THERMAL
INSULATION
for

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Airframes capable of flight in the atmosphere at velocities from Mach 5 up to orbital speeds (approximately 1.0 to 5.0 miles per second) are of interest as recoverable satellite boosters and glide re-entry orbital vehicles. Such flight speeds could permit large payloads because of the higher specific impulses available with airbreathing propulsion systems and could also provide maneuverability for landing in pre-selected areas.

Thermal problems much greater than those in present supersonic vehicles will be found at these hypersonic speeds. For example, a ramjet-powered Mach 7 vehicle that has been studied at APL[1] would encounter temperatures ranging from 1100°F on flat, nonlifting surfaces up to 2300°F on leading edges during cruise at 100,000 ft. Temperatures up to 4000°F would be found in the propulsion systems. Such temperatures as these are actually not much in excess of those that have been successfully dealt with in short-time, nonequilibrium flights in a "hot structure" vehicle where load-bearing members are also

subjected to heat loads. However, for conditions of sustained cruise above Mach 7, the problems associated with the "hot structure" appear currently to be almost insurmountable. Certain refractory metals and ceramics now under development do, in fact, show promise of serving as load-bearing members at up to 3000° or 4000°F, but the problems of thermal growth, buckling, and oxidation at such extreme temperatures are of enormous magnitude. It seems clear, therefore, that the most fruitful structural approach for hypersonic vehicles will be based on external insulation and on cooling of load-bearing parts to reduce temperatures to levels where more conventional materials and structural concepts can be used. Basically, such insulation should be non-load-bearing so that materials may be used near their melting points, rugged enough to withstand skin-friction drag and vibration, and light enough not to impose unacceptable weight penalties on the vehicle. It would also have to withstand high skin temperatures without buckling or peeling off for the duration of several flights.

These considerations have stimulated interest in a new type of insulation, made of existing mate-

[1] G. J. Pietrangeli, "An Airbreathing Mach 7.0 Transport," *APL Technical Digest* 1, Nov.–Dec. 1961, 2–9.

Aircraft flying at hypersonic speeds in the atmosphere encounter such high temperatures and resultant thermal stresses as to create critical problems of thermal growth, buckling, and oxidation. To meet these problems, a new type of surface insulation made of existing materials is being successfully tested. With a configuration like roof shingles, this insulation transmits all aerodynamic forces to the aircraft structure while providing maximum thermal protection during sustained flight.

HYPERSONIC VEHICLES

rials, which promises to be light and efficient.[2] The principles of this novel insulation can be understood by reference to Fig. 1. It consists of thin plates of a high-temperature alloy or ceramic which are attached to the base structure at a small acute angle. Because of resemblance of the structure to that of shingles on a roof, the term *shingle insulation* is used to describe it. The shingles are spaced so that about 90% of the volume of the insulation is made up of air or combustion gas whose pressure, by virtue of leakage paths across the surface, is essentially in equilibrium with the static pressure on that surface. In this way, the aerodynamic forces are transmitted through the insulation to the base structure. Conductive heat transfer through the structure is quite small because of the long resistive path through the shingles and by virtue of the low conductivity of the gas within the structure. Problems of thermal stress are overcome by using very thin shingles, and since the upper surface consists of a number of small segments which are free to expand indi-
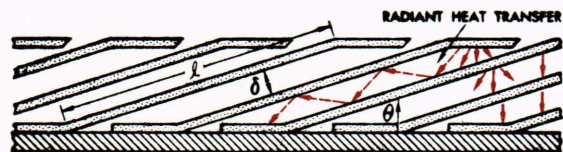

Fig. 1—Schematic drawing of shingle insulation.

vidually, there are no problems with gross thermal buckling. Substantial progress has been made on an insulation suitable for service up to about 2100°F on major areas other than stagnation points and combustion chambers. Modifications of the basic insulating structure are under development for service up to 4000°F.

Suitable methods have been developed for estimating the total heat transfer as the sum of heat being conducted through the shingle strips, heat conducted by the gas in the space δ, and heat transfer by radiation. From preliminary analysis, it was expected that a structure consisting of 0.008-in.-thick stainless steel or nickel base, super-alloy shingles inclined at about 7° would have a thermal conductivity of about 0.1 (Btu ft/hr °F ft²) when the upper surface was heated

[2] M. L. Hill, J. M. Akridge, and W. H. Avery, "Thermal Insulation for Hypersonic Vehicles," *ASME Aviation Conference*, Washington, D. C., June 26, 1962.

to 2000°F. Such a structure would therefore be quite effective in reducing the heat flux to the main portions of an airframe at speeds from Mach 7 to 12 at high altitude. Conductivity values of the order of 0.2 (Btu ft/hr °F ft²) at 4000°F are predicted for similar structures made of such ceramics as zirconium dioxide. This value is approximately one-fifth that of the best solid material available for use at such temperatures.

An experimental program has been carried out to determine whether the predicted structural behavior and thermal efficiency of shingle insulation can be achieved in practice. The specific areas that have been investigated are thermal conductivity in static air, structural behavior in supersonic flow, and thermal conductivity in supersonic flow. The results of these experiments show this to be a satisfactory type of insulation for a number of environments of practical interest.

Thermal Conductivity in Static Air

Cross sectional diagrams of two types of insulation that were fabricated for thermal tests are shown in Fig. 2. The shingles were inclined at an angle of either 7° or 14° and were made of Type 302 stainless steel in dies which "fold-stiffened" the edges and formed six dimples on each shingle to maintain a uniform spacing between them. Each shingle was pinned down at its trailing edge by louvers stamped in the adjacent shingle. This type of pinning permitted some slippage between shingles to allow for thermal expansion. The leading edges of the individual shingles were fastened to the base plate by spot welding and were spaced about 0.02 in. apart to allow for thermal expansion.

Apparatus for measurement of the thermal conductivity was constructed according to the schematic drawing in Fig. 3. The insulation panel was backed up with two separate water-cooled
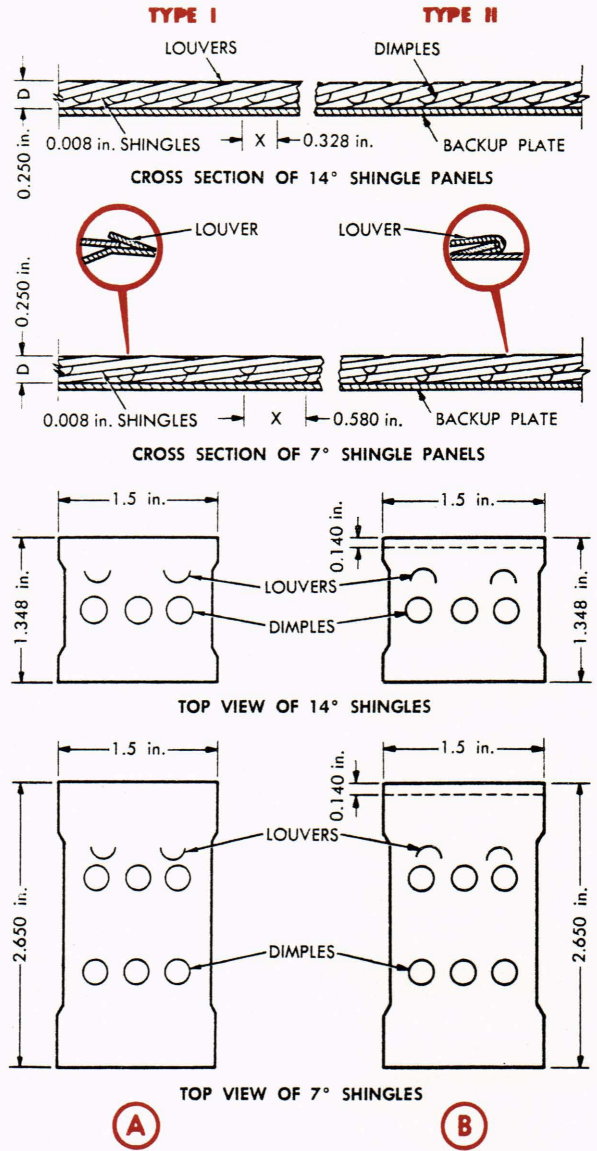

Fig. 2—Geometry of 7° and 14° staggered shingles, showing Type I and Type II louvers.
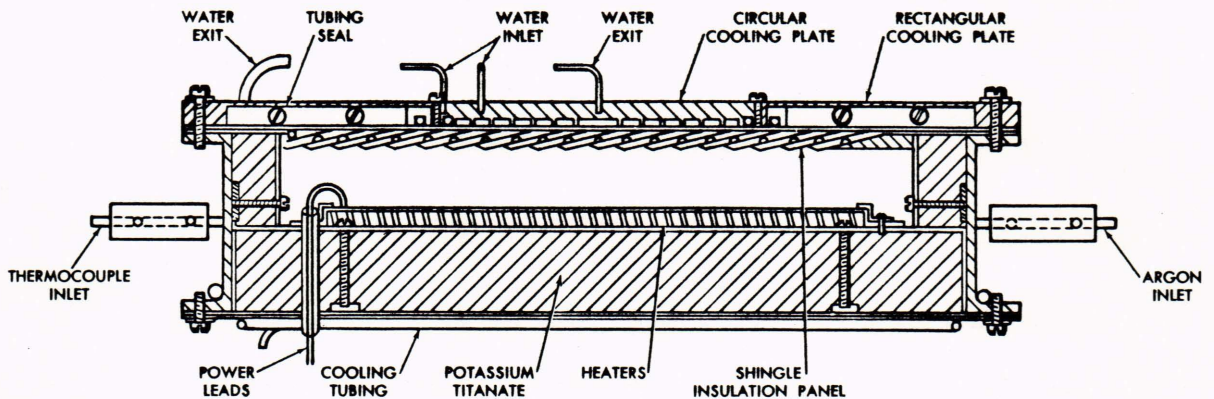

Fig. 3—Diagram of thermal-conductivity apparatus.

heat sinks. The central, 6.0-in.-diameter sink was sealed to the shingle base plate by a rubber "○" ring. Measurements of the flow rate and temperature rise of water in this central sink provided a measure of the quantity of heat flowing through the shingles. The temperature of the outer square heat sink was controlled to prevent lateral flow of heat from the center heat sink. The internal walls of the apparatus were covered with a 1.0-in. layer of potassium titanate insulation. A Nichrome resistance heater capable of dissipating 7 kw was mounted on the base.

The procedure followed for the heat transfer measurement consisted of allowing the shingle surface to come to a steady state at a selected temperature, after which data were recorded for a period of one to two hours. Thereafter, the surface temperature was raised in increments and the procedure of steady-state measurement was repeated. Measurements were also made during the cooling portion of the cycle and during reheating to determine whether any changes in conductivity had occurred as a result of heating to the higher temperature. It was found that the measurements were not very reproducible until the shingles had been heated to at least 1200°F; following this, reasonable reproducibility could be obtained regardless of the thermal history of the panel. This is believed to have resulted from changes in emissivity which must have occurred as the shingles became oxidized during the first heating.

Results obtained for the conductivity of the two configurations as a function of surface temperature are summarized in Fig. 4. Each point on these
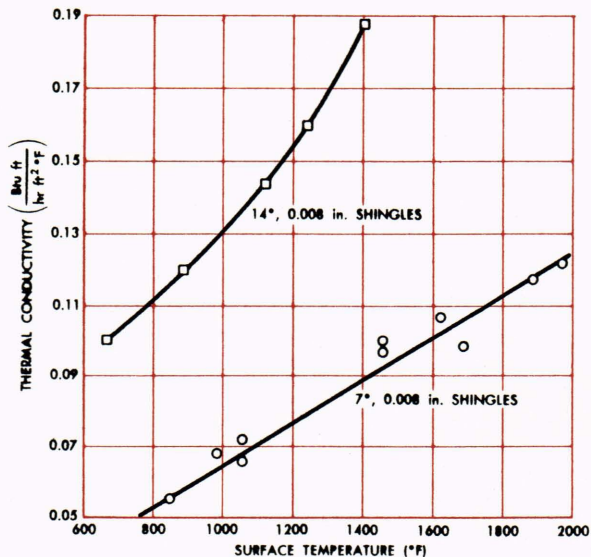
curves represents an average of at least five data points, and usually ten, at each temperature. The overall accuracy of the experiment is estimated to be about ±5%.

Other than oxidation, no pronounced changes in the structure occurred during these tests. A few of the trailing edges of shingles on the panel heated to 1960°F were warped slightly, but no significant distortion of the surface occurred.

Structural Tests in a Supersonic Free Jet at Sea Level Pressure

Nine one-square-foot panels of insulation were fabricated for structural tests. Both 7° and 14° staggered shingles were tested. Two thicknesses of shingles (0.005 in. and 0.008 in.) and two types of trailing edge attachment were employed on the 7° staggered shingles. The trailing edge attachment shown in Fig. 2A is referred to as Type I, while Type II, which proved to be far more satisfactory, is shown in Fig. 2B. A sharp 180° bend was made to stiffen each trailing edge and the reverse portion of the bend was inserted in the tabs of the underlying shingle during assembly.

Structural tests of shingles in supersonic flow were performed at the APL Propulsion Research Laboratory. A 4.0-in.-diameter free jet at atmospheric pressure was formed by a nozzle designed for Mach 1.6 at a chamber pressure of 62 psia and a mass flow of 15 lb/sec. Operation at up to Mach 1.75 could be obtained by a blowdown operation in which the nozzle was pressurized to about 80 psia. Runs were limited by the capacity of the air storage tanks to about five minutes' duration.

The panels were mounted on a stand fitted with a sharp leading edge to minimize shock losses. Each panel was subjected to a series of tests of increasing severity until they either had been destroyed or had survived five or more runs at the most severe condition. The "mildest" test consisted of exposing the shingles at 0° angle of attack at Mach 1.6. The panels surviving this test were then exposed at Mach 1.75 at angles of attack ranging from +8° to −8° and were finally exposed, at these same angles of attack, with a 0.25-in. by 1.0-in. bar in the jet at a distance of about 0.75 in. from the shingle surface. This bar caused a strong normal shock, severe turbulence, and large longitudinal pressure gradients on the upper shingle surface. Suitable static pressure probes were installed to determine how well these adverse pressure gradients were transmitted through the shingle to the base plate. The shadowgraph in Fig. 5 shows the rather violent conditions in the region of the shock bar when

Fig. 4—Thermal conductivity of 7° and 14° staggered shingles.

the jet was operated at Mach 1.6. Airflow was from right to left.

Insulation panels of Type I with 7° canted shingles and forward-facing louvers failed catastrophically during the first or second blowdown. Failure was associated with transient shock waves and pressure gradients formed while the nozzle was being brought up to pressure. The 14° structures of Type I were considerably more rugged and survived repeated testing at angles of attack from +8° to −8°. No tests were performed on these panels with the shock bar in place. Panels of
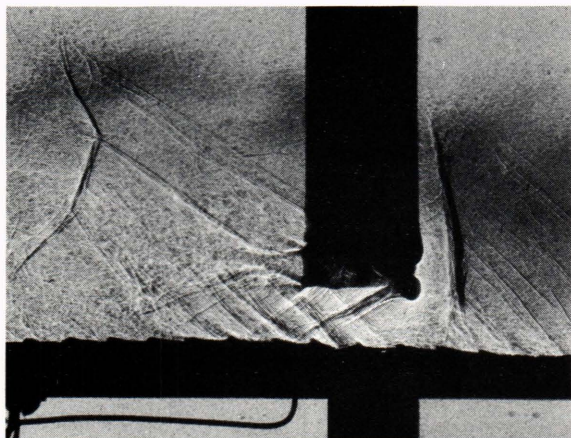

Fig. 5—Shadowgraph of a shingle test at Mach 1.6.

Type II with protected louvers and shingles as thin as 0.005 in. performed very well, remaining entirely intact and without oxidation after repeated runs over the entire range of angle of attack both with and without the shock-producing bar in place. The ability of the structure to transmit aerodynamic loads to the base structure was demonstrated during these tests, as was its ability to withstand permanently the large pressure gradients of the order of 50 psi per linear inch that existed in the region of the shock wave.

Performance of Shingles in High-Velocity Air

A series of shingle tests was also conducted in a Mach 5 wind tunnel at the Propulsion Research Laboratory to prove the structural integrity of shingles in an environment of high stagnation temperature at hypersonic velocity. We wished also to demonstrate that the shingles are effective as an insulation in this environment.

A photograph of one of the two models used is shown in Fig. 6. One model had shingles 0.005 in. thick and the other 0.008 in. thick. Both insulations were 0.25 in. thick and had 7° stagger with Type II trailing edge interlocks. The models were
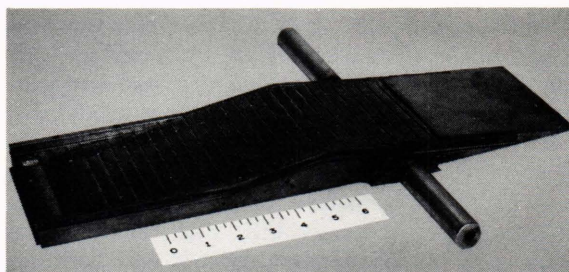

Fig. 6—One shingled wedge for a Mach 5 test.

mounted in the tunnel as shown schematically in Fig. 7. Tests of the structural performance of both models were made with stagnation temperature of 1750°F and stagnation pressures of 80 psia at a mass flow of 1.5 lb/sec. True simulation of Mach 5 at 95,000 ft was obtained with these conditions. Angles of attack ranging from +4° to −2° were employed. Provisions were also made for inserting a 0.25-in. water-cooled rod into the free stream to induce a shock wave to strike the model on the forward surface of the wedge.

When the model was set at 4° angle of attack, the 12° supersonic compression reduced the Mach number from 5.0 to about 4.1 on the forward ramp. This compression resulted in a relatively uniform heating of the forward surface to about 1350°F. Aft of the knee of the model, re-expansion of the gas occurred, and temperatures aft of the knee were below room temperature. Occasionally at low angles of attack, ice formed on the model in this area, clearly demonstrating the ability of the structure to withstand large thermal gradients.

Both models withstood several hours of testing at these conditions with no apparent distortion of the shingles. The photograph in Fig. 6 was made after the testing and shows that, apart from a minor amount of oxidation, there was no damage to the model.

Insertion of the water-cooled bar into the tunnel resulted in a strong shock wave that caused sharp pressure and temperature gradients on the compression surface. The surface temperature rose to 1650°F in the area of shock impingement and
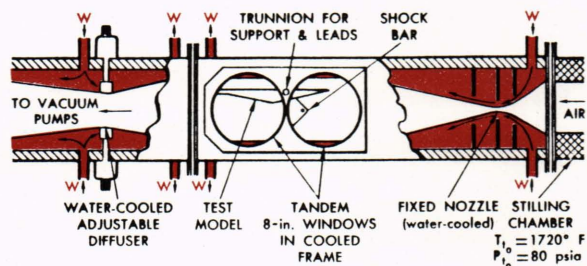

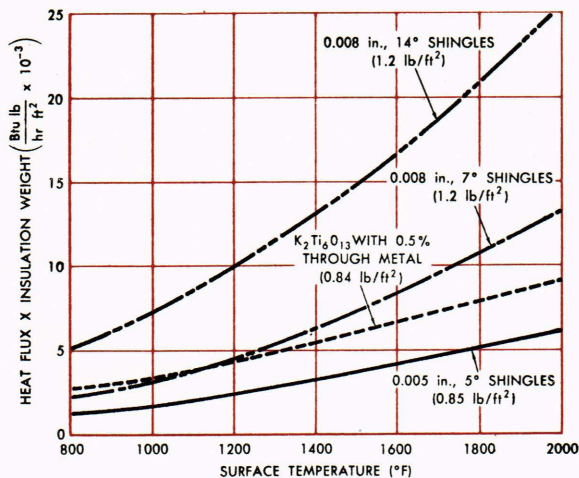Fig. 7—Diagram of the Mach 5 wind tunnel arrangement.

Fig. 8—Effectiveness to 2000°F of three configurations of shingles and of one other type of insulation.

decreased to about 1100°F within two inches aft of the line of shock impingement. No observable buckling or distortion of the shingle surface occurred.

The effective thermal conductivity of the shingle under conditions of Mach 5 flow, with the flat plate at zero angle of attack and with the shingle surface at 8° angle of attack, was determined by measurements of the temperature rise of water flowing through copper tubing attached to the base plate of the shingle structure inside the model. Stagnation temperatures were limited to 1400°F in these tests because of some structural damage to the air heater that occurred in the earlier tests. As a result, the maximum temperature that could be obtained on the compression surface during conductivity tests was 1050°F. The calculated value for conductivity at these conditions was 0.075 (Btu ft/hr °F ft²). This value of conductivity is only about 15% larger than that determined in static experiments (see Fig. 4).

It is evident from the results of these wind tunnel tests that the structures of 0.008-in.-thick shingles with a 7° stagger have more than adequate strength for many applications up to 2000°F. Actually, a thinner shingle material and more acute angle could probably be used to achieve lower heat flux. It would not be impractical to fabricate panels with a 5° stagger out of 0.005-in.-thick material, but further decreases in these two variables would introduce unreasonable difficulties in fabrication. An estimate of the heat flux through such a panel is shown in Fig. 8 where three configurations of shingles and one other type of insulation are shown for comparison. The latter, which has been studied elsewhere in various modified forms, consists of a structure in which a very efficient insulator, fibrous potassium titanate in this case, was provided with the necessary erosion protection by means of a thin metal cover; this was attached to the base by vertical webs or clips.

Up to 1100°F, the 7° shingles are nearly as good as a potassium-titanate-filled structure having a 0.005-in.-thick cover plate and 0.5% through-metal (bolts, clips, etc.) to hold it in place. Whatever methods of holding the cover on may be devised, it is very difficult to reduce this "short circuit" area below 0.5%. Conductivity of the through-metal is about 500 times as large as that of the insulation material, and the excessive heat flux through these short circuits can easily negate the advantages of the potassium titanate.

The 5° shingle configuration, employing 0.005-in.-thick shingles is seen, in Fig. 8, to be the most efficient from a heat-transfer point of view. This has not yet been tested structurally, but based on our tests of the 7° configurations it seems likely that it could be adequate for many environments of practical interest.

Conclusions

From the viewpoints of both weight and thermal efficiency, the use of shingle structures appears to be an attractive method of insulating airframes at hypersonic speeds. Structural integrity at high Mach numbers and altitudes has been proved, and we have established with reasonable certainty that even more severe environments can be endured. It appears likely that a shingle structure could be used at temperatures very near the melting point of the materials used since problems of creep and stress rupture are essentially absent. The segmented structure resulting from use of these shingles provides a means of avoiding the severe thermal stress and buckling problems associated with structures using continuous skins. Essentially no ductility of the materials is required to accommodate these stresses or those associated with flexure of the cooled load-bearing structure. This feature is expected to permit the use of refractory metal and ceramic shingles in some applications and to provide an extension of the useful temperature range up to 5000°F.

Further experiments at higher Mach numbers are now in progress, as are experiments on the use of shingles in higher pressure environments. Successful performance in such experiments as these is expected to lead to use of shingles in combustor and nozzle applications as well as for insulating high-pressure piping in aerodynamic test facilities.