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SKIN FRICTION AND AERODYNAMIC HEATING OF SUPERSONIC MISSILES

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A missile in supersonic flight experiences resistance of several kinds, much of which originates in the boundary layer. This is the layer of air in immediate proximity to the surface of the missile. There are two important aspects of this boundary-layer resistance - the actual friction drag to be overcome and the associated frictional heating. It is about these two aspects of supersonic flight resistance that I am going to talk.

On this first chart we show an actual flight history of a supersonic missile identical to this. The missile was rocket-launched to its maximum speed and temperature data were recorded in the period of coasting flight. Mach number, boundary-layer temperature, and skin temperature are plotted against time in seconds. Now this missile accelerated to a maximum Mach number of 2-1/2 in slightly less than 4 seconds. It did not remain long at this high speed, however, but slowed down rapidly as soon as the launching rocket was dropped. Here is a record of the boundary-layer temperature, which, because it depends principally upon the flight Mach number, decreased rapidly as the speed diminished. This is the record of the skin temperature. Because the skin of this missile was very thin, it had little heat capacity and heated rapidly at first (about 50° F per second). However, the boundary-layer temperature dropped so fast that soon it was below the skin temperature and the skin began to cool off. So while the thinness of the skin accounts for the rapidity of the initial rise - for if the skin had been thicker it would have heated more slowly - the fact that the missile did not stay for long at high speed is what really kept it from overheating. Six seconds of sustained top speed would have overheated the skin.

It is appropriate therefore to examine means by which this rapid heating of the missile skin can be retarded. One rather obvious way is to operate at higher altitudes, where the thinner air is less effective in heating the missile. Another way is to transfer as much heat as possible from the surface to the interior of the missile. Here in the ideal case, it would be necessary to heat the entire missile uniformly with the skin. In order to show how effective such measures could be, temperature-time histories for a typical missile, calculated assuming this ideal condition, and high-altitude operation, are given in the next chart. It should be appreciated that examples such as this are of necessity oversimplified and give values that are limiting rather than truly attainable. Flight is at a constant Mach number of 5.4 at an altitude of 100,000 feet, at which conditions the boundary-layer temperature is approximately 2000° F. The airspeed is just 1 mile per second, so the horizontal scale can be read in either seconds or miles.

This picture is much more optimistic than the preceding one. Despite a Mach number and boundary-layer temperature much greater than the values of the preceding example, the time rate of temperature rise is much less, being initially of the order of 1/3° per second. The solid line has been interrupted at a point where the temperature has become undesirably high for magnesium or aluminum alloy construction, after about 1000 seconds or miles. It is of some interest to note that the advantage of a higher limiting temperature possible with steel construction is, in the case where the over-all weight is the same for either construction, largely offset by the lower specific heat of steel which causes the steel missile to heat up faster.

The real key to aerodynamic heating lies in the boundary layer itself. Let us consider the kinds of flow which we find in the boundary layer. To demonstrate these flows we have set up a missile forebody model in such a way that a simulated boundary-layer flow will be rendered visible by the schlieren technique. At the very tip of the missile the flow is smooth, that is, laminar. Now this is a desirable state, in which friction and heat transfer are small. Such a flow is, however, unstable and tends to break down into a violently disturbed, that is, turbulent, state at some distance from the nose. In this turbulent state there occurs a violent scrubbing action which greatly increases both friction and heating of the missile.

Let us digress for a moment to consider what governs whether the flow is this desirable laminar or that undesirable turbulent type. The distance from the nose of the missile to the breakdown or transition zone depends principally upon the airspeed, density, and viscosity. These four factors - distance, airspeed, density, and viscosity - are combined in an index of flow conditions called Reynolds number. When this Reynolds number is sufficiently small the flow is laminar, when it becomes sufficiently large, then the flow will be turbulent.

Although laminar and turbulent boundary-layer flows have been the subject of much research at low speed, actually very little is known about this subject at supersonic speeds. In the next chart we have for you some very recent data on transition from the desirable laminar to the undesirable turbulent state, taken here in the 4-foot tunnel on a missile model at a Mach number of 1.6. In this figure the measured skin friction and derived heat-transfer coefficients are plotted for a broad range of test Reynolds number. The right-hand end of the scale corresponds to flight of a missile as large as this at $M = 1.6$ at an altitude of 40,000 feet. At low Reynolds number the skin friction coefficient values and trends correspond to current theory for laminar flows. Soon the coefficient begins to rise, indicative of the appearance of transition on the afterbody of the model. The rise continues as the transition zone moves forward. Finally the values and trend swing into agreement with those of current turbulent flow theory,

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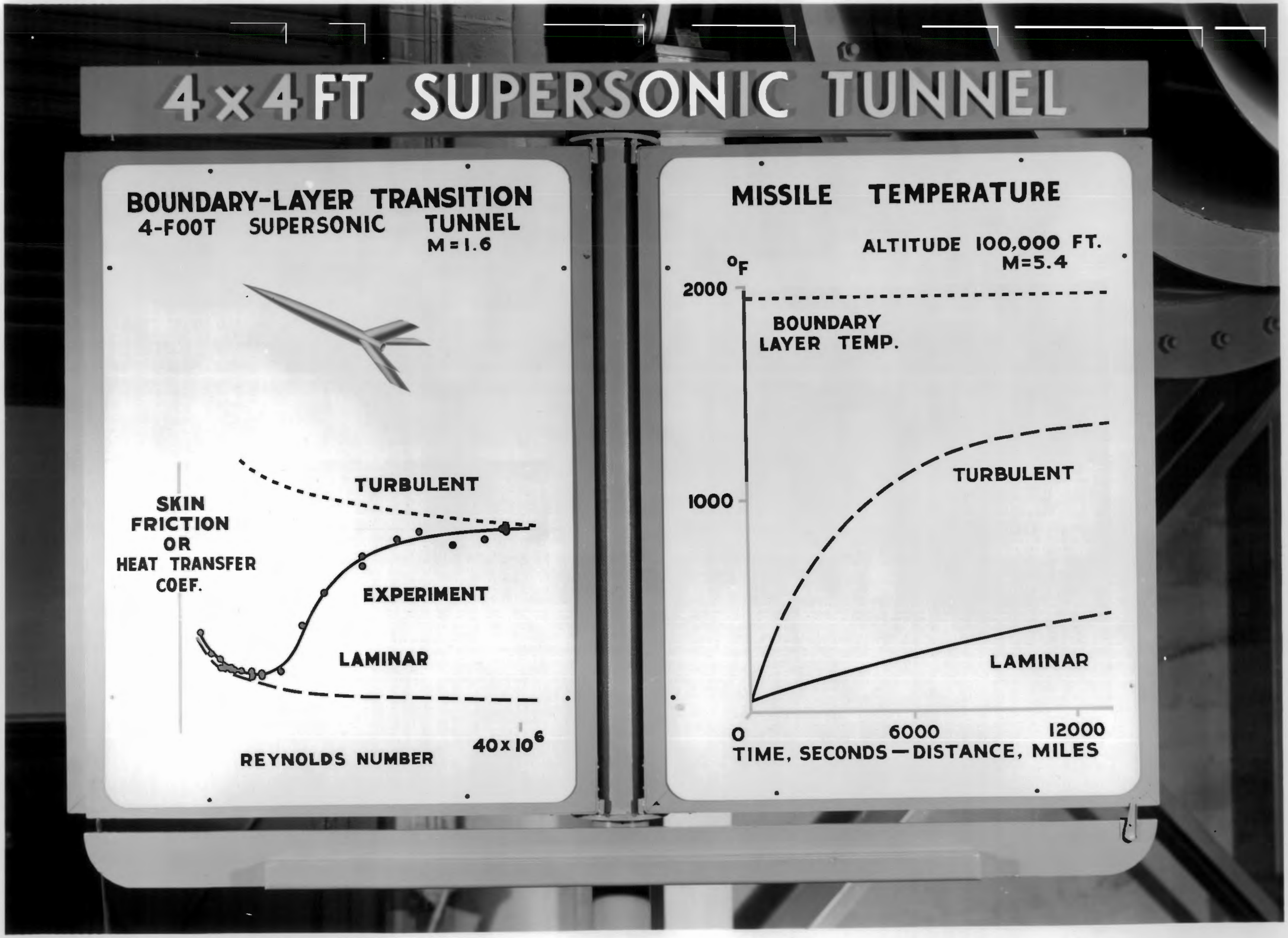
when turbulent flow prevails over practically the entire length of the missile. This figure illustrates dramatically the advantage of the desirable laminar over the undesirable turbulent boundary-layer condition. Even though skin friction is not the sole source of drag at supersonic speeds, still, attainment of fully laminar flow in place of turbulent suffices to cut in half the over-all drag of the missile tested.

Such performance as shown in this chart is ordinarily possible only with ideally smooth surfaces. The slightest roughness or even a deposit of dust on the surface causes the flow to become turbulent, with consequent high drag, even at low Reynolds numbers. This difficulty has thwarted attempts to obtain in practical subsonic aircraft the benefits of laminar flow, as many of you are all too aware. Why then are we now interested in laminar flow again, this time for supersonic flight? As we shall see in the next figure, it is because in supersonic flight we find conditions, favorable to the laminar state, which were not present in subsonic flight.

In this next figure the previously discussed missile temperature-time history, which was calculated for fully turbulent flow, is reproduced to a compressed time scale. It is noted that the missile temperature is much lower than that of the boundary layer. Such large differences are not encountered in low-speed flight. Theory has indicated that when such large differences do occur, they tend to stabilize the boundary layer and induce the desirable laminar state. Perhaps this action could be used to obtain laminar flow over the entire length of the missile, even at large Reynolds numbers. If such is found to be the case, then aerodynamic heating will be so greatly lessened that for the example under consideration, overheating would only occur if it were possible to sustain flight half-way around the earth.

Of course, there will be practical limitations on how closely we can approach the assumed ideal condition of temperature uniformity throughout the missile. Furthermore, aerodynamic heating is only one of the many problems, including propulsion, control, stability, and guidance, all of which must be solved before such long ranges are within our grasp. Nevertheless, the goal is certainly such as to encourage us to continue the current vigorous prosecution of supersonic boundary-layer research at large Reynolds numbers under typical heat-transfer conditions.

(Given at 4-Foot Supersonic Tunnel,
Alternate speakers: F. Bloetscher and B. H. Little, Jr.)



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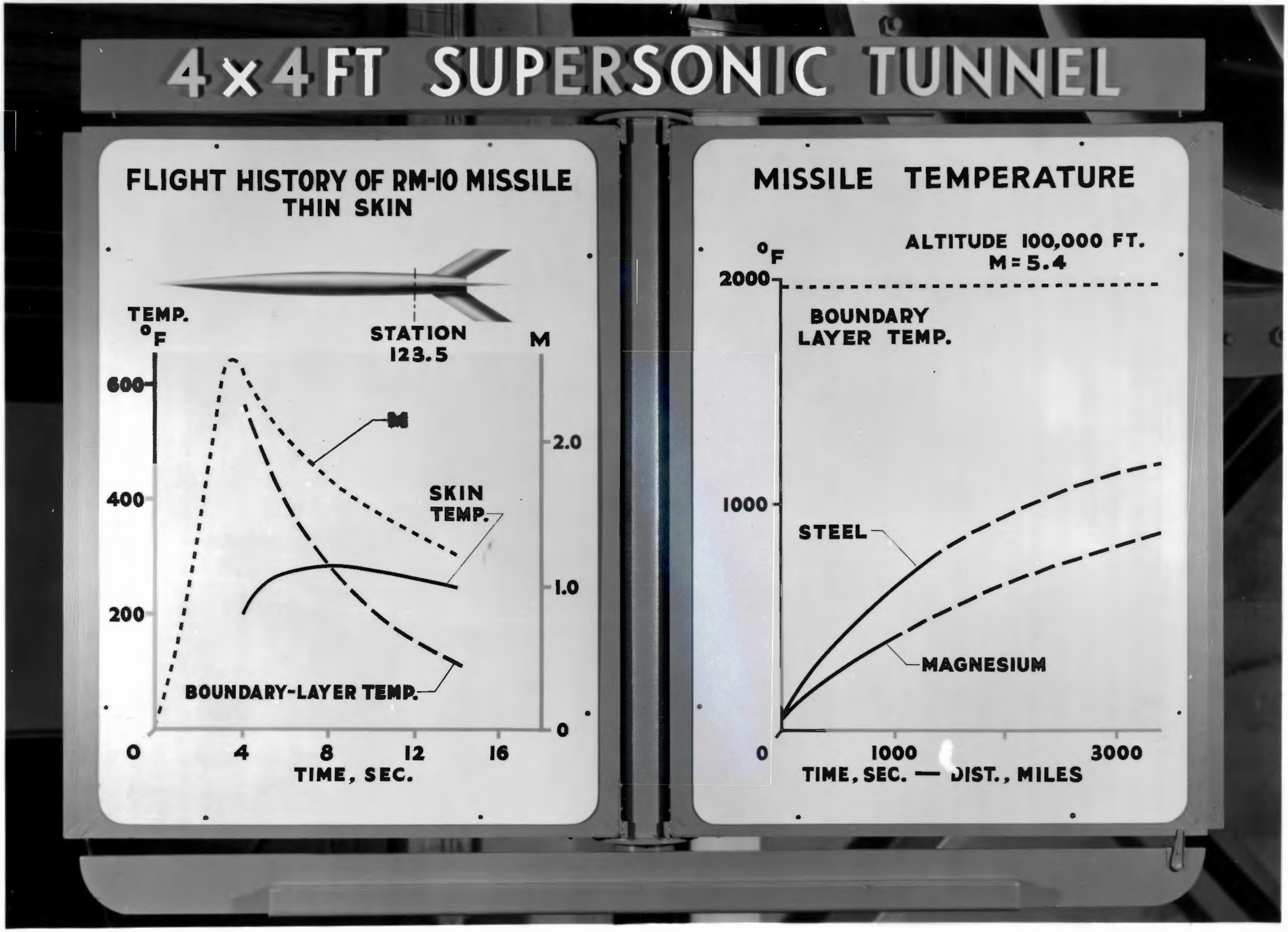

4 x 4 FT SUPERSONIC TUNNEL

FLIGHT HISTORY OF RM-10 MISSILE
THIN SKIN

MISSILE TEMPERATURE

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