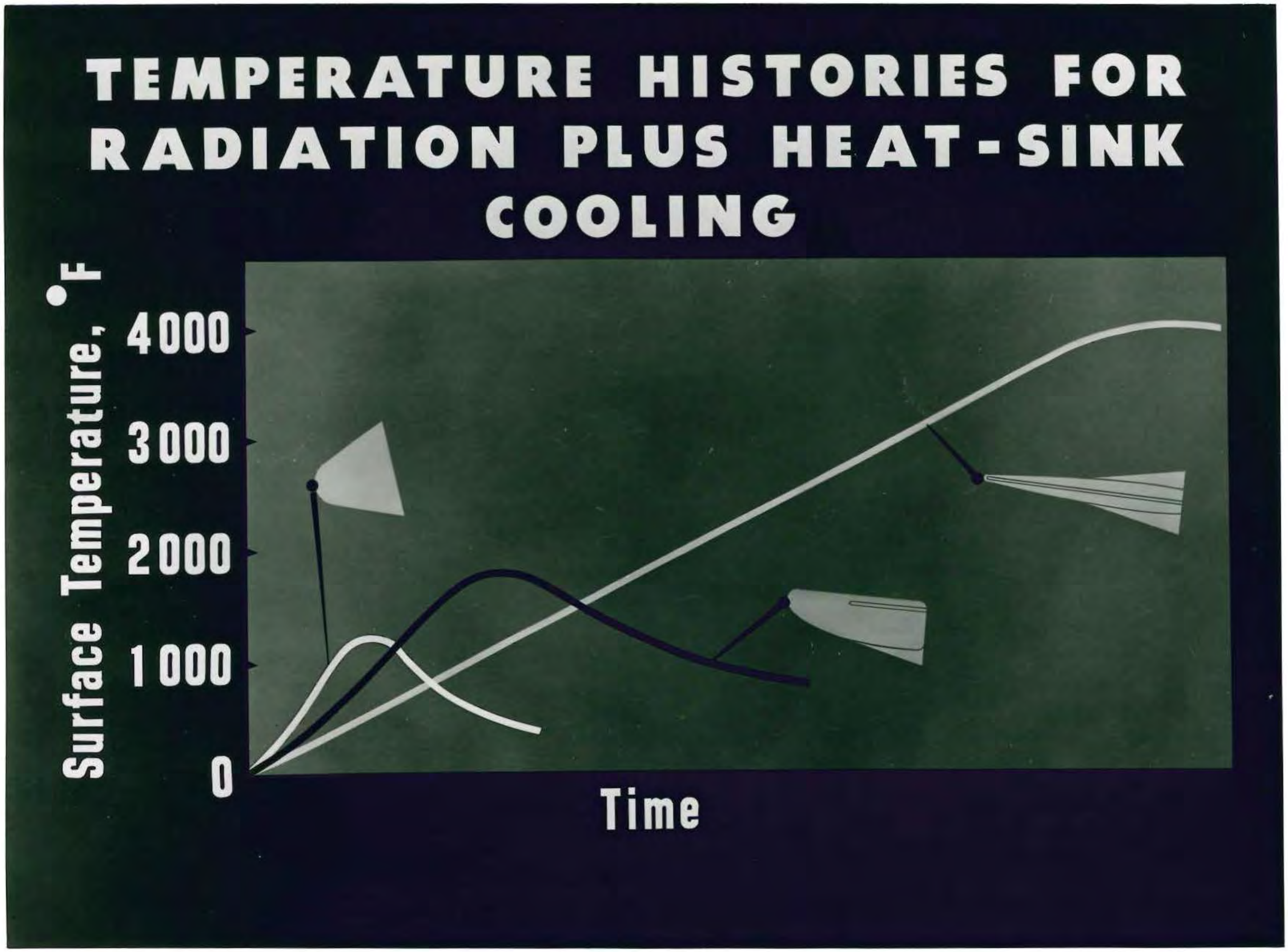

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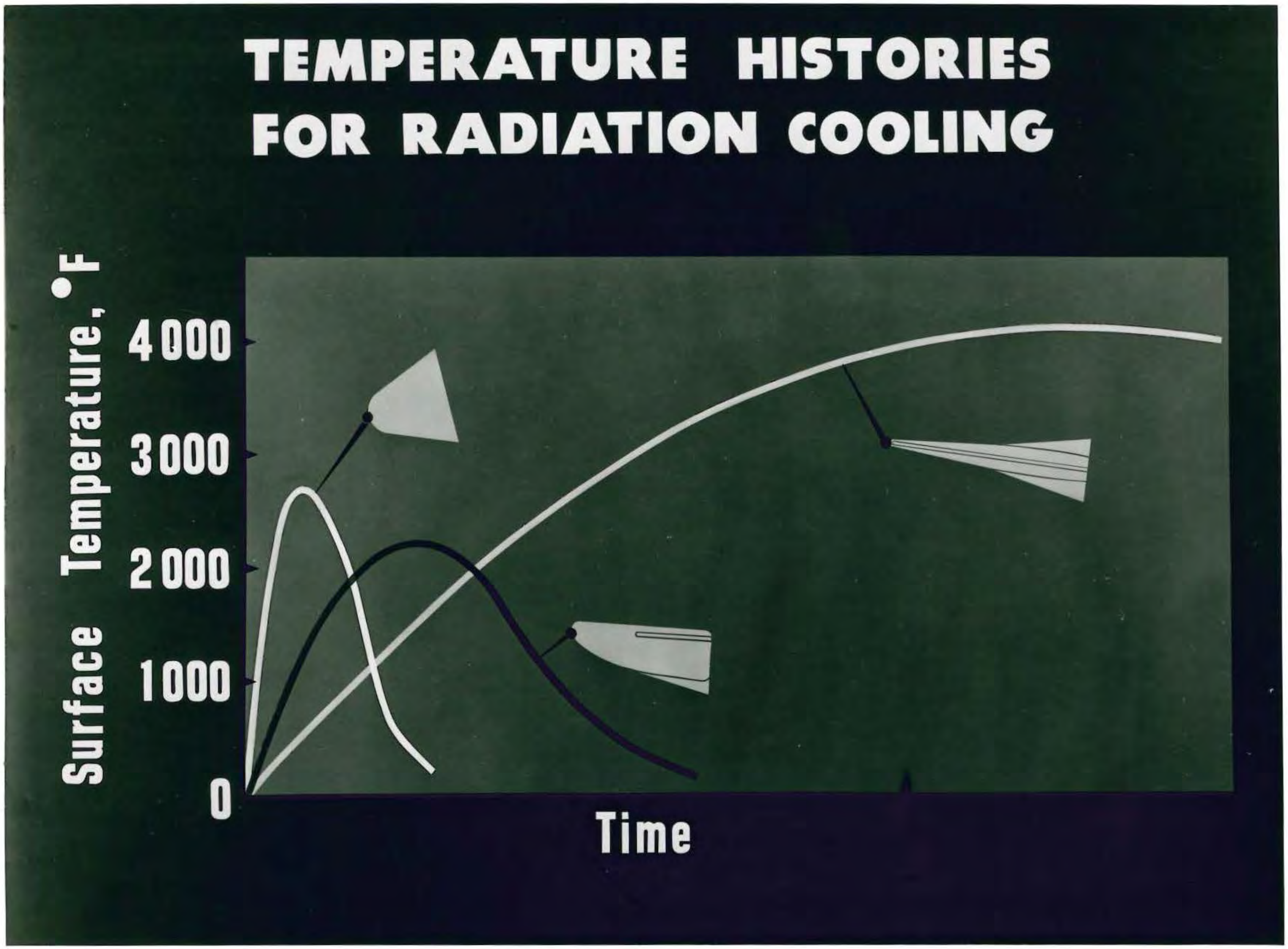

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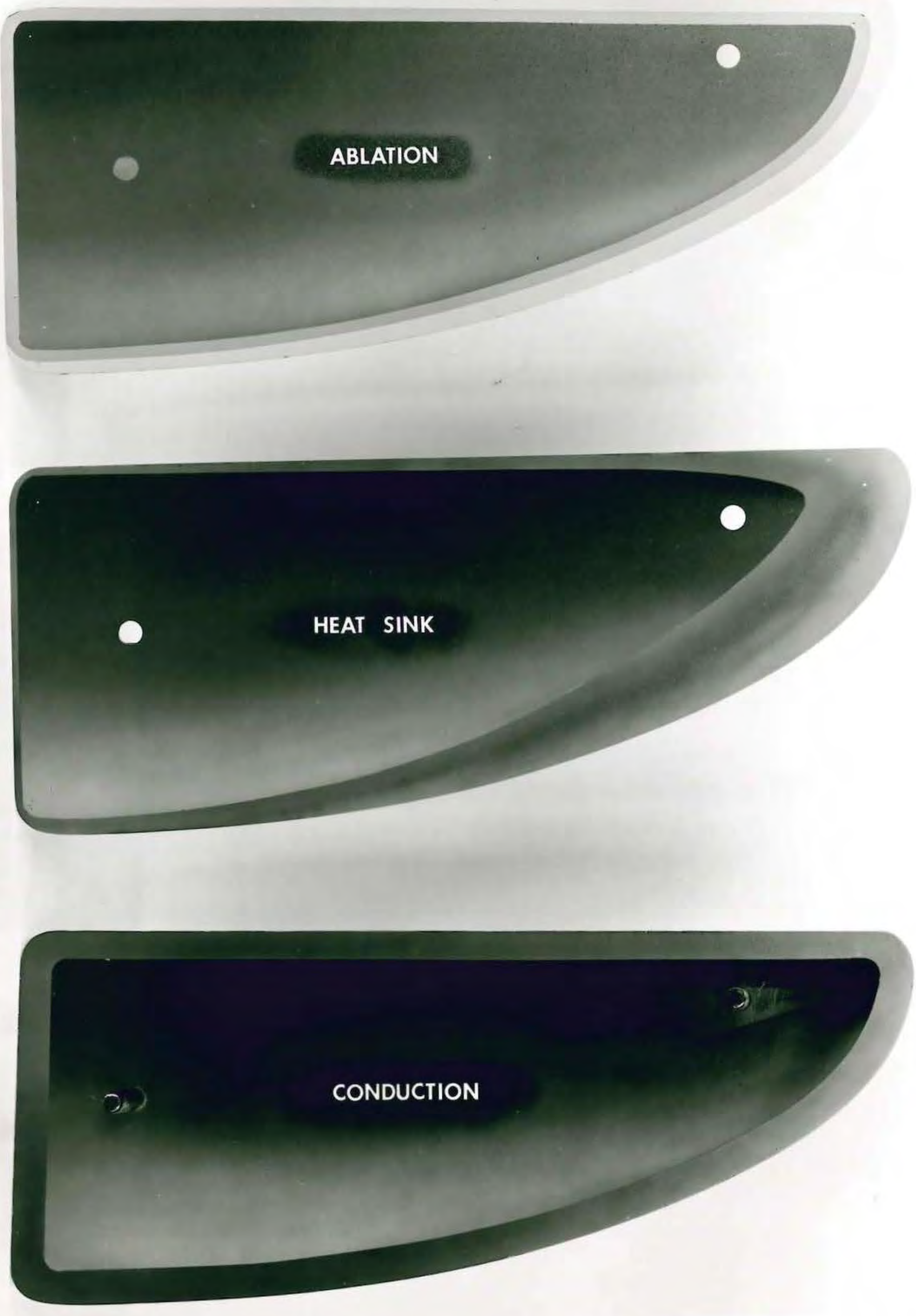

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