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CERAMIC AND COATING APPLICATIONS IN THE HOSTILE ENVIRONMENT OF A HIGH TEMPERATURE HYPERSONIC WIND TUNNEL

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ABSTRACT

The Langley Research Center's 8-Foot High-Temperature Structures Tunnel (8-Ft. HTST) is a Mach 7, blowdown wind tunnel used to investigate aerothermal-structural phenomena on large-to-full scale high-speed vehicle components. The high energy test medium, which provides a true-temperature simulation of hypersonic flow at 24 to 40 km altitude, is generated by the combustion of methane with air at high pressures. Since the wind tunnel, as well as the models, must be protected from thermally-induced damage, ceramics and coatings have been used extensively. The details of in-service applications, operating conditions, behavior of the ceramics and coatings used to date, and planned applications are presented and discussed.

Coatings have been used both to protect various wind tunnel components and to improve the quality of the test stream. Proper cleaning of components and coating with epoxy, zinc, and polyurethane layers has been used to protect the easily corroded surfaces of the combustion chamber interior wall and inlet air region; this process has effectively reduced the iron oxide debris in the test stream that can damage fragile models. The approach lip, which forms part of the film cooling injection region for the throat, was flame sprayed with nickel aluminide and zirconia to reduce the temperature (and resultant operating stress) of the metal. In addition, a nickel coating was applied to a large ejector expansion joint in the wind tunnel to prevent oxidation of the metal.

Use of non-intrusive data acquisition techniques, such as infrared radiometry, now allows more widespread use of ceramics for models to be tested in high-energy wind tunnels. A thick, castable alumina ceramic was bonded to an aluminum strongback to simulate the vertical tail of a Space Shuttle model for a test in the 8-Ft. HTST. For another test, the nose tip for a conical metal model was fabricated from a castable ceramic, and was attached to the metal by a spring loaded device to accommodate the difference in thermal expansion between the ceramic and the metal.

Planned modifications for the wind tunnel include more extensive use of ceramics in order to minimize the number of active cooling systems and thus minimize the inherent operational unreliability and cost that accompanies such systems. Metal wind tunnel components that are scheduled for replacement with ceramic components include the first minimum section, or throat, and the model support strut.

INTRODUCTION

Hypersonic wind tunnels simulate flight at high velocity and high altitude. These facilities must store high pressure gases and transport those energetic gases in a controlled manner, provide the proper flight simulation environment, meet strict safety requirements, and have a reasonable operational lifetime without undue or prohibitive maintenance. As the size and Mach number of a wind tunnel increase, problems with the design and operation problems increase. Some of the procedures and problems associated with wind tunnel design are covered in ref. 1. The high energy levels encountered result in high heat flux to the wind tunnel and models. Because of their high temperature capability and low thermal conductance, ceramics play a key role in these facilities. Blowdown wind tunnels present the additional problems of time dependent energy transport and heat flux. These phenomena result in high thermal stress as well as mechanical stresses induced by the containment of high pressure gases.

The Langley Research Center's 8-Foot High-Temperature Structures Tunnel (8-Ft. HTST) is a Mach 7, blowdown wind tunnel used to investigate aerothermal-structural phenomena on large-to-full scale high-speed vehicle components. The high energy test medium, which provides a true-temperature simulation of hypersonic flow at 24 to 40 km altitude, is generated by the combustion of methane with air at high pressures. Since the wind tunnel, as well as the models, must be protected from thermally-induced damage, ceramics and coatings have been used extensively. The details of applications of coatings and ceramics for tunnel protection and for ceramic aerothermal models are presented in this paper.

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THE 8 FT-HTST TEST FACILITY

The test facility (fig. 1) is a high temperature blowdown type wind tunnel that operates at a nominal Mach number of 7. The wind tunnel is used primarily to test and develop structures and thermal protection systems (TPS) that can withstand the severe environment of hypersonic flight including reentry flight of space transportation systems. The uniqueness of the facility is its extremely large size combined with hypersonic flight simulation capability. The test area extends for 4.3 m with a useable test core of almost 1.5 m in diameter. This combination allows many full scale flight components to be tested under realistic conditions; for example: the Hypersonic Research Engine (HRE) (see ref. 2); models of the Space Shuttle elevon (see ref. 3); reentry vehicles (see ref. 4); and other vehicles or components (see ref. 5). Size is an important parameter in aerothermal testing because internal vehicle heat transfer phenomena cannot be scaled. Ceramics have been used extensively as models or components of complete full scale flight vehicles. The high temperature capability and low thermal diffussivity of ceramics make these materials ideal for non-intrusive data gathering equipment such as scanning infrared radiometers.

A schematic of the wind tunnel is shown in figure 1. High pressure air and methane flow to and react in the combustion chamber. The pressure in the combustor can be as high as 27.6 MPa and the temperature as high as 2250 K. The hot combustion product gases are accelerated through a converging nozzle and then expanded by a diverging axisymmetric, contoured nozzle to Mach 7 into a free jet test chamber. The exit diameter of the nozzle is 2.44 m. The high velocity flow is decelerated in a supersonic diffuser, then flows through a mixing tube aided by a single stage air ejector, and finally exhausts through a subsonic diffuser. In addition to its aerothermal testing capabilities, the facility is equipped with radiant heaters in the test section. These heaters allow the static simulation of the high-temperature long-duration thermal environments typical of atmospheric reentry missions. Various components are made of ceramics to enhance operation, prevent thermal damage, and lower thermal stress. Coatings are used to prevent corrosion and prevent particles such as iron oxides from entering the test stream and damaging fragile thermal protection system test models by high velocity impact. Thus, ceramics and coatings are used to great advantage in the successful operation of the facility.

For a wind tunnel to be of value, reliability, durability of components, and reasonable cost of operation are prime considerations. The following will discuss areas and components of the wind tunnel where this philosophy has been implemented through the use of coatings and ceramics.

COATING APPLICATIONS

Combustor

The combustor design arrangement is presented in figure 2. The combustor consists of an outer housing or pressure vessel that is protected from the high temperature (2250 K) combustion gases by a double pass regenerative-type thermal protection system of liners. The pressure vessel is laminated SA-105 steel. The liners are 405 stainless steel (outer) and 201 nickel (inner). The pressure vessel is welded to two forged steel end barrels, on one of which is welded the combustion air manifold torus, and two high pressure closures of steel (air inlet area). The approach section of nickel and copper is the first part of the converging nozzle. At the end of the approach section, air is injected to cool the converging-diverging nozzle of Inconel 750.

The air enters the torus through two reinforced steel nozzles and is distributed through twenty holes in the forged barrel. The air is cold (270 K) as a result of the throttling process from the 41.4 MPa air storage bottle-field. The pressure is about three per cent above that of the inside of the combustion zone. The velocity is a maximum of 32 m/s in the twenty inlet holes in the forged barrel. The air flows downstream in the annular passage between the combustor pressure vessel and outer liner; the air then turns and flows upstream in the annular passage between the outer and inner liners. As the air flows upstream, it cools the hot inner liner and increases in temperature about 72 K. The air turns again and flows downstream through the fuel injector where the methane fuel reacts with the oxygen in the air elevating the temperature to as much as 2250 K at pressures between 4.14 MPa to 27.6 MPa. Inside this combustion zone the hot gas flows at a velocity of only 14 m/s. The time variant pressure may be as high as two to three percent of the total pressure and is centered about 30 Hz. This hot gas is first accelerated by the approach section to 90 m/s. At the end of the approach section, air is injected to film cool the nozzle. As the hot gases accelerate in the nozzle, the velocity increases to 880 m/s at the minimum (throat) while the pressure decreases to about 55 percent of the total pressure. In the diverging section of the nozzle, the gas is expanded to Mach 7 with a velocity of 2,000 m/s.

The pressure vessel and air inlet areas of the combustor had corroded as a result of exposure to cold high pressure air, and later, after the run-exposure, to warm humid ambient air. The ambient air reached these areas through the open flow path from the diffuser through the nozzle to the combustor. The oxidation was mild on the laminated pressure vessel and severe in the air inlet area. Particles of rust dislodged during tunnel operation, were entrained in the stream and accelerated to very high velocities, sometimes causing serious damage to objects impacted. For example, flight weight fragile TPS such as Reusable Surface Insulation (RSI) would have numerous impact craters, if exposed normal to the flow. Inspection of the air storage field and pipelines transporting the air revealed little or no oxidation. The air in these regions is very dry with a dewpoint of 205 K and the pipelines were coated with epoxy paint. The isolation and the main air flow control valve prevented ambient air migration to these regions.

The combustor pressure vessel was, therefore, cleaned and coated, because testing of TPS concepts such as Reusable Surface Insulation (RSI) (ref. 6) and newer TPS such as the multiwall concept (refs. 7 and 8) can not tolerate sustained high energy impact damage. The difficulty of the cleaning and coating effort was compounded by the inaccessibility of the air inlet area and the fact that the region is under high pressure (up to 27.6 MPa). Conventional acid cleaning with inorganic acids would result in possible hydrogen embrittlement with a consequent compromise of the pressure vessel integrity unless the metal was heated to 450 K for four to six hours (not possible because of size and mass).

Organic acid salts provided a solution to the cleaning problem (refs. 9 and 10). A 10 percent solution of hot ammonium citrate at 358 K in contact with the oxidized steel dissolved the iron oxides without attacking the steel. Since the ammonium citrate removes the oxides by a complexation type reaction rather than acid dissolution, the problem of hydrogen embrittlement is avoided. Any remaining organic acid was neutralized with trisodium phosphate and flushed away with hot, 358 K, water. After the process was complete, a phosphate conversion coating was applied. Again the neutralization was repeated until the pH of the circulating solution was 7. Next a 95 percent zinc/epoxy coating was applied by spraying. After this coating was dry, a light coat of epoxy primer was applied. The final step was to spray marine grade polyurethane on the prepared surfaces. The coating has been in service for about one year to date and has provided the desired clean test medium. There has been virtually no impact damage during the tests conducted since the combustor pressure vessel and air inlet area were cleaned and coated. Inspection and coating repair, if necessary, will be done annually.

Future scramjet and other engine testing will require oxygen replenishment of the combustion products (21% O_2), so the air will be raised to 40 percent by volume of oxygen content. The O_2 enriched air may not be compatible with organic coatings such as expoxy and polyurethane. These coatings will have to be removed, if this is the case, and coated with nickel, copper, or ceramics. The nickel coatings are very expensive but durable; easily applied non-metallics would be highly desired for cost considerations. Strong adherence, long life, effectiveness as an O_2 diffusion barrier to the underlying steel, and ease of repair would be guiding considerations.

Approach Section and Lip

The high temperature (up to 2250 K) and high pressure gases (4.14 to 27.6 MPa) are accelerated by a water cooled converging approach section as shown in figure 3. The velocity is increased from 14 to 90 m/s by the approach section. As the velocity increases, the heat flux increases; thus, the approach section is convectively cooled by water. After the flow has reached a Mach number of about 0.1, the nozzle is then film cooled with injected air. The approach lip is located at the very end of the approach section and forms part of the cooling air injection nozzle. The lip is made of copper and nickel and cooled by conduction to the water of the approach section and by convection to the coolant air. However, the heat flux to the lip was so high it would overheat and distort causing large distortions in the symmetry of the air film coolant. The temperatures and thermal stresses in the lip were lowered to acceptable levels by flame spraying a coating of gradated nickel aluminide and zirconia to the metal. The 0.25 mm coating was applied to the approach section and lip with the component heated to about 600 K. This procedure imposes a negative compressive preload on the coating when it is cooled. The nickel aluminide has a high bond strength and an intermediate coefficient of thermal expansion (CTE) that helps alleviate the strain incompatibility between the high CTE copper and the low CTE zirconia. Examples of this technique can be found by consulting refs. 11 and 12. The technique of using a gradated coating with a thermally induced compressive preload has been very successful. The coating has not spalled or degraded after five years of service and 400 thermal cycles.

Ejector Expansion Joint

The ejector expansion joint is located near in the pipeline supplying air to the air ejector (fig. 1). The expansion joint allows the wind tunnel to move and not overload the ejector air pipeline. During operation the joint has a 2.4 kPa differential pressure load; after the test run the metal surfaces are cold (Joule-Thompson effect) caused by throttling from 41.3 MPa to 2.41 kPa and exposed to humid ambient air after the wind tunnel run. This environment caused the expansion joint to corrode.

An electroless nickel plating was applied, by a process described in ref. 13, to the inside wall of the expansion joint to protect the steel from corrosion and to evaluate the durability of the coating under operating conditions. To date, there have been 110 cycles of wind tunnel operation with this coating. A recent inspection revealed the coating intact and non-degraded. Nickel coatings such as this could be used in other areas of the wind tunnel such as the combustion chamber, air piping, and related areas. Although this application was successful, coatings such as electroless nickel may be too expensive for large applications.

WIND TUNNEL CERAMIC COMPONENTS

Large Panel Holder

One of the large panel holders used for aerothermal and static radiation testing is shown in fig. 4. The panel holder is a large rectangular slab with a sharp leading edge, with the plane of the top surface faired to the lower surface by a 20 degree bevel. If required, aerodynamic fences are used to provide parallel flow over the surface. The relatively long length (102 cm) from the leading edge to the test panel location is required to properly develop a thick turbulent boundary layer for aerothermal testing. Test panels may be as large as 152 cm long and 108 cm wide.

During a typical aerothermal test (15 degree angle of attack) the panel holder will be exposed to a heat flux of 310 kw/m^2 and a shear stress of 240 Pa for 40 to 90 seconds. During a typical static radiation reentry heating simulation, the panel holder surface temperatures may be 1200 K for as long as 2000 seconds. The panel holder surface is covered with foamed fused silica blocks, shown in figure 4, to protect the underlying structure from these severe environments. The density and thickness of the blocks can be varied to suit the tests. The low thermal diffusivity of the foamed fused silica prevents the bond line between the blocks and the metallic substructure from exceeding 400 K. This low temperature permits the use of elastomeric bonding agents such as RTV-560. Elastomeric bonds not only provide adequate load transfer but also accomodate the thermal expansion mismatch between the structure and the silica blocks.

There probably is a slight amount of silica phase transformation to cristobalite on the surface that is removed as a fine dust and carried downstream by the flow. These particles are of little consequence to most test programs because the particles are so small and they travel parallel to the surface and do not impact test panels. The only tests that may have been influenced by these particles were tests of ablative TPS such as those of ref. 14. Further information about the panel holder and the flow conditions may be found in ref. 15. The silica blocks have never cracked or failed in service due to thermal loads although inadvertent mechanical loads such as falling objects have cracked the silica tiles.

Ceramic Throat Insert

The present (Inconel 750) nozzle in the 8-Ft. HTST (fig. 5(a)) requires a large amount of cooling air (as high as 30 percent of the total flow) to prevent overheating and cracking (plastic strain failure) due to the high thermal stresses. This large quantity of cooling air reduces the size of the useable test core and compromises the aerodynamic quality of the test medium. Active water cooling or transpiration cooling systems are not desirable because they require large modifications, are subject to malfunction because of complexity, and are costly. A ceramic throat that could be used as an insert would permit much higher surface temperatures and therefore require much less film coolant. Although ceramic nozzles are not new (see ref. 16), a reusable ceramic nozzle of the size required is beyond current practice. This concept is described in detail in ref. 17. The most promising concept, shown in fig. 5(b), is being built. The material will be composite of silica fibers with four directional orientations in a silica matrix. The silica fibers are oriented in four directions, 0 degrees radially and ± 60 degrees relative to the radial fibers in planes normal to the axis and the fourth fiber orientation parallel to the axis. The bulk silica is built up and densified by heating around the fiber matrix until the desired shape and properties are achieved. The details of the fabrication process are proprietary (Science Applications, Inc., Irvine, CA).

The ceramic insert will be located in the highest heat flux area of the nozzle to attain the greatest reduction of coolant air. Calculations indicate that the amount of air required for cooling can be reduced by at least one half with a gain in the usable test core of about 0.3 m in diameter (44 percent increase in area). The ceramic insert is prestressed in compression by air on the exterior of the ceramic insert. The cold high pressure air obtained during the startup of the wind tunnel is vented to a shallow cavity behind the insert, by the scalloped metal band next to the nozzle insert retainer. The cavity is sealed at the downstream end trapping the air on the outside of the insert. After the fuel ignites, the hot gas is accelerated in the nozzle reducing the pressure inside the insert. The pressure differential between the static air outside and the accelerated flow inside provides a mean compressive load of 9 MPa on the insert. The only axial loads on the insert are due to momentum change loads (thrust) and net downstream pressure loads. These loads are transferred to the metal nozzle through the metal positioning ring and metal pressure seal on the downstream end of the ceramic insert. This load path keeps the ceramic insert loaded in compression in the axial direction.

The ceramic nozzle was analytically evaluated in all the known tunnel operation environments. These environments included the thermal and mechanical loads encountered on flow start and unstart, operation at total temperature levels from 2250 K down to 270 K, operation at total pressures up to 27.6 MPa and all known transient loads. The most severe transient load is encountered when the fuel flow is stopped and the total temperature of the flow stream drops from 2250 K to about 300 K in less than one second with the air flow maintained so that all the methane can be purged. This condition can cause very high thermal stresses in the ceramic.

Analysis indicates that the design can accommodate all these loads. However, the maximum use temperature of the ceramic will be limited to 1420 K to minimize a silica phase change and enhance the nozzle's durability. Higher use temperatures could be possible, (1600 K) if a thin layer of silicon nitride was reaction bonded on the inside surface to elminate erosion problems. Calculations indicate that this too would be a viable concept. Evaluation of these designs will be made after some service time. However, before these expensive nozzles are evaluated, an inexpensive instrumented cast ceramic nozzle insert will be fabricated and tested to characterize the film cooling environment and to compare calculated predictions with those measured. This ceramic has a composition of 55 percent Al_2O_3, 38 percent SiO_2, 5 percent CaO, 1 percent TiO_2, 0.7 percent Fe_2O_3, 0.2 percent MgO, and numerous minor constituents. The ceramic is based on naturally pure andalusite, a polymophic form of sillimante ($Al_2 \cdot SiO_5$), quartz (SiO_2), and pyrophyllite ($Al_2O_3 \cdot 4SiO_4 \cdot H_2O$) and has reaonsably good thermal and mechanical properties. Calculations indicate that this ceramic cannot survive the maximum service temperature but could survive lower operational pressures and temperatures. This will be adequate for film coolant evaluation and will be used in an expendable mode. This is a cost effective approach because the cost of the material, including fabrication is about 1/10th of the silica composite substitute. The end goal of this project is to have a complete ceramic nozzle 126 cm long (see fig. 5b) capable of operation at 1600 K or higher with little or no refurbishment or replacement required.

Model Support Sting

The present water cooled stainless steel model support sting (see figs. 1 and 4) is a high cost replacement item. Plans are in progress to augment this sting with a lower cost, uncooled high strength steel sting encased with a thick castable ceramic for thermal protection. This is an attractive concept because it allows simple construction and the castable ceramics can be repaired in place by simple methods. Two alumina base candidate materials are being considered. The performance of these ceramics in the wind tunnel environment has been proven in model tests. One material is 90 percent Al_2O_3 with 3 percent MgO and 6 percent P_2O_5 plus numerous minor constitutents; the other material is 95 percent Al_2O_3 and 5 percent CaO. Both of these ceramics are easily processed and have adequate mechanical properties to survive thermal shock and localized heating. The processing will include an air dry at 350 K for 24 hours and a thermal soak (with the temperature being raised slowly) to 600 K for 4 hours. The new sting will permit varied model locations in the test stream; no cooling will be necessary; and large debris impacts will not be catastrophic.

AEROTHERMAL MODELS

Many models and concepts are tested in high temperature wind tunnels. Ceramic models are well suited to certain tests because of their high temperature capability and low thermal diffusivity. The ceramic models can be scanned by infrared or optical pyrometers providing detailed temperature images of the surface without the use of large numbers of thermocouples. Localized heating can easily be photographed when the temperature exceeds 1200 K; lower temperatures can be seen and recorded with the higher wavelength infrared instruments. When the thermal diffusivity of the material is low, the heat flux can be calculated from the temperature history of the surface. Thus, at elevated temperatures, ceramics in combination with radiometers can provide extensive information that previously required numerous thermocouples and heat flux gages.

Slip Cast Fused Silica Models

In the past many ceramic models were built of slip cast fused silica. Some of the work is reported in ref. 18. Most of this work was performed in the pilot facility of the 8-Ft. HTST. This facility is basically the same as the large wind tunnel, except that it is about 1/12th the size. The shapes ranged from simple blunt flat faced reentry models to complete flight vehicles. A hypersonic aircraft complete with engine inlets is shown in fig. 6. This work is reported in ref. 18. The hottest areas such as the nose (fig. 6b) and engine inlets are at temperatures as high as 1500 K with the freestream total temperature being 1800 K at Mach 7. The models tested were relatively small (8-12 cm in length); larger models such as the planetary entry body described in ref. 19 were built and tested. A photograph of the model in the test section of the 8-Ft. HTST, and during the tests, are shown as figs. 7 and 8. The temperature was obtained by the use of a variable exposure photographic pyrometer as described in ref. 20. This technique only works when the temperature of the surface is 1200 K or higher. The low thermal conductance of the ceramics enable detailed temperature measurements since the temperature field is not altered by rapid conduction to cooler areas of the model. Scanning infrared radiometers (ref. 21) enable the measurement of temperatures as low as 250 K and up to 2500 K. Each slip cast fused silica model required about 300 to 600 hours to build. However, the models held up well in the wind tunnel environment. Today, most ceramic models are made of castable alumina-silica material instead of the slip cast silica because of its lower cost, high strength, and easier fabrication (about 160 hours).

Gas Jet Nose Tip (GJNT) Tests

The nose of a reentry vehicle in the earth's atmosphere is subjected to high aerodynamic heating as well as rain and suspended particle erosion. One concept for protecting the nose (see refs. 22 and 23) is a forward facing sonic or supersonic jet directed through the tip of the nose inducing a secondary counter flow which displaces the bow shock wave and blankets the tip with a protective layer of cool gas. Nosetip cooling by discrete fluid injection is not new (ref. 24), but the use of the gas jet nose tip (GJNT) for erosion protection as well as cooling is fairly recent. A metal and ceramic model to test the concept is shown in figure 9. The purpose of these tests was to measure the temperature distribution on the ceramic nosetip of the model (fig. 9) and the temperature, heating, and pressure data on the metal shell far downstream of the injection point.

The model shown in fig. 9 is essentially an 18° cone. The nose is made of a cast alumina silica ceramic and the aft skirt is made of thin rib-stiffened 303 stainless steel. The ceramic nose assembly is shown in detail in fig. 10. In a test the ceramic reaches temperatures as high as 1700 K near the aft end. Thermal expansion of the assembly is accomodated by the spring loaded nose tip with the spring being compressed as the ceramic expands. The internal structure is used to transport high pressure cold (275 K) gaseous nitrogen used for cooling to and out the nose tip. The low thermal diffusivity of the ceramic and short test times (10 to 40 seconds) kept the internal temperature low enough so that rubber O-rings and washers could be used for sealing the high pressure gas. The alumina silica ceramic (45 percent Al_2O_3, 50 percent SiO_2, and 3 percent CaO with the remainder being MgO and Fe_2O_3) was cast in a fiberglass mold to the contour and geometry shown and required no machining. The ceramic slurry (about 8 percent water) was poured into the mold and vacuum cured for 15 minutes. After 24 hours the model was removed from the mold and allowed to air dry an additional 12 hours. A two step, thermal curing cycle, 12 hours at 530 K and 5 hours at 1640 K, completed the fabrication process.

Two infrared (IR) scanning systems were used to remotely determine the model surface temperatures. A scanning IR camera with a 3 1/2 degree lens was mounted above the model and another radiometer with an 8 degree lens viewed the model from the side. The test data from both the scanning IR radiometers were recorded on FM wide band analog magnetic data and a disc recorder. The data were played back on various displays for instant viewing. Quantitative information was later generated from this data by calibrating the camera responses as functions of surface temperatures. The digitized data tapes were reduced to engineering units as required. The temperature fields were plotted as isotherms as shown by figure 11 (typical). The figure shows the increase in temperature as the distance from nose increases. The data beyond 30 degrees from the windward ray are deleted because of the rapid decrease in emissivity with view angle. The model was at a 5 degree angle of attack which caused the nitrogen flowing through the nose to cool the ceramic unsymetrically.

The recorded temperature histories and ceramic thermal properties were input to an analytical procedure (ref. 21) to calculate heat flux to the nose. This method is only accurate during the initial temperature rise of the material when radiation is negligible. For the GJNT tests this was only true during the first 2 to 5 seconds of each test. The method yields convective heat transfer coefficients with an accuracy of about 10 percent. More rigorous analyses are available (refs. 24 and 25) which consider conduction in depth, heat storage, and radiation. These analyses employ finite difference numerical methods and require long computational times and are therefore used sparingly to check the faster method of reference 21. Remote data gathered with scanning radiometers using a ceramic as the model in high temperature environments solves the problems associated with the use of large numbers of thermocouples. In fact in certain applications, such as the GJNT test, this was the only feasible way of obtaining the information needed. After 5 to 6 test runs of up to 40 seconds each (fig. 12) surface cracks appeared on the ceramic nose and it was replaced. The superficial cracks, enhanced for photography with an alcohol wash, were the result of severe multidimensional thermal gradients encountered at high angle of attack (20 degrees).

Space Shuttle Vertical Tail Model

A section of the Space Shuttle vertical tail (model mounted upside down) with a hemispherical dome cylinder assembly fitted to the simulated tail is shown as fig. 13. The dome assembly is attached to a cylindrical skirt section which in turn is mounted to an existing sting. The cylindrical skirt section and tail simulation are insulated with molded sections of a castable alumina with a small (3 percent) amount of magnesium oxide and phosphorous pentoxide (6 percent) present. The molded sections on the cylindrical skirt are 3 cm thick and those on the simulated tail are 8 cm thick. The dome assembly was made of blocks of low density silica covered with a thin coating (0.4 mm) of high density silica impregnated with silicon carbide to increase the emittance of the blocks. Conical cavities were cut in the silica to simulate instrument (IR or photographic) window view ports. The model was used to determine heating distributions on the complex dome and vertical tail at Mach 7.

Two thermography systems were used to remotely determine the model surface temperatures. A scanning IR camera was mounted at the top of the test section near the lip of the nozzle and viewed the model from a forward vantage point. The data was recorded and reduced in the same manner as the GJNT test described earlier. A photographic pyrometer as described earlier (ref. 20) was used to supplement these data measurements.

The configuration of figure 13 produced a very strong shock wave interaction (ref. 27) that caused intense heating of the ceramic vertical tail. The heat transfer coefficient was as much as five times that of the spherical dome stagnation point coefficient. This severe thermal load had no detectable effect on the cast ceramic used to simulate the vertical tail. Although too heavy for flight, this ceramic could have many other applications where severe thermal loads are a problem.

Canard Model

Canard control surfaces mounted near the forward area of an aircraft or missile are subject to and induce interference heating which can approach four times (ref. 28) that of the normal boundary layer heat flux. This high heating may be reduced by the injection of a coolant gas upstream of the canard. A cast ceramic canard with a steel substructure was built (figs. 14 and 15) to investigate these phenomena. The ceramic was the alumina-silica composition used for the GJNT model and it was separated from the steel by soft asbestos cloth to accommodate thermal expansion mismatch. Pressure orifices were also cast in the canard. The canard will be mounted on a Rene' 41 cone as shown in fig. 16 and tested to determine the effect of the canard on the heat transfer to the instrumented curved surface of the large cone with and without film cooling upstream of the canard as well as the heat transfer to the canard itself. The large cone can be fitted with a GJNT, a film cooling nose tip (FCNT), and a transpiration cooled nose tip (TCNT). The canard will be used with all three. The cone itself is heavily instrumented and can measure surface phenomena (heat flux, pressures, etc.) as well as conditions remote from the surface by the use of eight retractable boundary layer probes. The canard will be mounted in a forward location replacing one of the boundary layer probes (see fig. 16). The bow shock wave from the nose of the cone will intersect the canard when mounted in the forward location. The large cone will also be used for extensive tests of mass injection cooling. Scanning IR radiometers mounted above and to the side of the model will make detailed temperature measurements on the canard and thermocouples will be used to measure temperatures on the metal cone. The small size and shape of the canard plus expected high temperatures make extensive thermocouple instrumentation impossible. The use of the ceramic canard with a scanning radiometer makes the detailed thermal measurements practical. The canard will be tested with the approach boundary layer both laminar and turbulent, and with and without coolant mass injection from the nose of the cone. To determine the performance of the ceramic, the initial canard model was exposed to elevated temperatures by heating with acetylene torches. The ceramic did crack near the stainless steel strongback and near the pressure orifices; however, the component remained structurally sound and intact. More separation between the steel and the ceramic will be used for the final wind tunnel model by increasing the thickness of the asbestos cloth.

CONCLUDING REMARKS

Ceramics and coatings have been used to enhance or facilitate operation of the NASA Langley 8-Ft. High Temperature Structures Tunnel. Coating applications included coatings for oxidation protection and gradated coatings of nickel aluminide and zirconia to lower thermal stress. Ceramics are being used for wind tunnel components such as the throat insert or to protect components such as the large panel holder. Generally, the ceramic components permit higher operational temperature, enhance the flow quality and size, are inexpensive, easy to repair, and require no active systems. Silica, as a composite, will be used for the nozzle and is used as foamed fused insulation blocks for a large test panel holder. New castable alumina-silica compositions will be used for experimental nozzle inserts and to thermally protect a rugged model support sting.

Ceramic aerothermal models have been used extensively because of the needed high temperature capability combined with low thermal diffussivity. This combination of properties, when used with optical pyrometers or scanning infrared radiometers, allows accurate thermal images of the surface to be obtained with film or stored on magnetic tape for instant playback or computer processing. These same properties also permit the calculation of heat flux using surface thermal history. Ceramic models have been made of slip cast fused silica and cast alumina-silica compositions. The models have usually had complex shapes and a minimum of instrumentation because the data could be obtained remotely. Future tests will make more extensive use of ceramics for elevated temperature evaluations of aerodynamic configurations and thermal protection systems.

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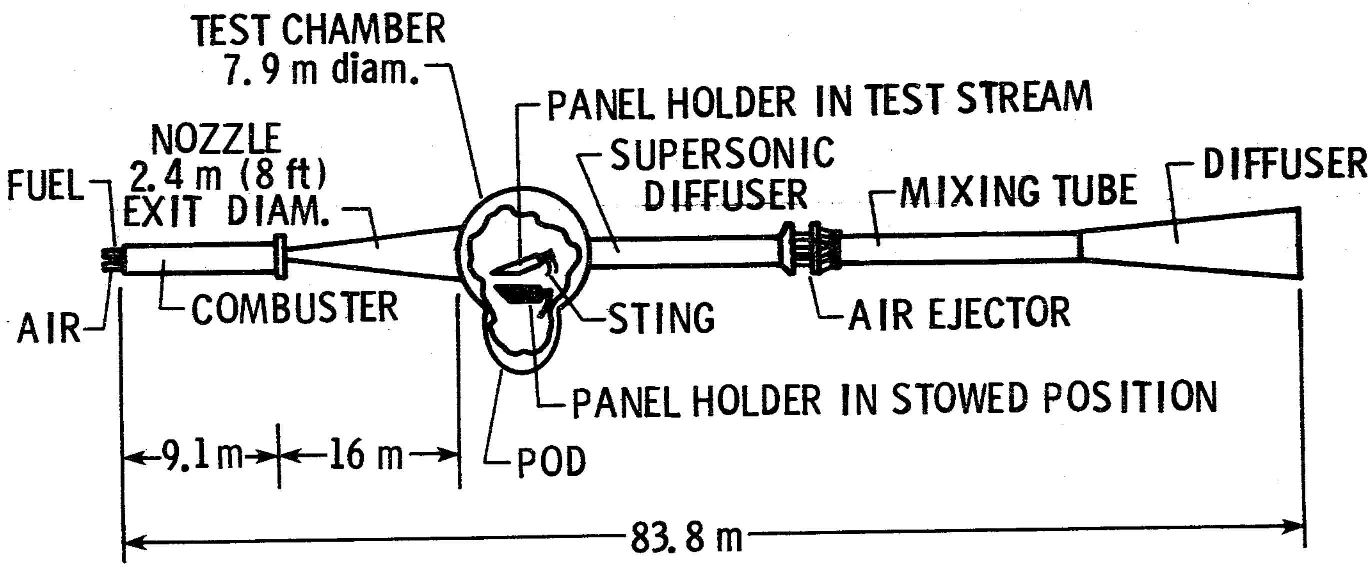


Figure 1.- NASA Langley 8-Foot High Temperature Structures Tunnel.

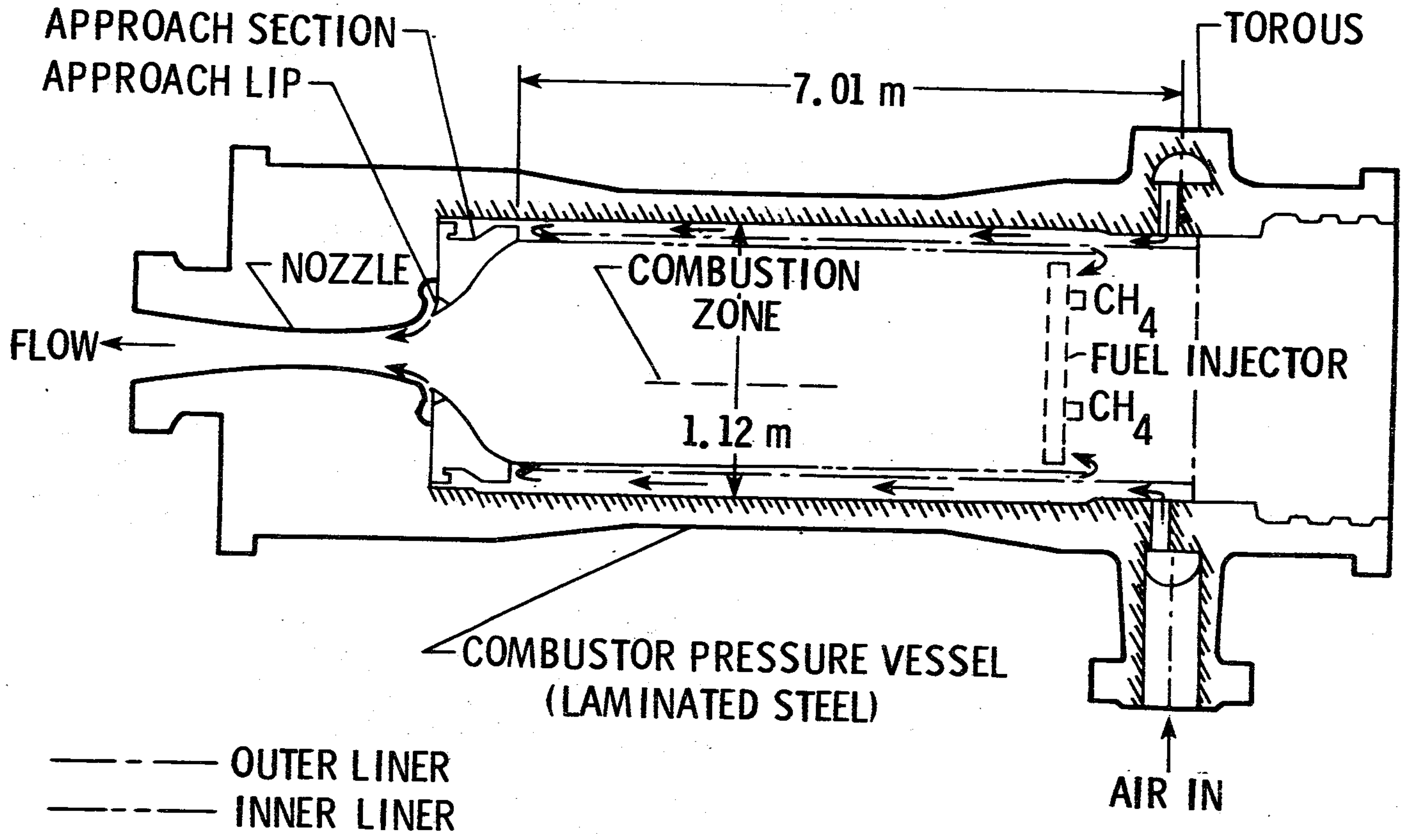


Figure 2.- Combustor pressure vessel, air inlet area, and nozzle.

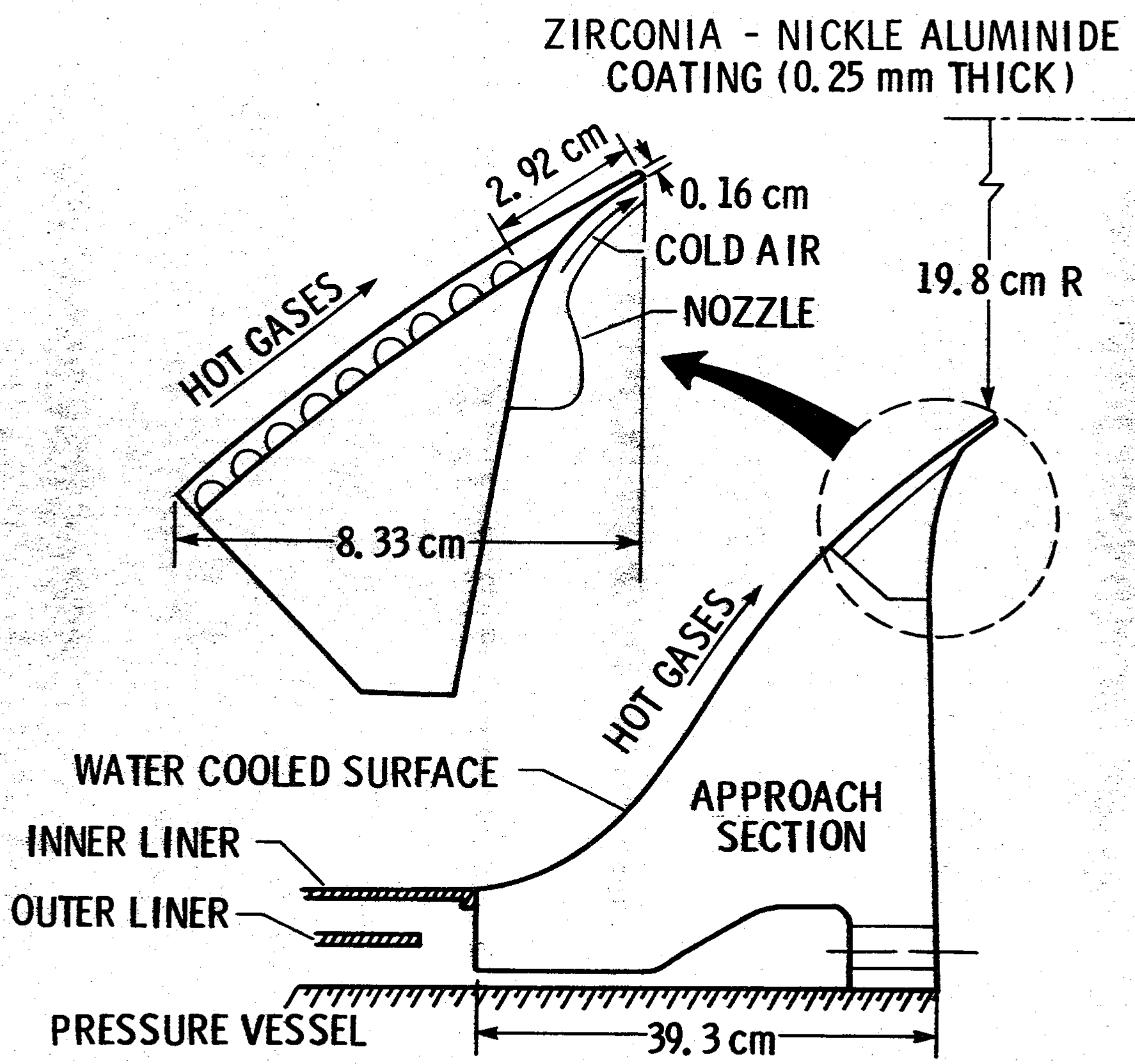


Figure 3.- Nozzle approach section and lip.

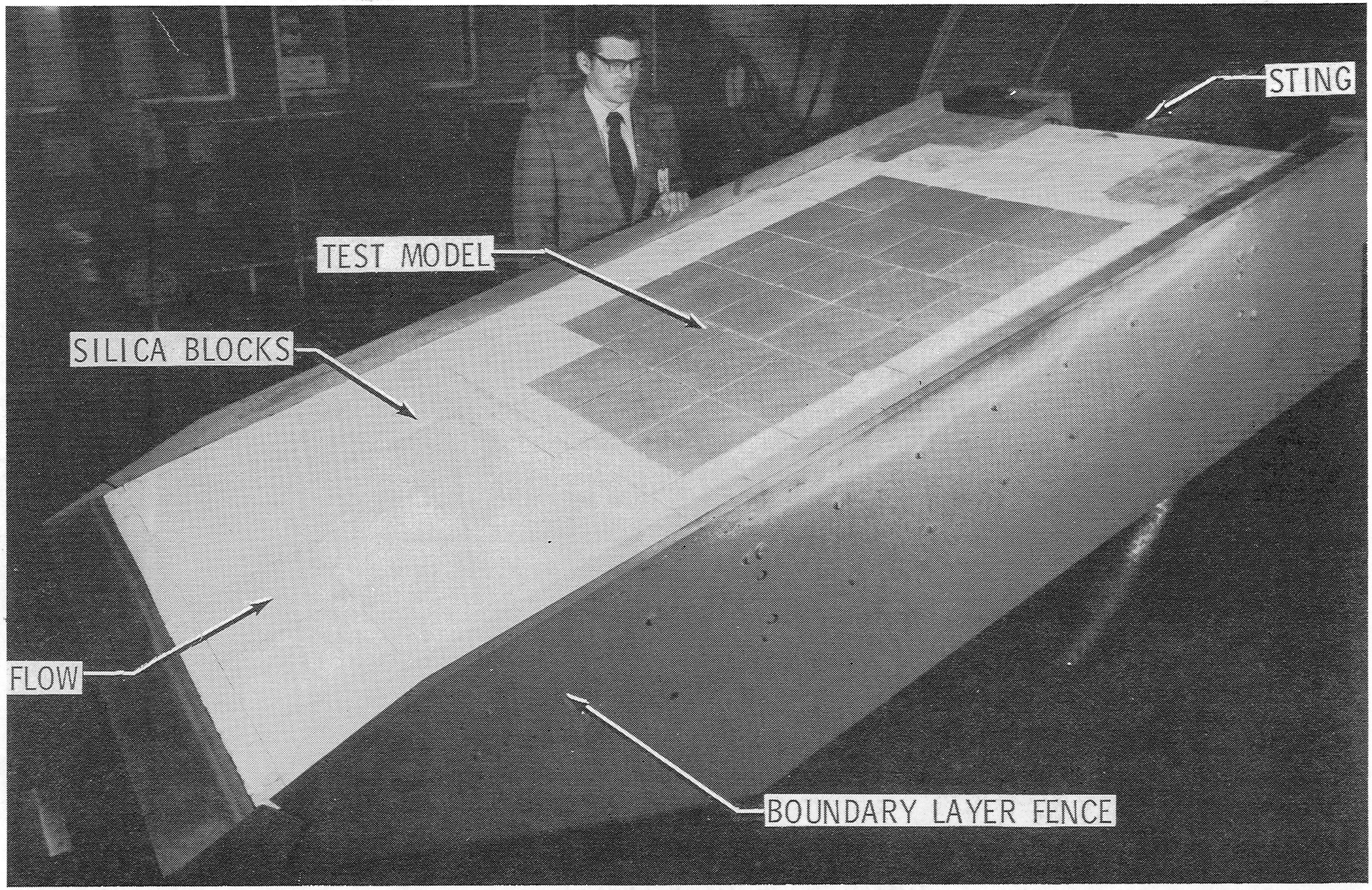
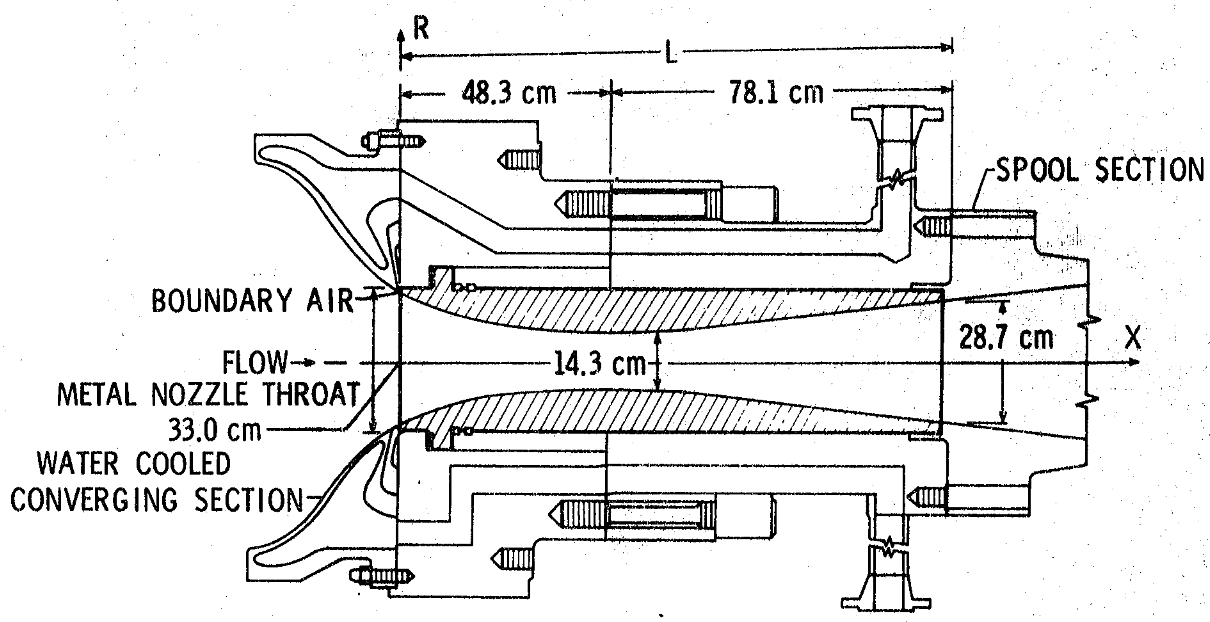
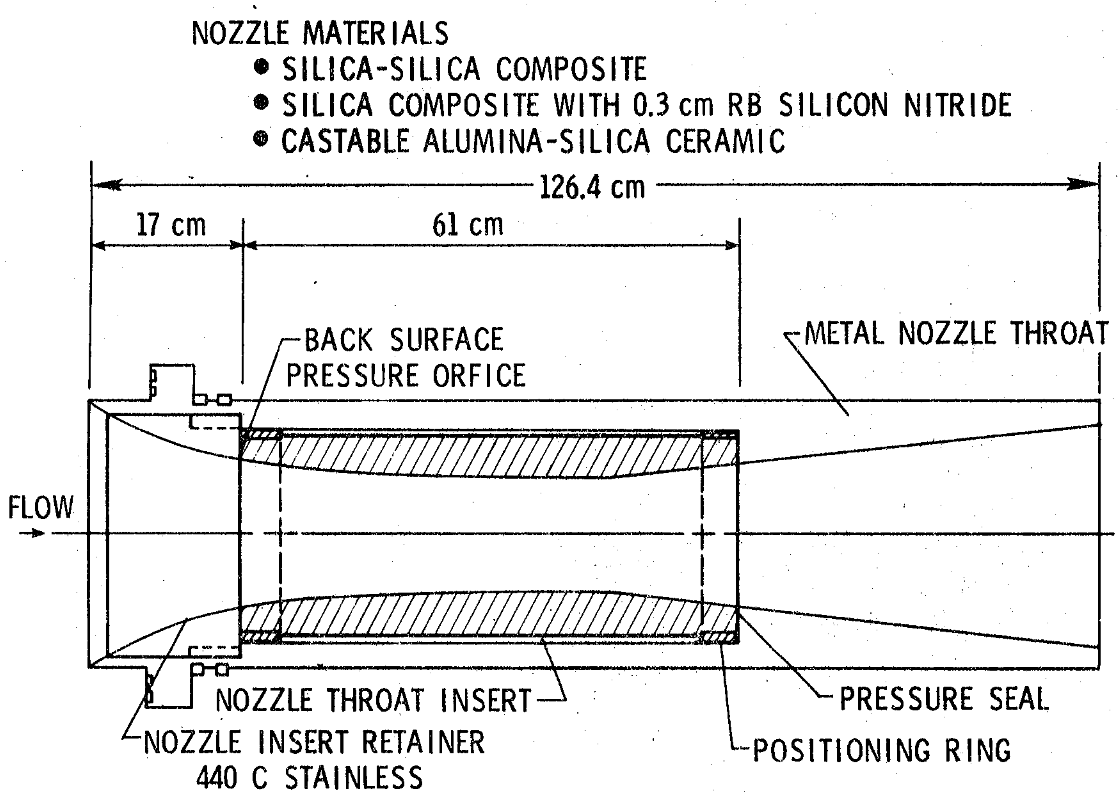


Figure 4.- Panel holder in 8-Ft. HTST.

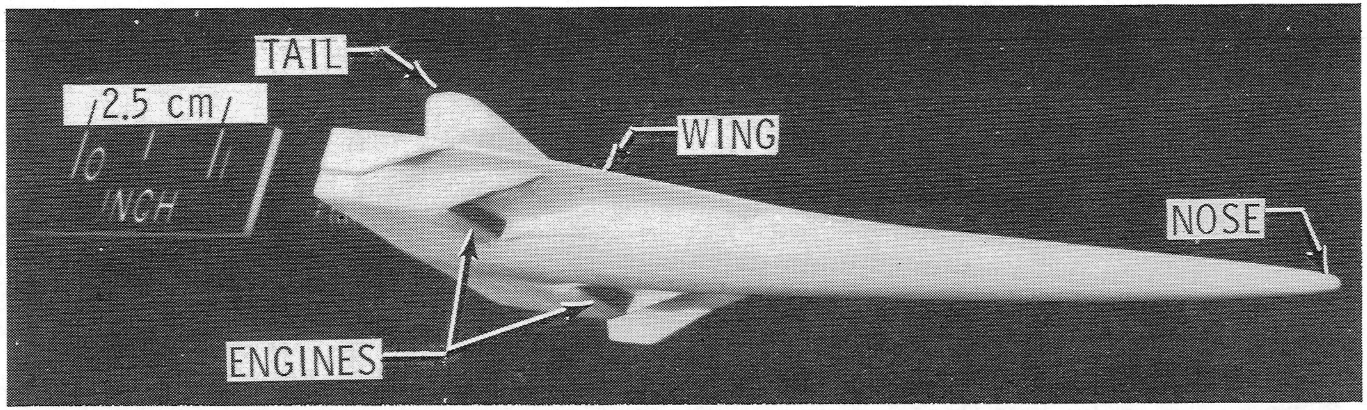


(a) Present nozzle insert-throat assembly.

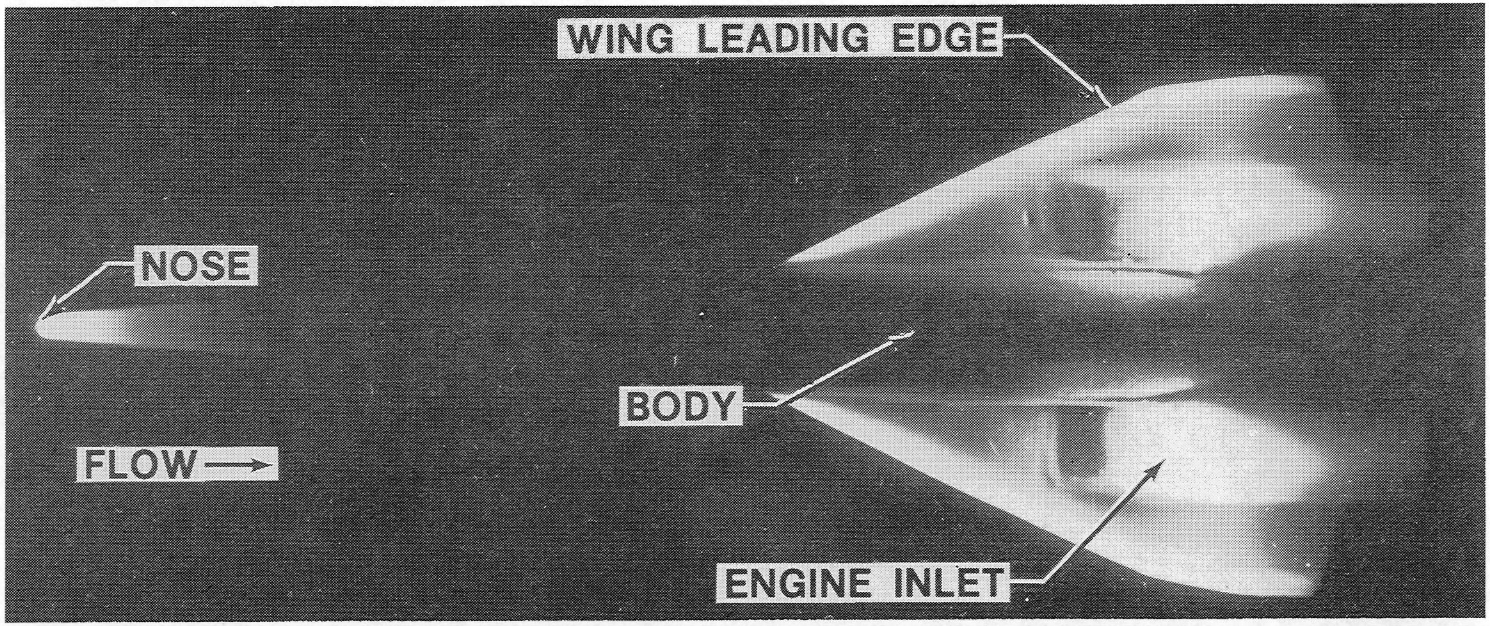


(b) Ceramic throat insert and assembly.

Figure 5.- 8-Ft HTST nozzles, present and future.



(a) Model before test.



(b) Model of hypersonic aircraft during test.

Figure 6.- Hypersonic aircraft model of slip cast fused silica.

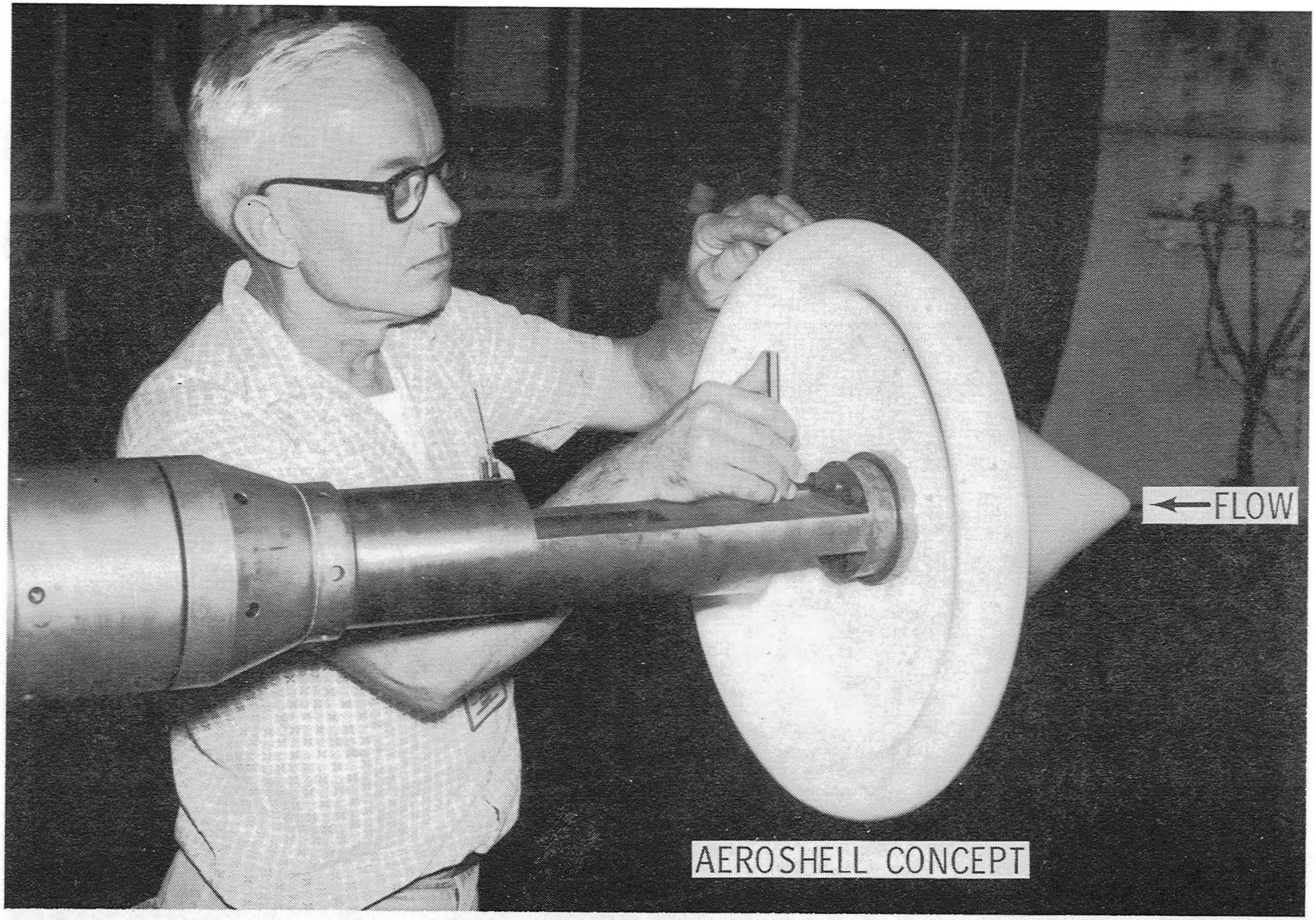


Figure 7.- Reentry body of cast silica.

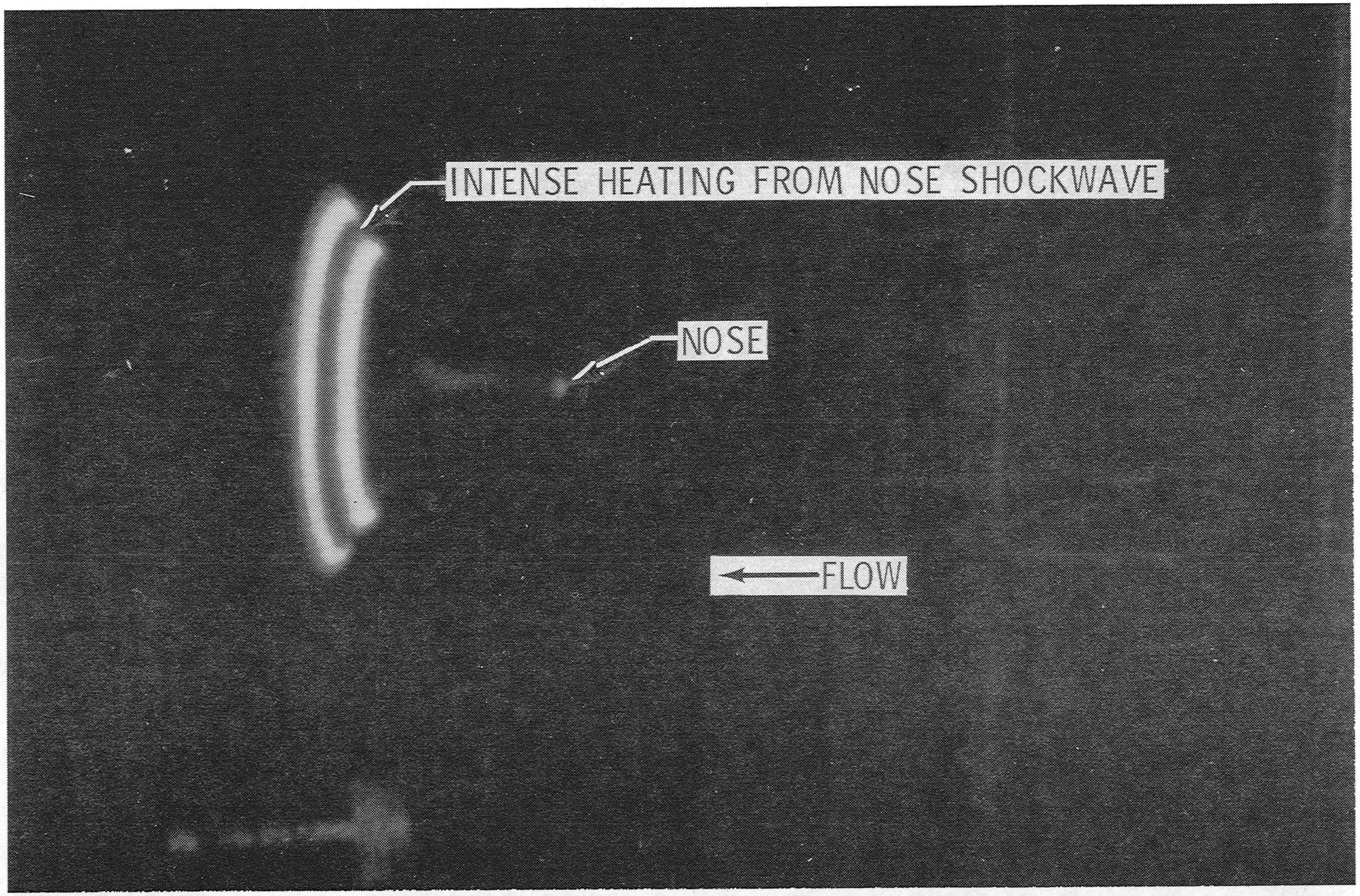


Figure 8.- Reentry body during aerothermal exposure.

Figure 9.- Photograph of GJNT model in test section of the 8-Ft. HTST.

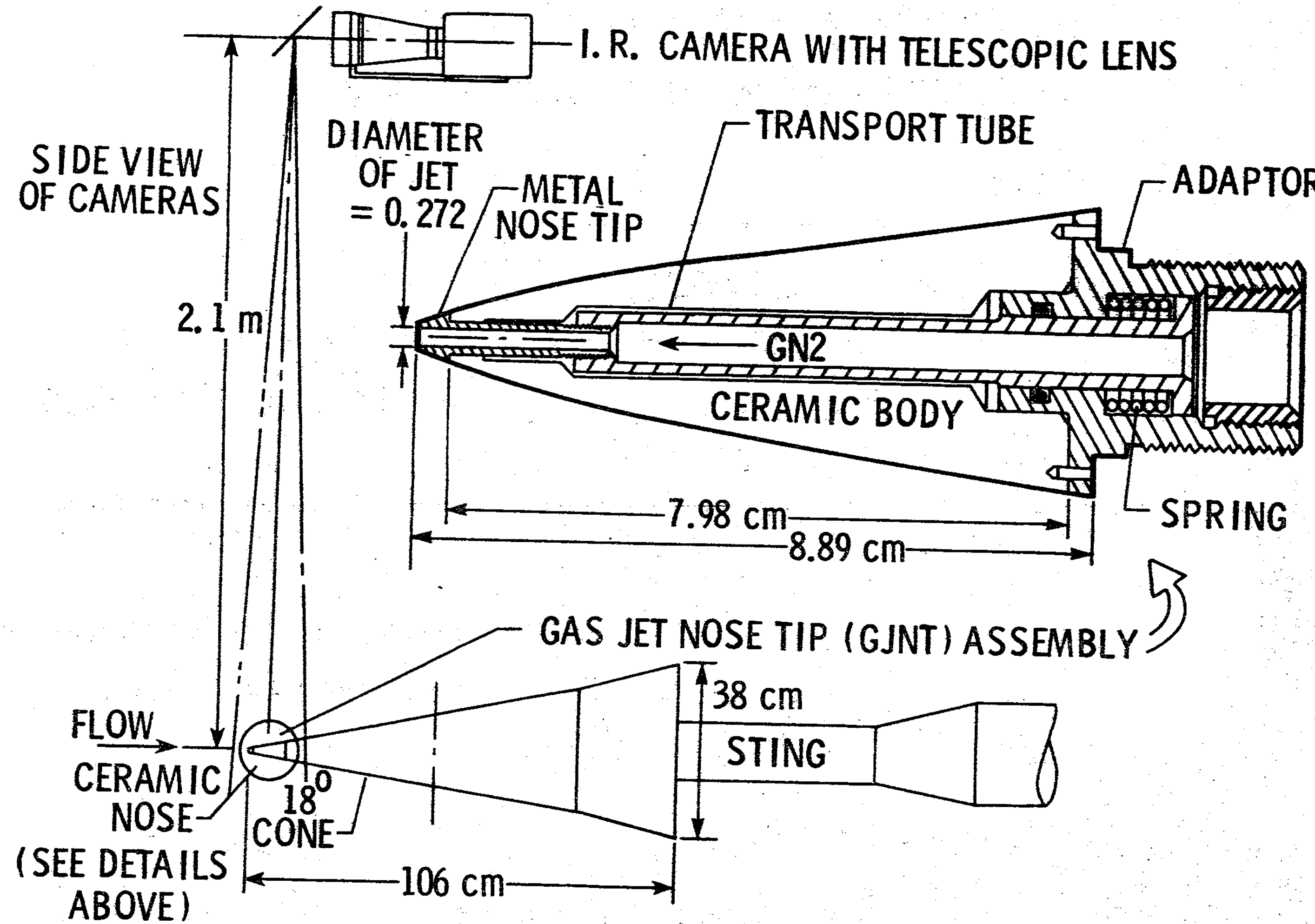


Figure 10.- IR camera, model, and GJNT assembly.

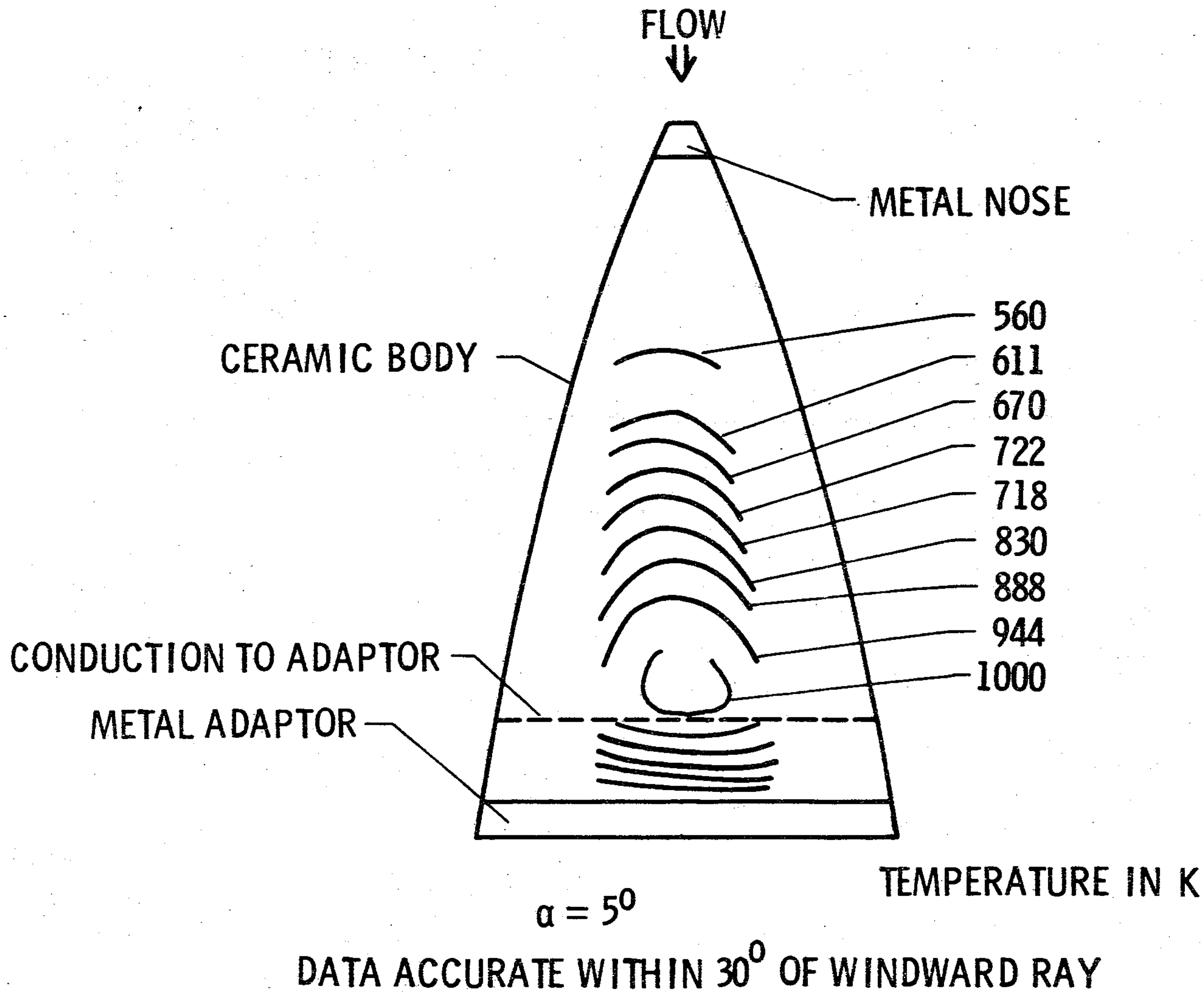


Figure 11.- Temperature isotherms on ceramic GJNT.

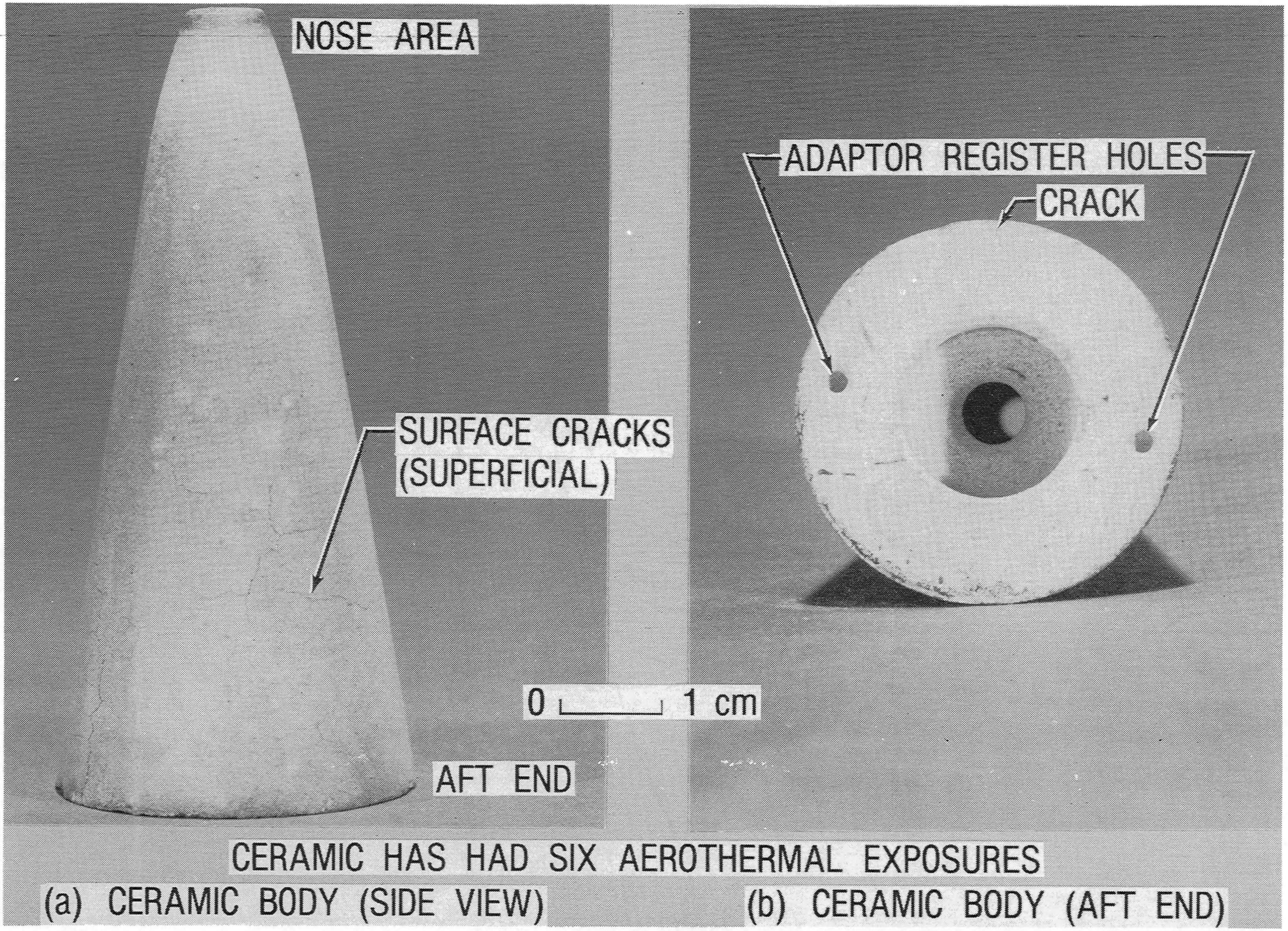


Figure 12.- Ceramic nose.

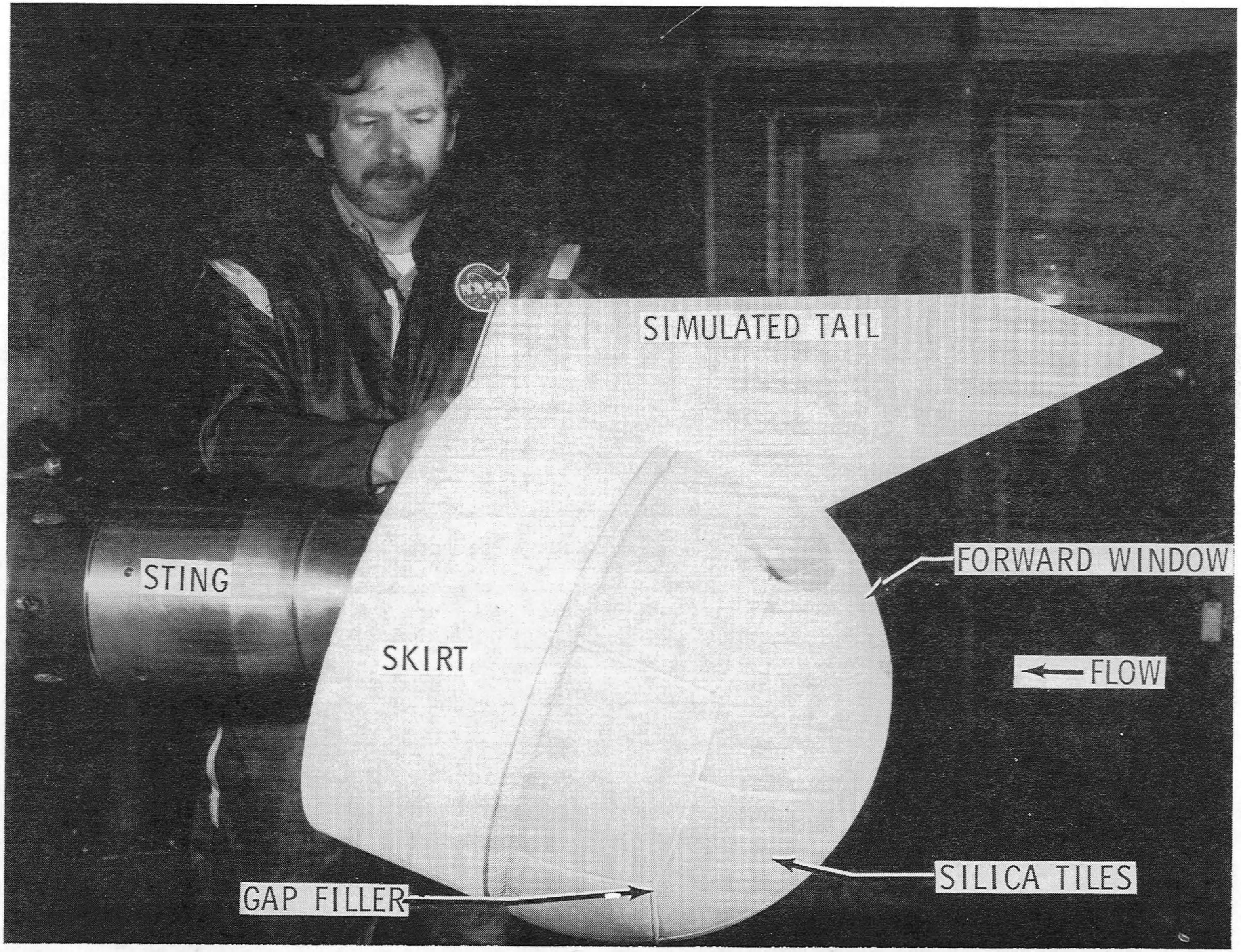


Figure 13.- Vertical tail-pod model.

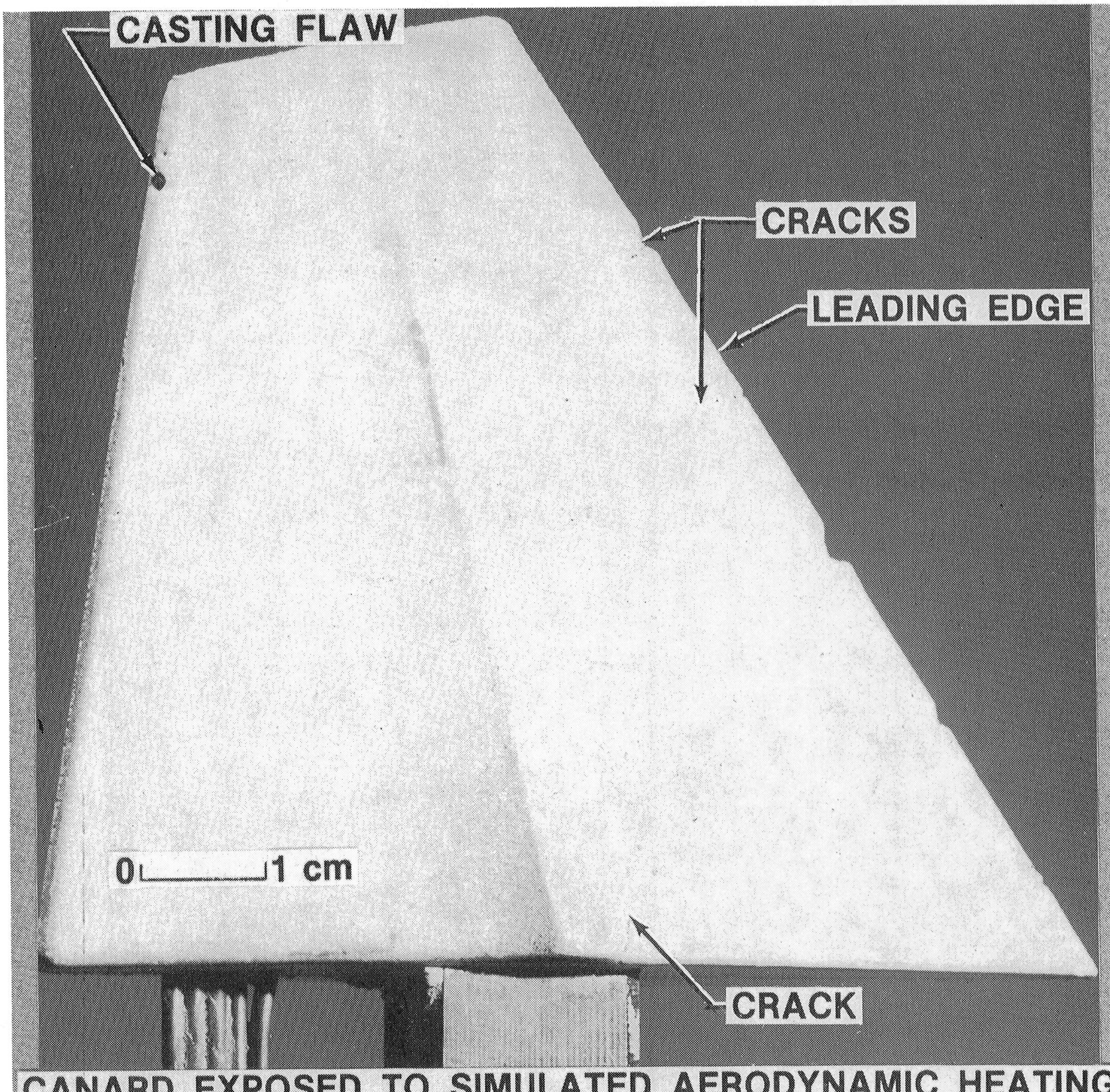


Figure 14.- Side view of ceramic canard.

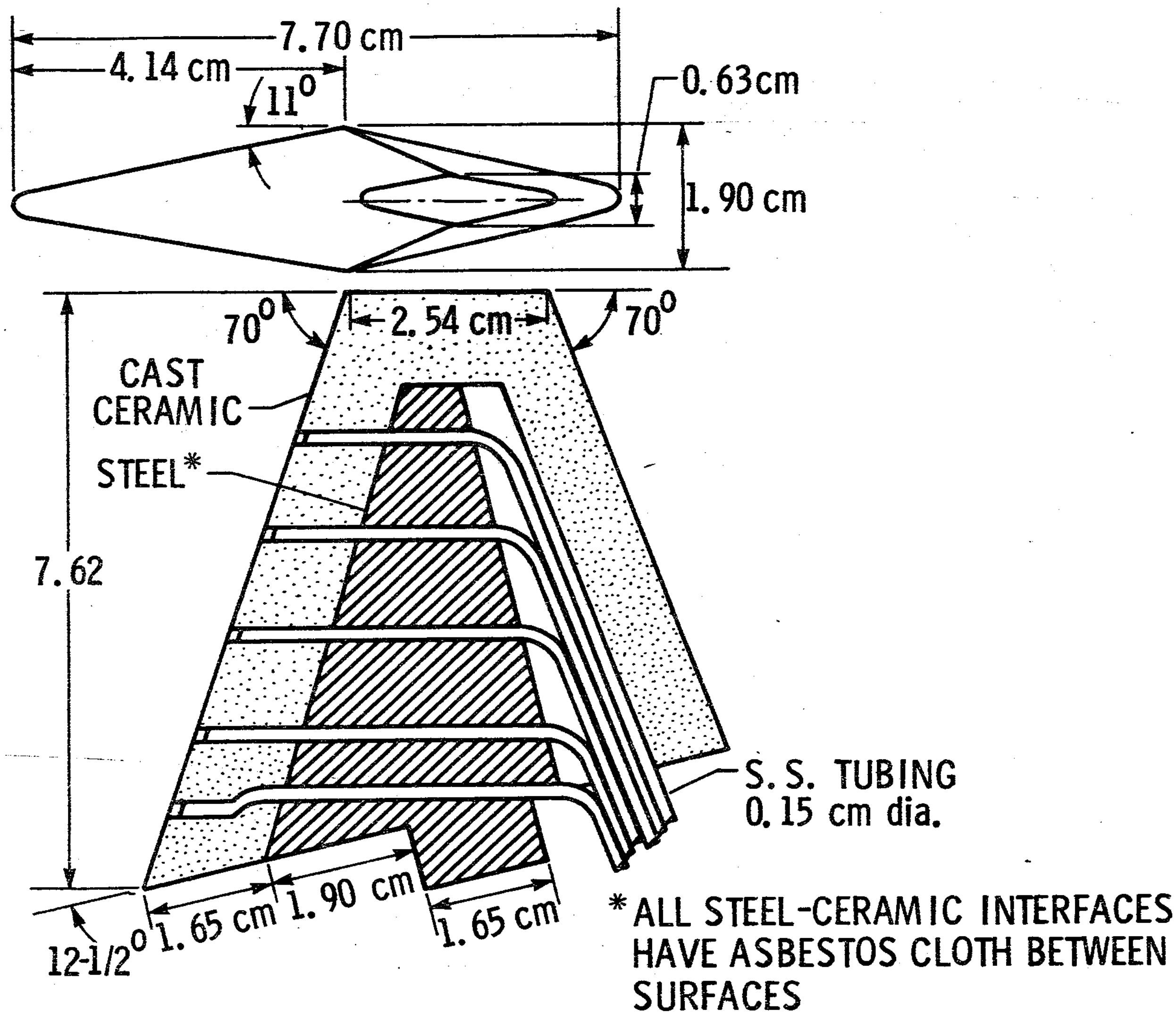
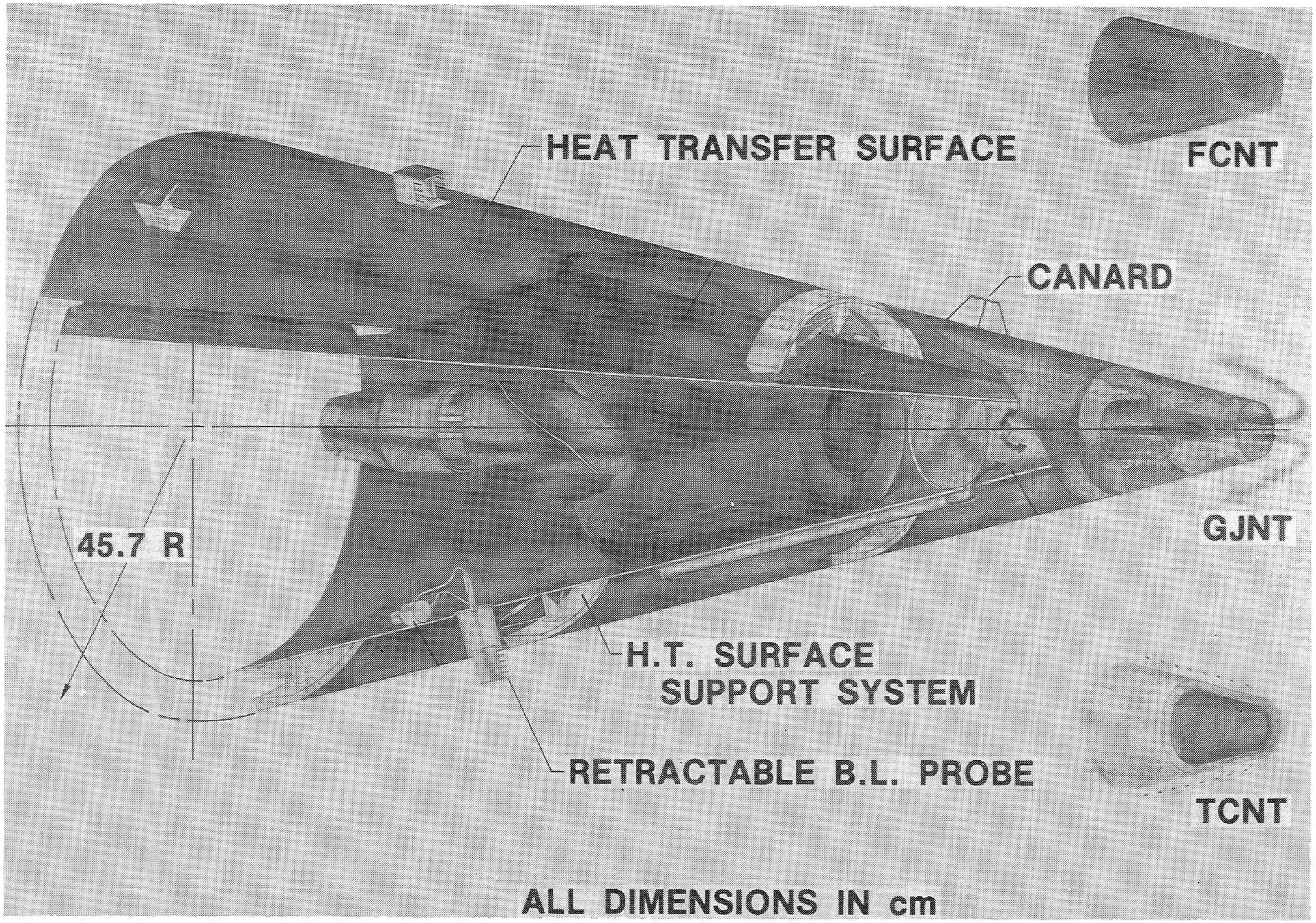
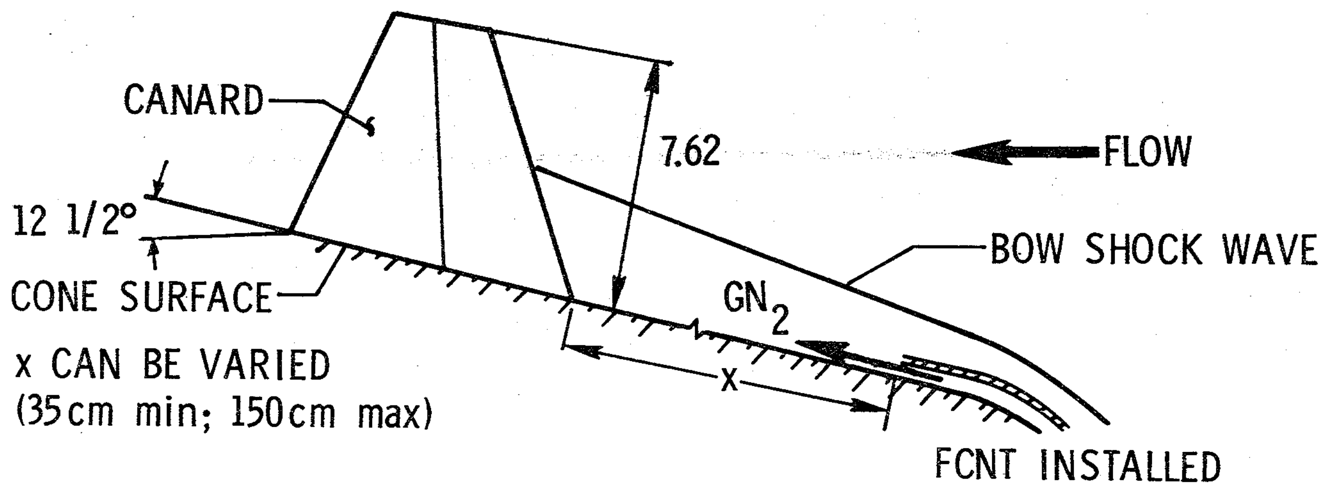


Figure 15.- Canard schematic.



(a) Multi-purpose cone.

Figure 16.- Multi-purpose cone model with canard.



(b) Canard installed on cone.

Figure 16.- Concluded

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16. Abstract The Langley Research Center's 8-Foot High-Temperature Structures Tunnel (8-Ft. HTST) is a Mach 7, blowdown wind tunnel used to investigate aerothermal-structural phenomena on large-to-full scale high-speed vehicle components. The high energy test medium, which provides a true-temperature simulation of hypersonic flow at 24 to 40 km altitude, is generated by the combustion of methane with air at high pressures. Since the wind tunnel, as well as the models, must be protected from thermally-induced damage, ceramics and coatings have been used extensively. Coatings have been used both to protect various wind tunnel components and to improve the quality of the test stream. Planned modifications for the wind tunnel include more extensive use of ceramics in order to minimize the number of active cooling systems and thus minimize the inherent operational unreliability and cost that accompanies such systems. Use of non-intrusive data acquisition techniques, such as infrared radiometry, now allows more widespread use of ceramics for models to be tested in high-energy wind tunnels. The details of in-service applications, operating conditions, behavior of the ceramics and coatings used to date for the wind tunnel and models, and planned applications are presented and discussed.

17. Key Words (Suggested by Author(s)) Ceramics, Coatings, Aerothermal Models	18. Distribution Statement Unclassified-Unlimited Subject Category 27

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