N95- 11968

TEST MODEL DESIGNS FOR ADVANCED REFRACTORY CERAMIC MATERIALS

05555
309895
513-27
22328
p. 12

Huy Kim Tran
Ames Research Center
Moffett Field, California

SUMMARY

The next generation of space vehicles will be subjected to severe aerothermal loads and will require an improved thermal protection system (TPS) and other advanced vehicle components. In order to ensure the satisfactory performance of these newly developed materials and components, testing is to be performed in environments similar to space flight. The designs and fabrication of the test models should be fairly simple but still accomplish test objectives. In the Advanced Refractory Ceramic Materials test series, the models and model holders will need to withstand the required heat fluxes of 340 to 817 W/cm^2 or surface temperatures in the range of 2700 K to 3000 K. The model holders should provide one dimensional (1-D) heat transfer to the samples and the appropriate flow field without compromising the primary test objectives. The optical properties such as the effective emissivity, catalytic efficiency coefficients, thermal properties and mass loss measurements are also taken into consideration in the design process. Therefore, it is the intent of this paper to demonstrate the design schemes for different models and model holders that would accommodate the test requirements and ensure the safe operation in a typical arc jet facility.

INTRODUCTION

Future space vehicles such as the National Aerospace Plane (NASP), Mars and Lunar return vehicles , and other planetary probes reentering the earth atmosphere at hypersonic speed, will require an adequate Thermal Protection System (TPS). Thus, development of such TPS requires new research programs for high temperature heat shields. Recently, a program called Advanced Refractory Ceramic Materials has been initiated at Ames to develop and search for new materials for future space vehicles. A series of high temperature materials such as zirconium diboride and hafnium diboride were tested in the Ames 60MW plasma arc-jet facility. Preliminary results showed that the diboride materials are promising candidates for high temperature heat shields (ref. 1). One of the limiting aspects of the test series is that the samples were too small for any thermal, optical property and recession rate measurements. Consequently, in order to further characterize these new materials, more testing is required. Therefore, a second phase of arc-jet testing is initiated which requires new model and model holder designs. The model designs for the phase II arc jet test will accomplish the following objectives.

1. Study the scaling effect (larger sample size) on the thermal performance of materials such as mass loss measurement, recession rate, thermal shock, and thermal stress.

2. Measure the effective emissivity, catalytic efficiency coefficients and thermal conductivity.

3. Observe the geometry effects, i.e., material directional effects, on thermal performance materials applications.

Model design for arc jet testing requires some basic understanding of the high temperature supersonic flow in wind tunnels and heat transfer. These basic concepts are essential in determining the model size, geometry, and instrumentation options that will satisfy the test objectives. The next section gives a brief description of a typical arc jet facility and its capabilities followed by the essential considerations in the model designing process. Simple heat transfer equations are outlined to assist the designer in determining the overall model size and geometry. It also points out other factors which affect the final model configuration. Based on the above considerations, the next section describes the chosen model designs for the phase II arc-jet tests . A coupon sample model is used to investigate the scaling effect and to obtain thermal and optical measurements. Leading edge and nose tip models are designed to explore the geometry effects as well as the possibilities of new applications for diboride material.

DESCRIPTION OF THE AMES 60 MW ARC JET FACILITY

The Ames 60MW Interactive Heating Facility (IHF) is used to simulate earth re-entry flight conditions of space vehicles. It is a plasma arc blow-down type supersonic wind tunnel where the test gas is heated by electrical power using the 8-cm constricted arc heater (fig. 1). After leaving the arc heater column, the highly energized gas is supersonically expanded by a convergent-divergent nozzle and is discharged into an evacuated test chamber where the test article is located. The temperature, velocity and pressure of the test gas can be varied to simulate atmospheric re-entry for the space vehicle by using different nozzle exit areas of the divergent nozzle section. The stream can attain enthalpy up to 56 MJ/Kg and velocity up to Mach 8.

DESIGN CONSIDERATIONS

When a supersonic stream flows over a blunt body, a wedge or a compression corner, a shock wave is created. This is caused by a large change in density, pressure, temperature, velocity, etc. across an extremely thin region of the shock layer. In the arc jet facility, the flow is not only supersonic in the test section but the gas itself is highly energized. The kinetic energy of the gas in the free stream is converted into internal energy that results in a very high temperature shock layer near the surface. This phenomenon is referred as the aerodynamic heating effect.

The aerodynamic heating effect can be understood by simply considering that the kinetic energy in the free stream is converted into internal energy and radiant energy at the shock . Part of this energy is being used to heat the air which causes the increase in temperature across the shock and the other portion goes into heating the body. At the surface, the energy in the shock layer is transferred to the body by conduction. For a blunt body, a detached strong shock is generated and a portion of the energy in the shock layer is conducted to the body while the remainder is convected downstream past the body (fig. 2(a)). For a slender body with a sharp nose, e.g., NASP, the shock is oblique and nearly attached at the nose or leading edge. In this case, nearly all of the internal energy is conducted to the body at the nose tip and leading edge (fig. 2(b)).

INTERACTION HEATING FACILITY

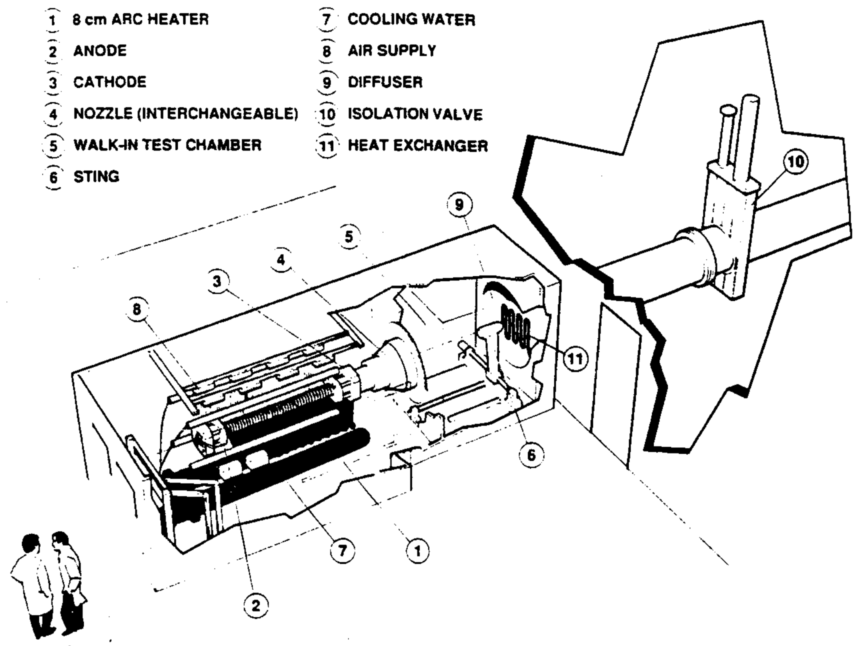


Figure 1. Schematic of Ames 60 MW interactive heating facility.

The primary design parameters for the arc jet model are the nose radius and final geometry. These parameters are affected by the imposed heat flux, stream enthalpy and flow field requirement. The section below describes the methodology in determining the model overall configuration for a given flight condition.

MODEL SCALE (NOSE RADIUS CALCULATION)

It is essential to determine the actual cold wall heat flux on model surface which includes both geometry and surface chemistry effects. The flow field and shock shape are also dictated by the body's shape. Therefore, the nose radius calculation is based on the given corrected cold wall heat flux or surface temperature in the following manner.

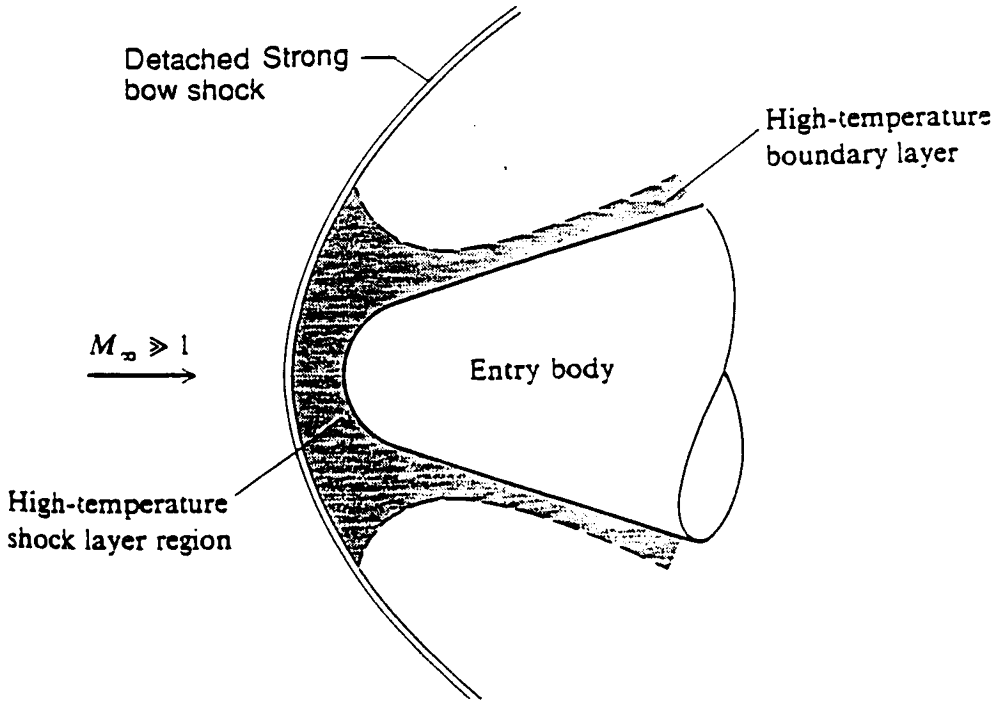
a. Cold wall heat flux known

If the heat flux is known, the radius of the test model can be calculated by considering the following:

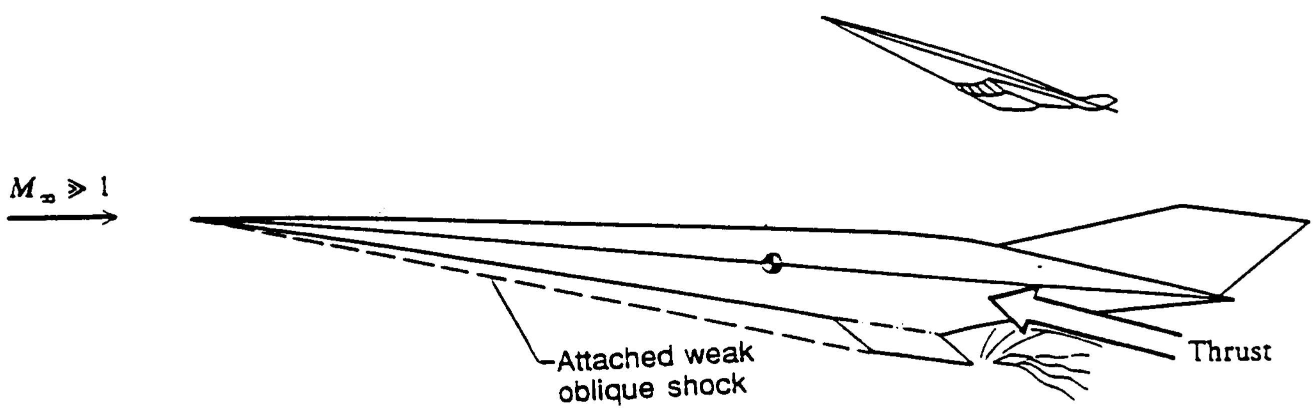
The convective heat transfer rate at the stagnation surface of a spherical nose can be empirically written as (ref. 2)

$$\dot{q}_{conv} = \rho_e u_e C_h (H_r - h_w) \tag{1}$$

Note that there is little if any radiation flux in these arc jet tests. This equation emphasizes the difference in enthalpy as the "driving potential" for aerodynamic heating where h_w is wall enthalpy. H_r is



a) Detached Shock Wave on a Blunt Body (Ref. 2)



b) Attached Shock Wave on a Slender Body; e.g., NASP. (Ref. 2)

Figure 2. Flow field and shock shape of typical entry bodies.

the recovery enthalpy (i.e., total enthalpy near the shock), C_h is the heat transfer coefficient, and ρ_e and u_e are the boundary layer edge density and velocity, respectively. Equation (1) can be simplified to give

$$\dot{q}_{conv} = C\sqrt{\frac{P_{t_2}}{R}}\,(H_r - h_w) \tag{2}$$

Equation (2) is often referred to as a simplified Fay-Riddell expression (ref. 3). The nose radius of a hemispherical body at a given flight condition can therefore be approximated by

$$R_{hemi} = \left(\frac{C(H_r - h_w)}{\dot{q}_{conv}} \right)^2 P_{t_2} \tag{3}$$

where P_{t_2} is stagnation pressure(in PASCAL); R is the nose radius of a sphere (in cm), $\dot{q}_{conv}$ is in W/cm^2 and C is a proportionality constant and is taken to be 0.3531. The wall enthalpy, h_w, is often neglected for cold wall heat flux and H_r is the free stream recovery enthalpy in MJ/kg.

To obtain the effective radius in other geometries such as a flat face cylinder, a correction factor, f, is used. This factor is obtained from the ratio of heat flux on different model geometry to that on a hemisphere. For a flat face cylinder, f is taken to be 0.53-0.57 (ref. 4).

$$R_{eff} = f\, R_{hemi} \tag{4}$$

b. Surface temperature known

In some instances, the surface temperature becomes more important because of the uncertainty in heat flux calculation due to surface chemistry effects or there is an upper use limit temperature. In this case, the convective heat flux in equation (2) can be calculated by using the Stefan-Boltzmann equation and assume that the given temperature is the radiative equilibrium temperature.

The Stefan-Boltzmann equation is

$$\dot{q}_{conv} = \dot{q}_{eq\ rad} = \sigma \varepsilon T_{eq}^4 \tag{5}$$

where

$\dot{q}_{eq\ rad}$ is the equilibrium radiative heat flux in W/cm^2
σ is the Boltzmann constant and equal to 5.669E–12 W/cm^2–K^4
ε is the emissivity.

Surface chemistry or wall catalysis is another important consideration in calculating the surface convective heat flux. It is defined as the recombination rate of dissociated species at the surface. For a fully catalytic surface such as a metal, the recombination rate is very large; i.e., the mass fractions at the wall are their equilibrium values at the local pressure and temperature at the wall. At partially catalytic surfaces, the recombination rate is finite; i.e., there is a gradient of mass fraction at the wall. Finally, when there is no recombination at the surface, it is said to be a non-catalytic surface (e.g., oxides). Surface catalysis is not well understood because of the complex physical nature of gas-surface interaction. Consequently, to simplify the model design process, the surface is assumed to be either fully catalytic or non-catalytic. Past experience and study indicate that the aerodynamic heating of a fully catalytic surface is about a factor of two more than that on the non-catalytic surface (ref. 2).

MODEL DESIGNS

1. Coupon sample arc jet model:

In the Advanced Refractory Ceramic Material phase I arc jet test, a series of heat fluxes were imposed on the test samples. The results indicated that the upper limit heat flux for the reusability of diboride material is about 340 W/cm^2. The surface of the diborides is also considered to be fully catalytic. This heat flux occurred at a corresponding enthalpy of 27.9 MJ/Kg and stagnation pressure of 1.013E-06 PASCAL. This test condition is also similar to that was used in late 1960s and 1970s arc jet testing at ManLab (ref. 1). Thus, in phase II testing, the similar test conditions are used in model scaling calculations.

A flat face cylinder is chosen for model geometry for several reasons. First, the temperature and pressure gradient across the surface are small which result a uniform heating distribution across a large portion of sample surface. This, in effect, allows an accurate measurement for recession rates and thus a better characterization of material thermal performance. Secondly, for optical property measurements such as the emissivity and radiative flux for catalysis calculations, the model surface has to be large enough so that there is a sufficient reflected area for sensor detection. Thus, using equation (3) and taking the instrumentation constraints and facility operating limitation into consideration, the allowable radius for a spherical model is 8.478 cm for heat flux of 340 W/cm^2. From equation (4), the radius of a flat face cylinder is calculated to be about 5.08 cm.

Figure 3 shows the schematic of the coupon sample model assembly. To study the scaling effect and measure the optical properties, the radius on the coupon sample for phase II testing is three times as long as that of phase I. In order to accurately measure the recession rate and mass loss, the heat transfer needs to be one dimensional, i.e., no side heating around the model. Unlike the hemisphere geometry, the peak heating on a flat face cylinder does not occur at stagnation point but rather at the corner region. It has been shown that the edge heating effect occurs at about 0.75 of X/R ratio where X is the distance from the sample center to the edge (ref. 4). To eliminate the edge heating effect and provide a uniform heating distribution on the sample surface, a high density (POCO PGSC-1) graphite ring with a thick wall (1.40 cm) is used. Several layers of Grafoil are used to insulate the sample from the graphite ring so that the heat transfer to the test sample is one dimensional. This particular graphite ring can accommodate a 3.556 cm radius and 0.635 cm thick coupon sample.

An adiabatic wall condition is needed to further ensure the 1-D heat transfer requirement. This is achieved by placing a zirconia reflector plate between the back face of test sample and the holder . The length of the graphite ring can be determined by using an one-dimensional Fourier equation for heat conduction (ref. 7):

$$\dot{q}_{cond} = \dot{q}_{conv} = -K\frac{\partial T}{\partial x} = -K\frac{\Delta T}{\Delta x} = -K\frac{T_2 - T_1}{L} \qquad (6)$$

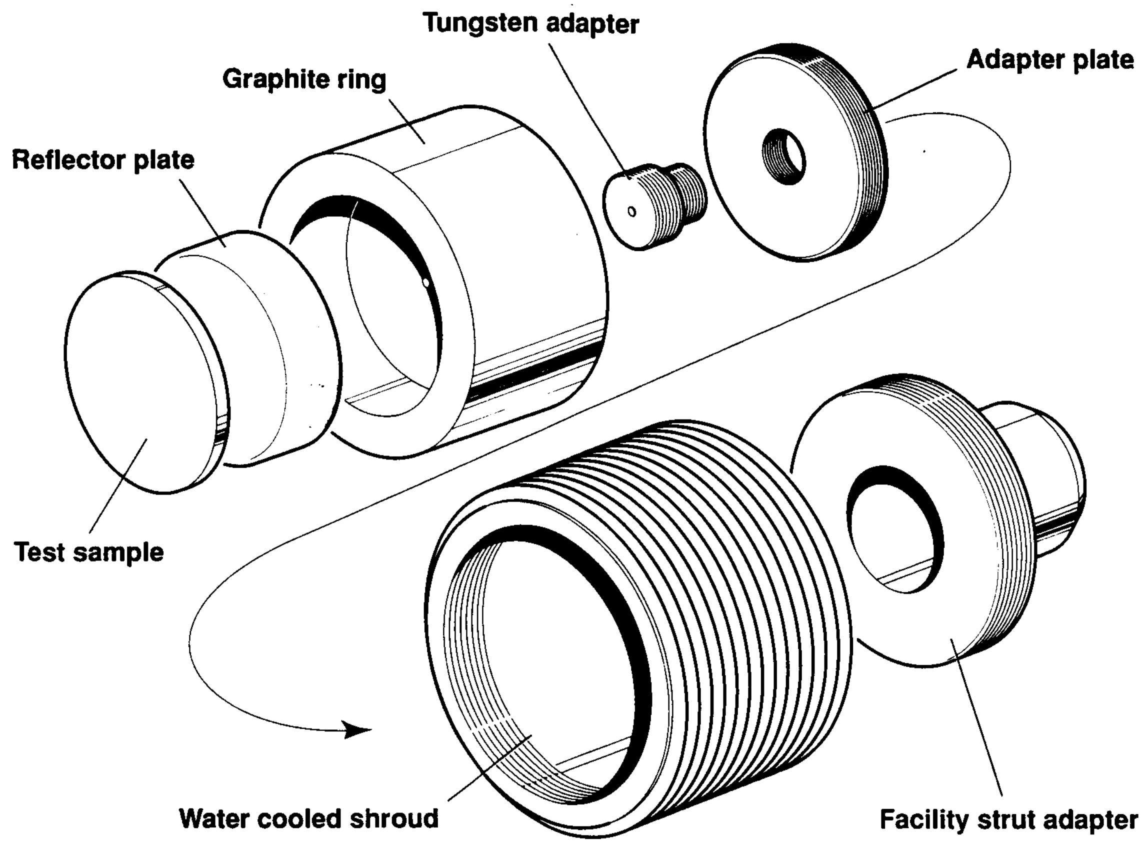


Figure 3. Isometric view of coupon sample model.

where

K is the thermal conductivity of holder material, W/cm^2–K
T_2 is the surface temperature, K
T_1 is the desired interface temperature, K
L is length of the holder, cm

The graphite ring is connected to the water cooled shroud by a two-end threaded tungsten adapter. The shroud conducts most of the heat from the graphite away and prevent the melting of the facility water cooled strut. In a oxidizing environment such as that in the arc jet facility where the free stream consists of 21% oxygen, the use of tungsten is not recommended due to its high oxidation reaction rate. However, if it is protected by other material that is oxidized more rapidly such as graphite, tungsten can be used to withstand the high temperature application.

The installation of surface thermocouples in the diboride material is extremely difficult due to its high mechanical strength. It was decided that the surface temperature could be obtained by placing one thermocouple at 0.081 cm from the sample's surface. The back face temperature is monitored by installing a thermocouple at the contact surface between the reflector place and sample. The thermal conductivity and effective emissivity can be calculated by using these temperature results along with the corrected black body temperatures from pyrometers.

The effective emissivity can be calculated by using the Stefan-Boltzmann equation (ref. 7);

$$\sigma \varepsilon_b T_b^4 = \sigma \varepsilon_{eff} T_s^4 \tag{7}$$

where

σ is the Boltzmann constant
ε_b is the emissivity = 1.0 for a blackbody
ε_{eff} is the effective emissivity of the material
T_b is the corrected black body temperature from the pyrometer, K
T_s is the surface temperature from the thermocouple, K
Thus, the emissivity of the material, ε_{eff}, can be calculated by

$$\varepsilon_{eff} = \left(\frac{T_b^4}{T_s^4} \right) \varepsilon_b \tag{8}$$

2. Leading edge arc jet model

The third objective of this test series is to investigate geometry effects and materials applications. It is believed that the diborides can be used as reusable material for leading edge application for future hypersonic vehicles. In fact, the diboride materials were used to construct the leading edges and nose tip for the Air Force FDL-5A lifting body program (ref. 6). The results were not encouraging due to thermal stress problems. In recent years, the manufacturing process has been improved, so it is reasonable to re-evaluate the performance of diborides as a potential material for leading edge configurations. The leading edge radius chosen for the arc jet model is 0.953 cm. This value is based on the the full scale dimension of the leading edges radius of the NASP (ref. 8).

Figure 4 shows the exploded view of components of the leading edge model for the Advanced Refractory Ceramic Materials phase II arc jet test. The design consists of two removal end caps, main body and back plate. Each end cap is aligned with the main body by two guide pins and attached by two machine screws. The leading edge is held by the end caps with two tungsten pins. The main body is insulated from the high temperature leading edge by the grafoil.

The contours applied on the main body and radius on the end caps are the design's main features which minimize the shock impingement from the oblique portion of the bow shock. Another important feature in the leading edge model is the attachment between the back plate and main body. The back plate is in contact with the leading edge assembly only at the attachment areas where the screws are located. This minimizes the heat transfer from the body to the plate and takes advantage of cooling by convection. The whole assembly is then mounted on the facility water cooled strut. Notice there is no additional cooling shroud placed in between the test model and facility strut. This is due to the considerable drop in heat flux at locations away from the stagnation point. The test conditions imposed on the leading edge model are similar to those of NASP flight conditions. In this case, the imposed heat fluxes range from 260 to 817 W/cm^2 and the enthalpy is in the range of 18.6 MJ/Kg.

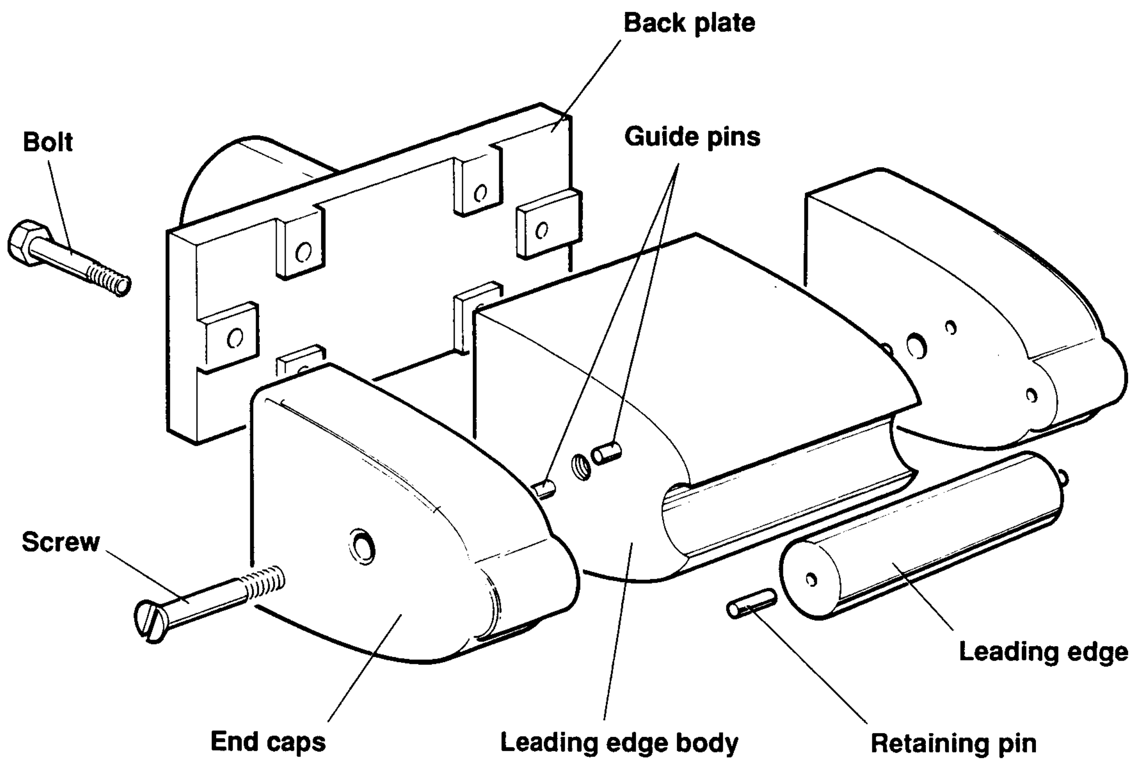


Figure 4. Isometric view of leading edge model.

3. Nose tip model

The use of diboride materials for nose tip applications is also being considered, in particular for the Pegasus SWERVE (Sandia Winged Energetic Reentry Vehicle Experiment) program. The test model consists of a nose tip and a skirt made of diboride material, a graphite sleeve and a tungsten strut. These components shown in figure 5 are assembled into a slender cone with a small blunt nose tip that is similar to the SWERVE configuration. The test model is then mounted on a water cooled cone shroud (not shown) which is installed on the facility model support system. The flare in the skirt and sleeve is used to deflect the attached shock to prevent flow impingement which might result in melting of the facility strut.

The purpose of designing this model is to study the thermal performance of the diboride materials in a high heat flux and very low Reynold's number flow regime. Because of the small radius, the nose tip model will experience rarefied or non-equilibrium flow. Mass loss measurements are taken at post test, and the recession rate is evaluated by using the high speed motion picture film.

CONCLUSION

It is shown that the size and geometry of an arc jet test model can be calculated by using simple heat transfer equations. The flow field requirement and shock shape are also important factors in selecting the final model geometry. If the model radius is too small, a rarefied flow regime results, which has a more severe effect on the thermal performance of materials. The model however needs

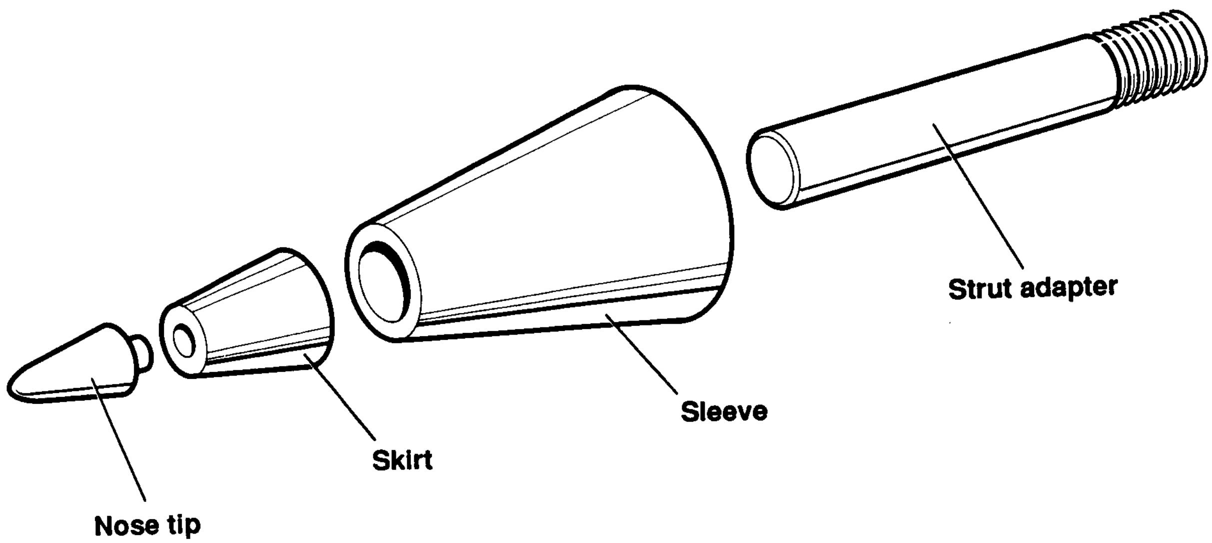


Figure 5. Isometric view of nose tip model.

to be large enough if optical and thermal property measurements are to be obtained. In the Advanced Refractory Ceramic Materials phase II arc jet tests, three model assemblies are designed to satisfy the test objectives. The coupon sample model increases the sample size from 1.27 cm in phase I to 3.56 cm in diameter in phase II. Its holder is designed to provide 1-D heat transfer to the sample and adequate protection for facility hardware. Leading edge and nose tip models are designed to fulfill a third test objective of determining geometry effects on material performance. These models and holders are used to study material performance in a rarefied flow regime and to ascertain possible applications for future hypersonic vehicles.

ACKNOWLEDGMENTS

The author would like to express her thanks to Dr. W. D. Henline for his invaluable suggestions on technical aspects of this paper and to Mr. M. Smith for his contributions in the leading edge model design.

REFERENCES

1. Rasky, D. J.; Bull, J. D.; and Tran, H. K.: Ablation Response of Advance Refractory Composites. Advanced Ceramics Association, 15th Annual Conference on Composites, Materials & Structures, Restricted Session, Cocoa Beach, Florida, Jan. 1991.

2. Anderson, J. D., Jr.: Hypersonic and High Temperature Gas Dynamics . McGraw Hill, Inc., 1989, pp. 248.

3. Fay, J. A. and Riddell, F. R.: Theory of Stagnation Point Heat Transfer in Dissociated Air. Journal of the Aeronautical Sciences, vol. 25, no.2, Feb. 1958, pp. 73-85.

4. Zoby, E. V. and Sullivan, E. M.: Effects of Corner Radius on Stagnation-Point Velocity Gradients on Blunt Axisymmetric Bodies. NASA TM-X-1067.

5. Smith, A. M. O. and Clutter, D. W.: Machine Calculation of Compressible Boundary Layers. AIAA J., vol. 3, no. 4, April 1965, pp.639-647.

6. Strauss, E. L.: Ceramic Nose Cap and Leading Edges for High Performance Weapon Systems. Tech. Report No. AFFDl-TR-72-19, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, OH, April 1972.

7. Holman, J. P.: Heat Transfer, 7th Edition, McGraw Hill Inc., 1990.

8. Goldstein, H. E.; Cagliostro, D.; and Smith, M.: Spinning Leading Edge Concept for NASP. First National Aerospace Plane Technology Symposium, May 20-22, 1986.

BIOGRAPHY

Huy Kim Tran:

My family and I left Vietnam in 1979 in a small fishing boat and spent the next year and a half in the refugee camp in Indonesia waiting for the admission to the United States of America. We arrived in Woonsocket, South Dakota in spring 1981 and moved to California during that summer. I attended De Anza Junior College and transferred to San Jose State University (SJSU) several years later. I started working at Ames 1982 as an intern through Foothill-De Anza Internship Program, and continued on as a student assistant at different locations at Ames throughout my college years. I received a Bachelor of Science degree in Materials Engineering in 1987 and a Master of Science degree in Mechanical Engineering in 1990; both from SJSU. Presently, I am working in the Thermal Protection Branch as a research scientist. I am the lead engineer in a new project entitled Light Weight Ablators and am also the test/design engineer for the Advanced Refractory Ceramic Materials program and the NASP-Government Work Package 95, Internal Insulation Development.