CARBON PHENOLIC HEAT SHIELDS FOR JUPITER/SATURN/URANUS ENTRY PROBES

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MR. MEZINES: I am going to limit my talk to carbon phenolic heat shield technology. As you probably know, these materials have been around for a number of years and we have assimilated a lot of fabrication and flight experience on these materials from our numerous RV programs.

In this presentation I am going to cover three areas. First of all, I will summarize the heat shield results from the outer planetary probe mission studies that we've done in the last couple of years. Secondly, I will attempt to demonstrate the applicability of missile flight data to planetary entry conditions; and finally, I will summarize the results of some recent plasma jet testing of carbon phenolic conducted in our ten megawatt facility.

Figure 6-1 illustrates the common probe design that we have developed for exploration of the outer planets. We propose to use a carbon phenolic heat shield material and tailor the thickness of the material to accommodate each of the probe missions.

We have selected an integral heat shield approach over concepts utilizing an intermediate insulation layer in order to eliminate a high temperature interface problem and permit direct bonding of the carbon phenolic to the structural honeycomb sandwich. The sandwich is filled with a very fine powder to minimize degradation of its insulation properties by the high conductive hydrogen/helium gases during the long atmospheric descent phase. The inner portion of the forebody heat shield has been hollowed out to reduce both weight and heat conduction.

The afterbody heat shield is made of a low density elastomeric material which is light-weight and RF transparent.

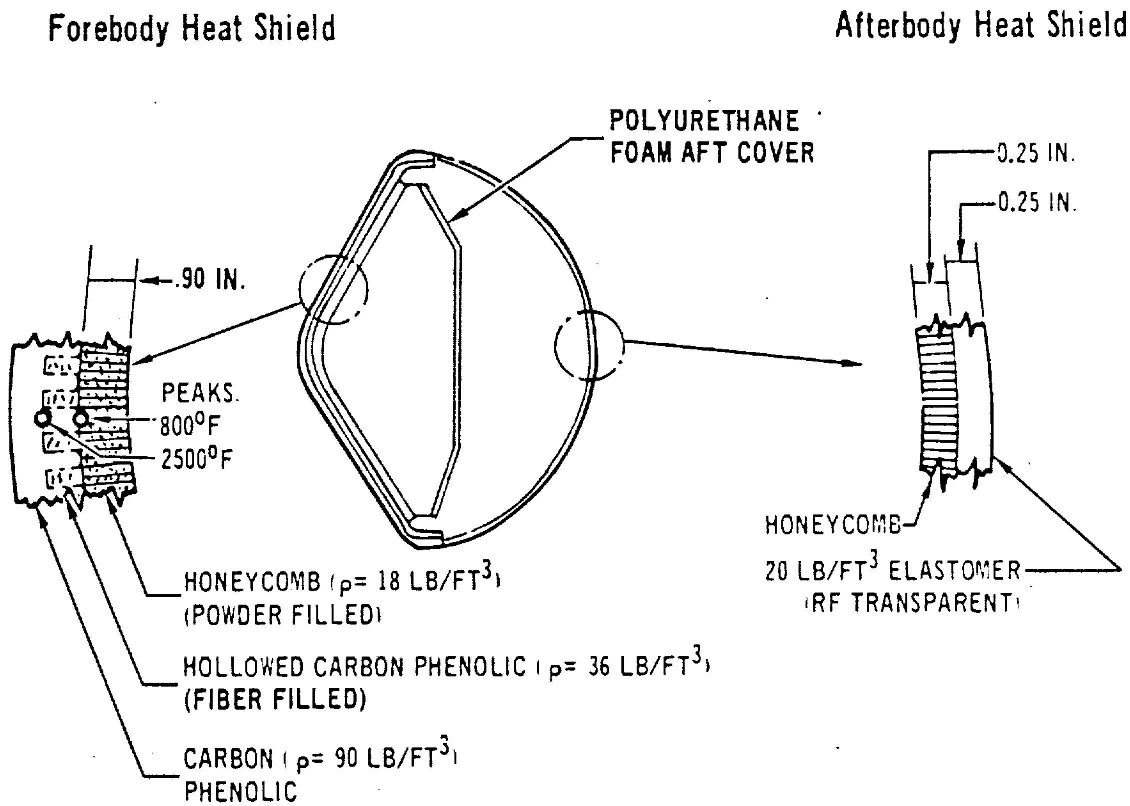

Figure 6-1. Planetary Probe Heatshield

Figure 6-2 depicts the convective and radiative heat flux associated with entry into each of the planets. As indicated, the fluxes are very high, in the 40,000 to 50,000 BTU/FT^2 sec range, and predominantly radiative. These fluxes and the heat shield requirements to be shown later were computed by Aerotherm Corporation under contract to NASA Ames.

The magnitude of heating associated with each planetary entry is very strongly influenced by the initial entry angle and atmospheric mode/assumed. For instance, steep entries into the cold atmospheres of Saturn and Uranus result in heating rates as high as those encountered in a shallow entry into the Jupiter nominal atmosphere, even though the entry velocity at Jupiter is 50 percent higher than entry into the other planets.

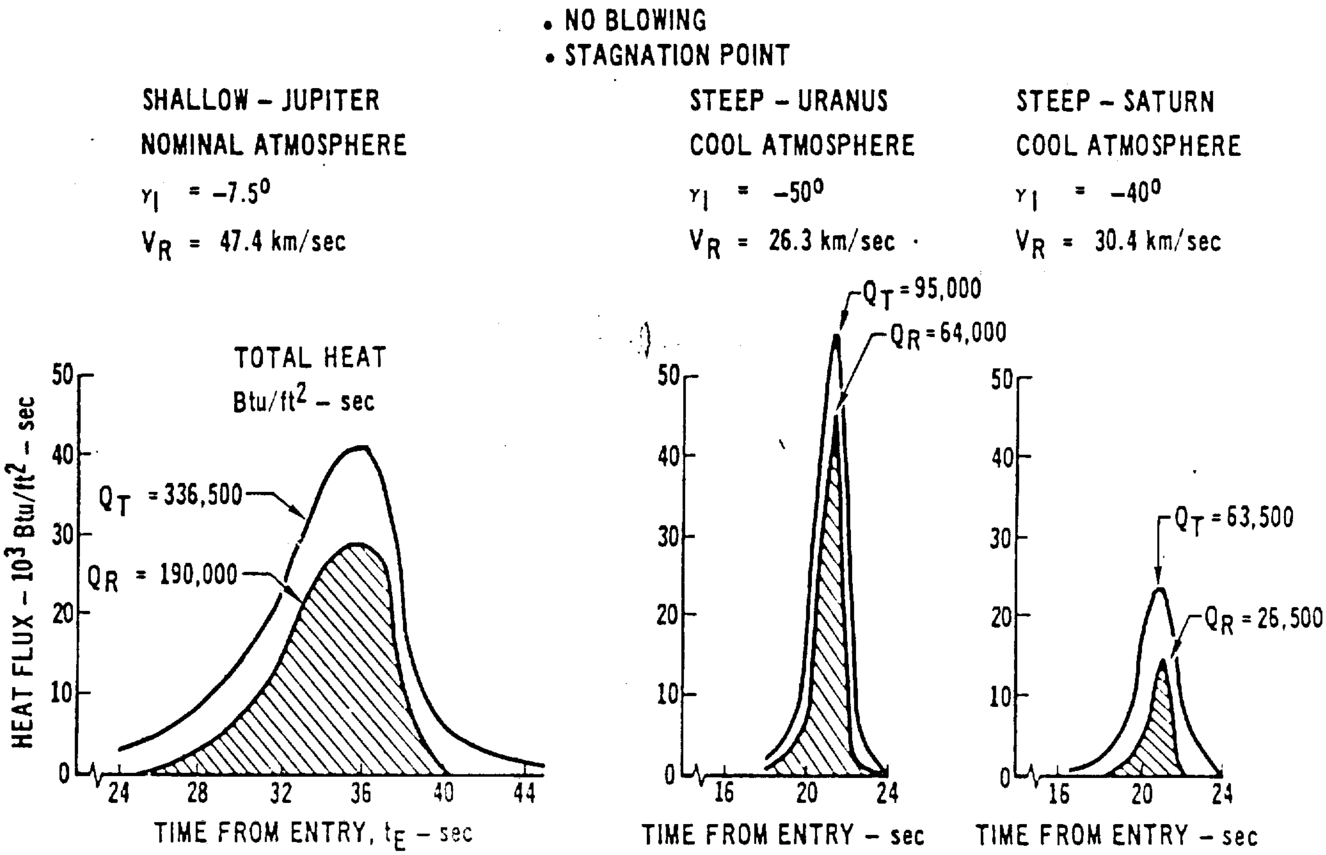

Figure 6-2. Planetary Entry Heating Environments

The high heating rate for the Uranus entry is due to the large proportion of helium dictated by the cold atmospheric model. The high helium/hydrogen ratio results in not only a higher deceleration load and stagnation pressure but also in higher shock layer temperatures and much higher radiation fluxes. Selection of the shallow Jupiter entry condition was made on the basis of the preliminary Pioneer 10 data which indicated that the atmosphere composition is near the solar abundance ratio (nominal model) and better knowledge of the planet's ephemeris data permit shallow entry with very small uncertainty in entry angle.

Heat shield thickness requirements for each of the outer planets is established by analyzing a number of critical entry trajectories which bound the entry envelope and atmospheric model uncertainty. In general, steep entries coupled with the cold atmospheres model definition results in high heating rates and high surface recession rates whereas shallow entries and warm atmosphere lead to milder heating rates but longer durations and higher insulation requirements.

For Saturn, the shallow-warm atmosphere entry sized the heat shield even though the peak heat flux was only 2300 BTU/FT^2-sec and practically no surface recession occurred. Conversely, entry into the Uranus cold-dense atmosphere model results in very high heating rates so that material recession sizes the heat shield thickness requirements. For Jupiter, we have purposely limited the entry angle to very shallow values (about 7.5°) in order to alleviate the heating and heat shield requirements. Furthermore, the Pioneer 10 data indicate an atmosphere composition corresponding to the current nominal atmosphere.

The heat shield thickness shown in Figure 6-3 is based on 2000°F backface temperature. A number of insulative approaches can be used to reduce the temperatures below the 2000°F level. For Saturn/Uranus, our baseline approach is to hollow-out the carbon phenolic below the 2000°F isotherm whereas for the Jupiter heat shield we have elected to forfeit the weight savings provided by the hollowed-out layer in order to increase the inherent safety margin.

Figure 6-4 illustrates the similarity in entry heating and pressure between planetary probe and mission flight entries. The missile body point of interest is the control surface that was protected with a carbon phenolic heat shield. Heating rates on the missile nose tip are even higher but stagnation pressures are sufficiently high (above 100 atmospheres) to exclude the applicability of these data for planetary heat shield designs.

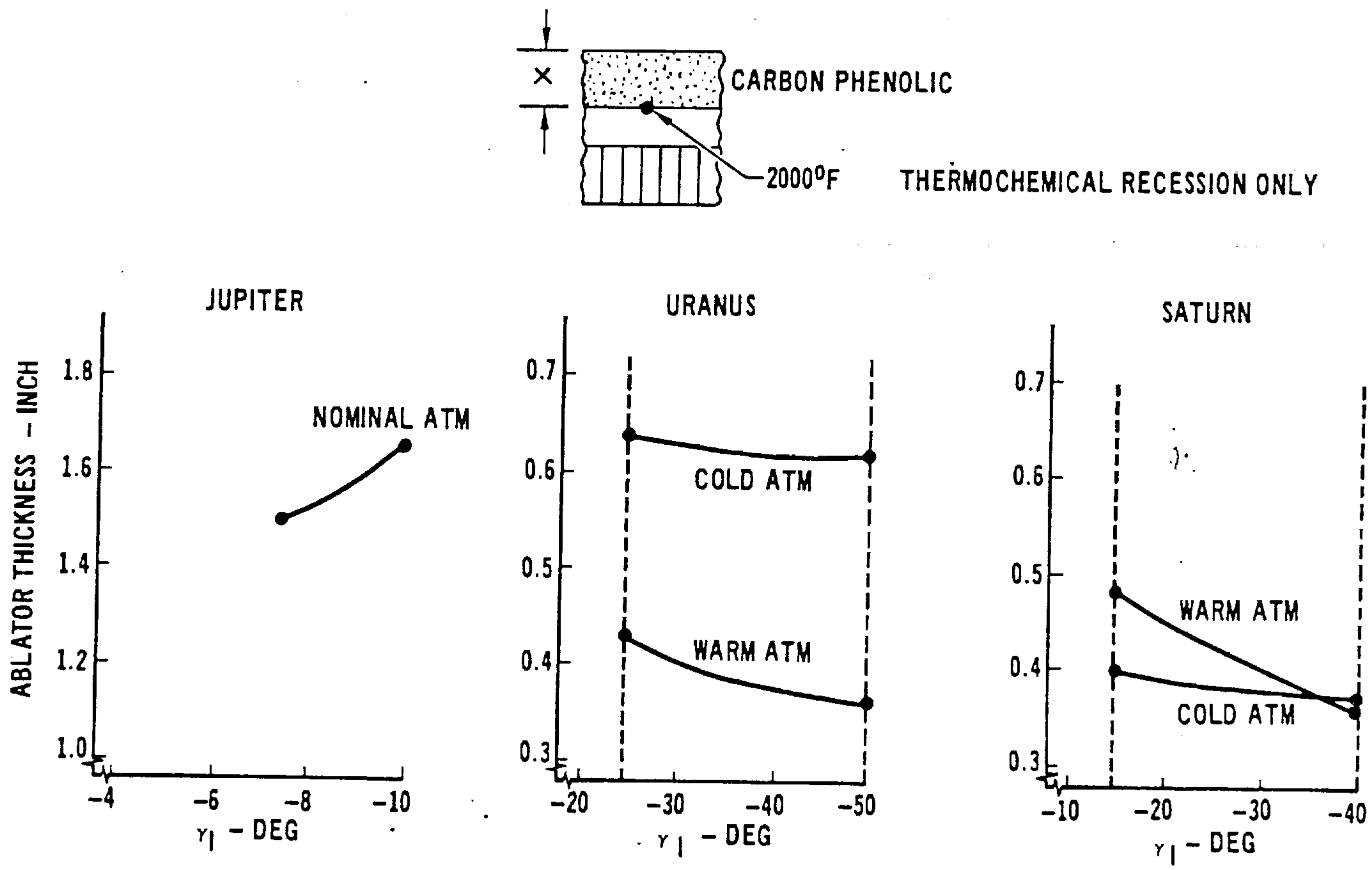

Figure 6-3. Heat Shield Requirements

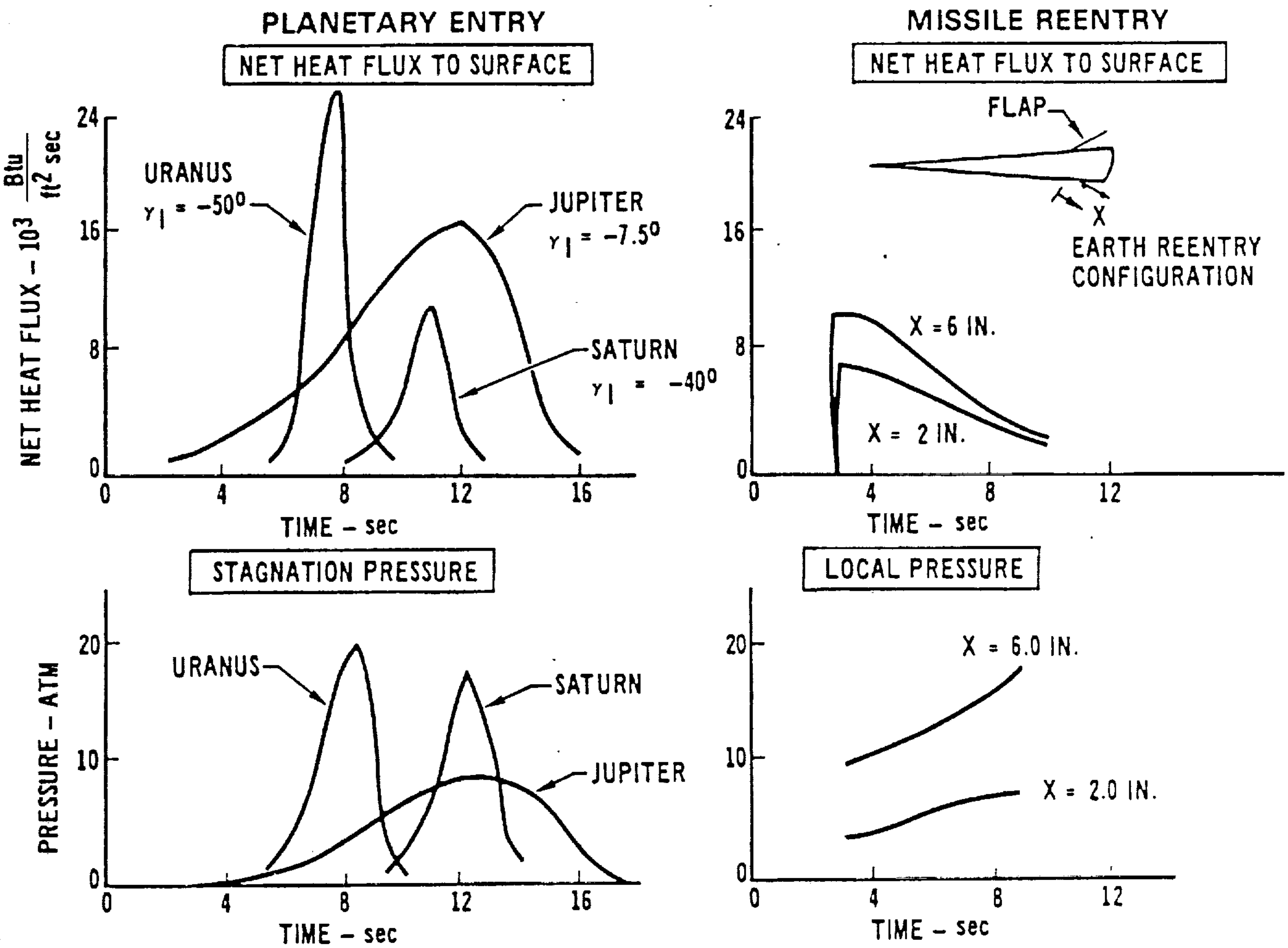

Figure 6-4. Planetary Entry Environments

The comparison in heating is in terms of net heating to the surface; i.e., the reduction in heating due to ablation blowing and hot wall correction has been applied. The comparison is made in this manner since blowing greatly reduces the planetary heat flux but only slightly affects the turbulent heating on the flap. Furthermore, it is presumed that there is no effect in material performance between convective and radiative heating for Carbonaceous materials since the incident radiant energy is absorbed on the surface. If one accepts this assumption, then they could use the missile flap data to base the probe heat shield design. Note, that the pressure levels between planetary and missile entries compare favorably. Pressure is important since mechanical erosion for carbon phenolic ablators has been correlated in terms of this parameter.

Mechanical erosion represents the greatest uncertainty in predicting material performance during planetary entry. The central question is how the material recedes, does it recede primarily due to chemical reaction and sublimation (thermochemical recession), processes that absorb large amounts of energy per pound of material consumed; or is there a large fraction of material removed by bits and pieces (mechanical erosion) resulting in a reduction of material effectiveness. Causes for mechanical erosion have been attributed to preferential oxidation of the binder, high surface temperatures with large temperature gradients and high aerodynamic shear and large pressure gradients. For lack of adequate analytical techniques, we have resorted to empirical correlation of ground test or preferably flight data. The correlation shown in Figure 6-5 is based on the missile flight data discussed earlier. The correlation is in terms of measured total recession rate, mechanical and thermochemical included, ratioed to the predicted thermochemical recession rate versus surface pressure and net heat flux to the surface.

A high degree of uncertainty is present in the application of this correlation to planetary entries, primarily because of

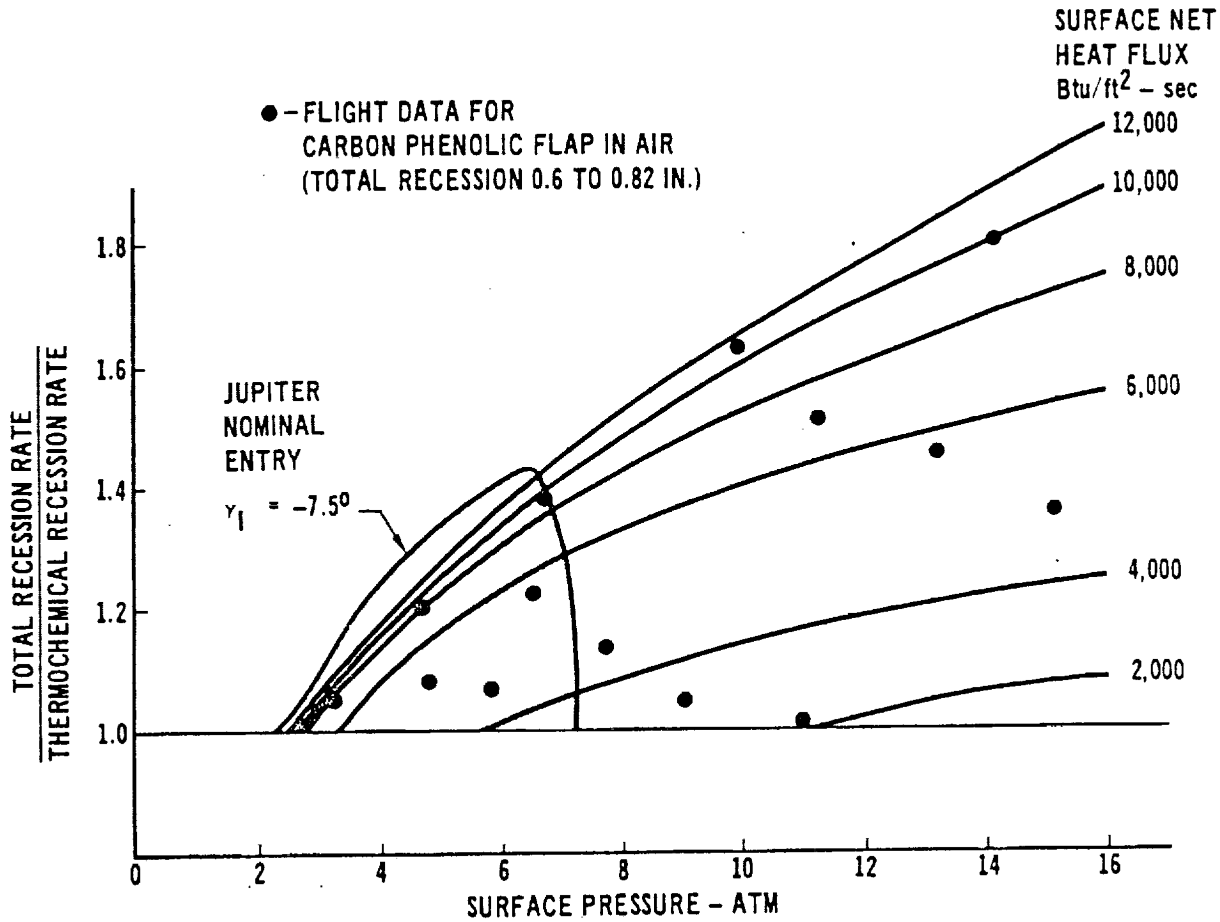

Figure 6-5. Mechanical Erosion Correlation of Missile Flight Data

the difference in environments. However, the correlation is presumed to yield conservative estimates of mechanical erosion since the aerodynamic shear levels were much higher than those expected on the probe.

The Jupiter heat shield thickness based on computation of the thermochemical and mechanical recession and insulation requirements for an 800°F bondline temperature are illustrated in Figure 6-6. Assuming a constant forebody ablative thickness and adding the honeycomb and powder insulation weight results in an aeroshell mass fraction of about 53 percent. Although this is a relatively high weight penalty, it is within the probe weight allotment.

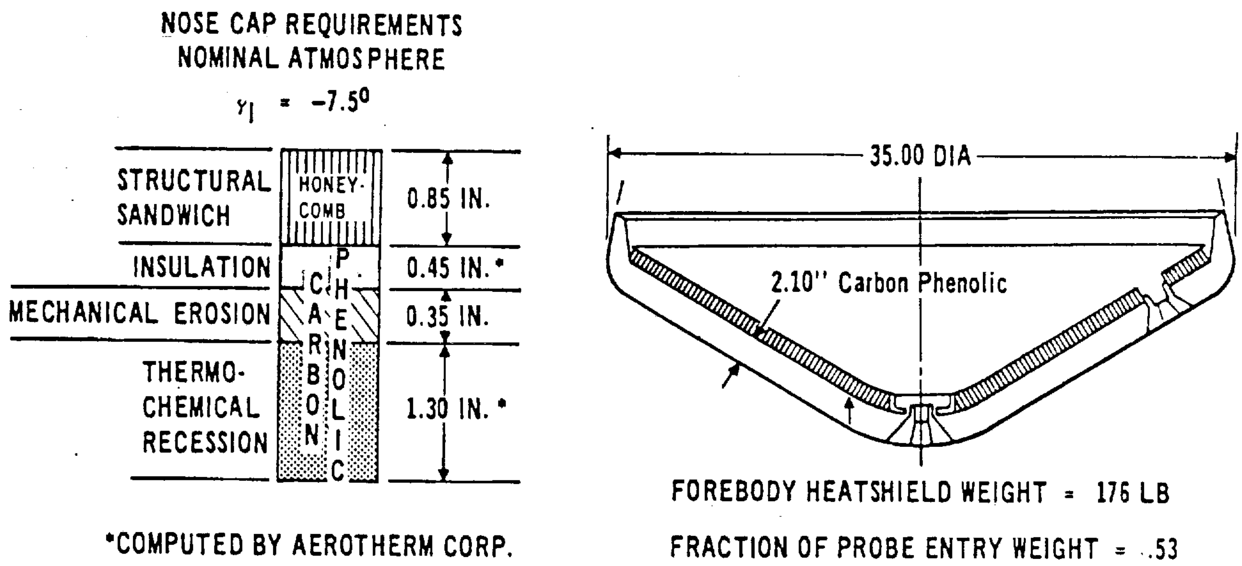

Figure 6-6. Carbon Phenolic Heatshield for Jupiter Entry

A plasma jet test program (Figure 6-7) was conducted in the MDRL 10 Megawatt Facility to obtain performance data on carbon

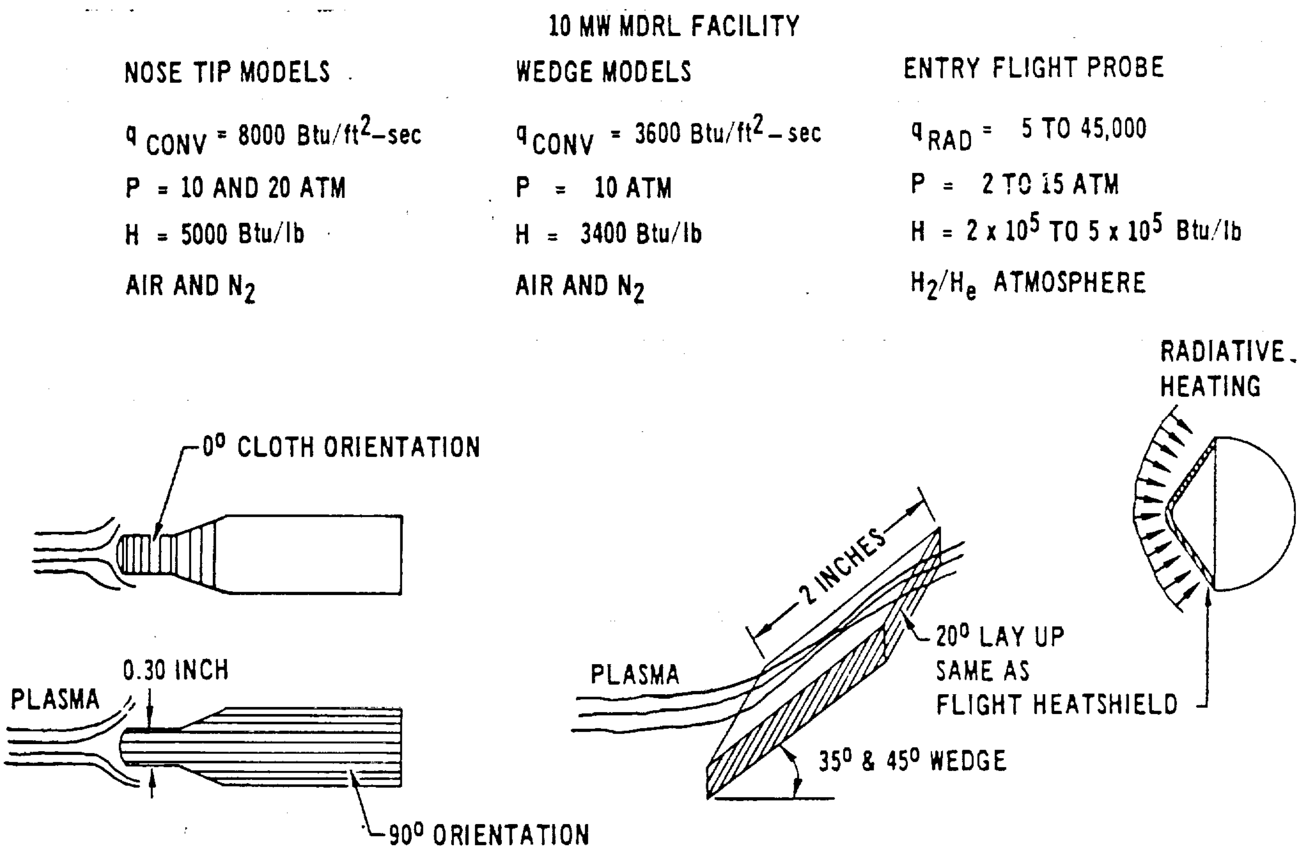

Figure 6-7. Plasma Jet Test Program

phenolic at the possible highest heating rates but at moderate pressures between 10 and 20 atmospheres. A key objective was to evaluate the mechanical erosion phenomena in an oxidizing (air) and an inert environment for possible extrapolation to the hydrogen helium planetary atmospheres. Both nose tip and wedge models were tested in air and nitrogen plasma streams. Much higher heating rates are feasible with the nose tip model, however, the wedge model besides providing a larger test specimen, is also more representative of the flight heat shield in regards to the cloth orientation with the boundary layer flow.

Theoretical ablation predictions have been made to correlate the measured recession rate data. As shown in Figure 6-8, a fair degree of matching the data was achieved in our initial analytical effort and work is continuing in this area to resolve some of the discrepancies. A major problem is the uncertainty in the nose tip recession rate measurements. Contributors to the uncertainties are the relatively small total recession experienced, the initial swelling of the material and the lack of sufficient data points to provide a good average value. Recession measurements were obtained from measurements of the before and after test specimen thickness and from motion picture views of the receding surface. The nose tip motion pictures showed small flakes of carbon phenolic laminates being removed (mechanical erosion) in both the air and nitrogen runs but at a higher rate in air tests. The small nose tip size and the flat laminate lay-up contributed to this mechanism of removal.

Although a number of discrepancies are indicated by the data, the trend of the data indicates a higher mechanical erosion in air than in nitrogen and higher erosion rates in the turbulent higher shear wedge environments.

MR. VOJVODICH: Sam, I think this will probably be a question of general interest, and that is: In the Saturn and Uranus cases you show, as you decrease the entry angle, the heat shield

GAS STREAM	CLOTH ORIENTATION (DEG)	COLD WALL HEAT FLUX Btu/ft^2-sec	SURFACE PRESSURE ATM	MEASURED RECESSION RATE (INCH/SEC)	PREDICTED THERMOCHEMICAL RATE (INCH/SEC)	MEASURED / THEORY
		NOSE TIP DATA (LAMINAR)				
AIR	0	6300*	10	0.058	0.057	1.01
N_2	0	6300*	10	0.025	0.035	0.72
AIR	0	6800*	20	0.087	0.070	1.14
N_2	0	6800*	20	0.022	0.031	0.70
		WEDGE DATA (TURBULENT)				
AIR	20	4560**	13	0.064	0.050	1.28
N_2	20	2630	13	(+ 0.005) (SWELLING)	0.006	-

*HEAT FLUX MODIFIED BY NOSE TIP SHAPE CHANGE
**HEAT FLUX BASED ON CUSPED CALORIMETER DATA

Figure 6-8. Preliminary Comparison of Plasma Jet Test Data with Theory

weight goes up. In the case of Jupiter, as you are decreasing the entry angle, the heat shield weight is going down; will you comment on that.

MR. MEZINES: The total heat shield thickness is the sum of the recession thickness plus the insulation thickness needed to limit the backface temperature to a certain value. In general, increasing entry angles result in higher recession but lower insulation requirements. The total thickness or the sum of these two thickness may or may not increase with higher entry angles but will depend on which mechanism predominates. For Jupiter entries, recession is the dominant mode, thus total thickness requirements are higher with increasing entry angles. Conversely, for the Saturn/Uranus entries, the insulation requirement sizes the heat shield thickness; thus higher entry angle entries require less thickness to achieve the same backface temperature.

DR. NACHTSHEIM: Our next speaker is John Lundell who will describe the evaluation of graphitic materials in the Ames high-powered gas dynamic laser.