THE SOLAR PROBE SHIELD/ANTENNA MATERIALS CHARACTERIZATION

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ABSTRACT

This paper considers the development process used to select the shield/antenna material satisfying the design requirements of the Solar Probe mission that will encounter a flux of 3000 suns at perihelion. A joint U.S. - French testing program was devised that would screen samples of carbon/carbon to determine the fabrication process that would produce the best thermal-optical and thermal-mechanical properties, lowest mass loss, and acceptable RF properties for temperatures up to 2400 K during shield operation. The U.S. testing program relied on three facilities to measure thermal-optical properties, emissivity, and mass loss. The facility for optical property testing consisted of a high intensity halogen lamp whose beam passed through a window in a vacuum chamber containing the sample. As the beam intensity was increased, the increasing temperature of the sample was measured by contact thermocouples for various angles of incidence. The temperatures were introduced into a heat balance equation to determine the absorptivity/emissivity (α/ε) ratio given the known heat flux input. The emissivity of the samples were determined, independently, by another specially calibrated facility that used Joule heating of the samples and measured the emissivity by remote pyrometry that had been precisely calibrated. The mass loss from the samples was measured in an special furnace facility that heated the samples over a progressively longer duration while the mass of the samples was measured precisely between each heating interval. Thermal-mechanical properties were measured using standard techniques at the NASA Langley Research Center and its subcontractors.

The French testing utilizes a specially designed chamber facility at the CNRS 1000 kW Solar Furnace at Odeillo Font-Romeu. The test facility (MEDIASE) is a highly instrumented vacuum chamber that is located at the focus of the furnace . This facility provides the best solar simulation for the carbon/carbon samples in our testing program by using concentrated solar radiation. The vacuum chamber has a unique hemispherical window that allows high vacuum operation even while the window has a temperature of over 700 K. The test samples can be heated to temperatures as high as 2400 K to simulate the solar flux at perihelion. The instruments in the MEDIASE chamber include a two color pyrometer, a spectroradiometer, a quartz crystal microbalance and a mass spectrometer. The data collected from these instruments are sufficient to identify

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Keywords: Carbon/carbon composites, optical properties, electrical properties, mechanical properties

the thermal-optical properties of the materials, as well as their mass loss characteristics at high temperatures including the emitted species.

The test specimens were chosen from various fabrication techniques to identify how the techniques would affect the final carbon/carbon characteristics. Six specimens from four companies were tested. These samples varied in fiber, tow size, weave geometry, starting resin, and densification technique. The test results suggest some consistent trends. The fabrication process that affected the materials to the greatest extent was the final densification. Chemical Vapor Infiltration (CVI) as the final densification process led to the most desirable optical properties. The most significant trend was a reduction of the α/ε ratio at higher temperatures for the CVI densified materials. The other materials demonstrated an increase in this ratio for higher temperatures. In addition to the CVI densification, the results suggest that a final seal coat of pyrolytic graphite enhances the reduction in α/ε at high temperatures. This is an ideal solution to the Solar Probe shield design to reduce its operating temperature at high solar flux. The materials that had CVI densification also exhibited the highest values of elastic modulus and mechanical strength. Radio reflectivity tests were run on the materials and they demonstrated reflectivity suitable for an antenna reflector at the X-band frequencies to be used on the Solar Probe.

1.0 INTRODUCTION AND BACKGROUND

The destination of the Solar Probe is the atmosphere of the sun. It will approach the sun within 2 million kilometers of the sun's surface (a perihelion radius of 4 solar radii) while traversing the sun's atmosphere or corona as shown in Figure 1 to make fundamental observations of the least understood environment in the solar system (See Ref. 1 and 2).

Figure 1. Solar Probe Perihelion Mission Profile as Seen from Earth

The spacecraft configuration is shown in Figure 2 with the large elliptical shield dominating the configuration. The shield is an elliptical parabola which has a dual function as a shield and as a high gain antenna (Ref. 3, 4, 5, 6, and 7).

Measurements of the plasma environment including the birth and acceleration of the solar wind are the principal scientific objectives. To accomplish these measurements the spacecraft must not produce excessive outgassing or sublimation that could ionize and contaminate the natural plasma environments that are measured. The scientific community has suggested the magnitude of contamination that is acceptable and has given a specification of less than 2.5 milligrams per second at perihelion.

Figure 2. The Folar Probe Configuration at Perihelion

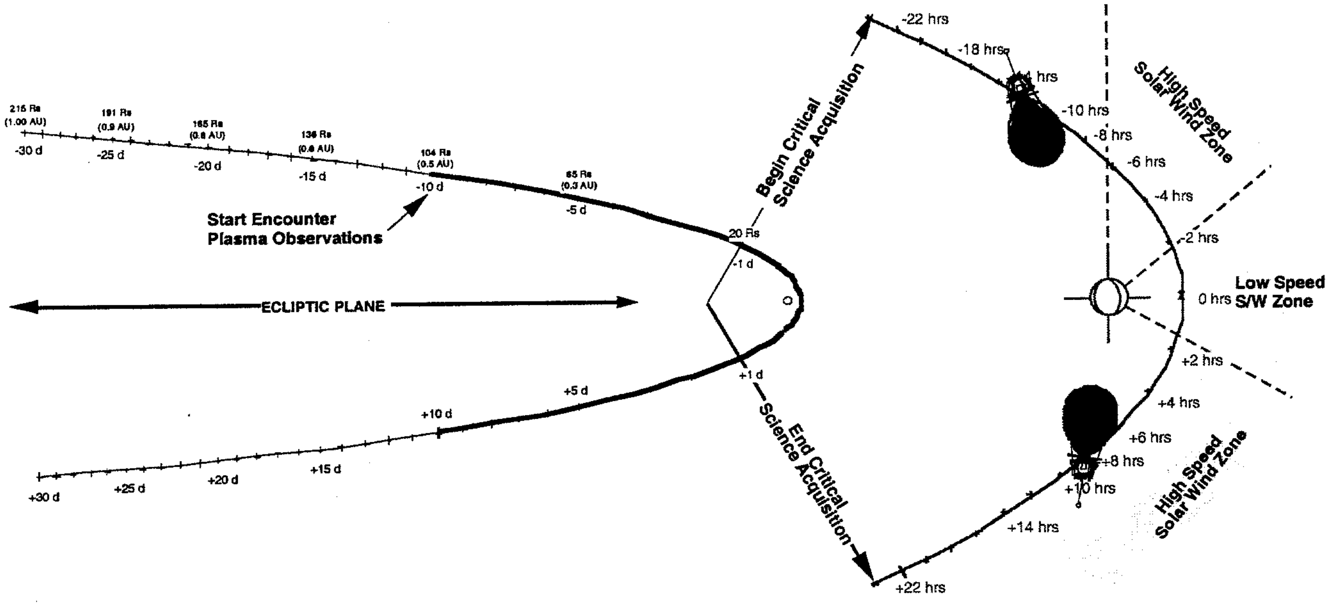

Figure 1 Perihelion Mission Profile as Seen from Earth

To travel to a perihelion radius of four solar radii ($4R_s$) requires a very high energy launch capability. In order to maximize the launch capability and minimize launch costs, the spacecraft must be as small and lightweight as possible while satisfying the scientific payload accommodation requirements. In addition, for a spacecraft traveling to $4R_s$ and maintaining its electronics at room temperature (approximately 300K) a shield is required to shade the electronics while the shield itself is operating at extremely high temperatures (greater than 2000 K). The combination of these requirements led to the selection of carbon-carbon as the ideal shield material because of its low density, high strength, and high temperature characteristics. Carbon-carbon was also chosen because of its extensive recent history of development and its well known properties. The only properties that are not as well known are the thermal-optical and mass loss properties of its surface. These are the properties that are very important to the Solar Probe mission. Thus, the key challenge of the program discussed in this paper was to determine these properties at the extreme solar fluxes and temperatures expected at perihelion.

The program began by fabricating many samples of carbon-carbon with various fabrication processes. The intent was to understand the thermal-optical properties of carbon-carbon depending on the fabrication techniques and thereby select the best technique for the full scale shield. A collaborative program between France and the U.S. was established for testing the materials. The results of this testing program will be discussed in detail below.

2. FABRICATION PROCESSES FOR THE CARBON-CARBON SAMPLES

Six samples of carbon-carbon were fabricated for the U.S. test program by four industrial partners. The fabrication characteristics of the samples are summarized in Table 1. It was expected that the thermal-optical properties would depend on the final densification technique. Three techniques were used as shown in the table: phenolic densification, chemical vapor infiltration (CVI), and pitch densification. It was expected that the CVI technique would be important but the other techniques were also studied. Thus, four of the six samples used CVI densification in addition to variations in fiber, tow size, pre-pregnation technique, and weave as shown in the table.

In an effort to understand how the surface appearance might affect the surface properties, images of the samples were made using a scanning electron microscope. Figure 3 shows two such images that emphasize the extremes of surface appearance as a result of the fabrication process. Figure 3a is the image of the pitch densified sample and illustrates the rough linear features that are typical of the process. In comparison, Figure 3b shows the relatively smooth final surface of the CVI process that was evidently very important to the final results discussed below.

Table 1. Carbon-Carbon Test Samples

Coupon #	Company	Fiber (Pitch Fiber)	Tow Size	Prepeg	Densification	Weave
1	C-CAT	P-100	2K	Phenolic	Phenolic	8 HS
2	BFG #1	K-321	2K	Hi-K	CVI	5 HS
3	BFG #4	P-30	2K	Phenolic	CVI	5 HS
4	BFG #5	K-321	4K	Phenolic	CVI	Tape
5	FMI	P-55	2K	Pitch	Pitch	8 HS
6	SAIC	T-300 HT (PAN Fiber)	3K	Phenolic	CVI + Sealcoat	8 HS

3.0 TESTING FACILITIES FOR THE SHIELD SAMPLES

Testing materials for the Solar Probe shield presents many new facility challenges. The generation of almost 3000 suns (400 W/cm^2) in a deep space vacuum environment has required extensive new facility development in the U.S. and in France. The earliest attempts to achieve this environment began in the 1980s when a vacuum chamber facility was designed (Ref. 8) in conjunction with the CNRS solar furnace facility.* Although some preliminary tests were completed using this facility, a new facility (MEDIASE, Ref. 9) was designed (see Figure 4) and is now functioning at the CNRS-IMP. The MEDIASE has very sophisticated instrumentation (as shown in figure 4)for high temperature testing of sample materials. It uses multiple optical instruments to measure temperatures in many spectral bands (Ref. 9). In addition, it can measure the mass loss from the samples using a quartz crystal microbalance and a mass spectrometer. It can also inject high energy particles (e.g., ions) into the chamber to more accurately simulate the environments close to the sun.

Some smaller U.S. test facilities have also been used. A testing program (Ref. 10) was initiated in 1996 with Lockheed Martin Astronautics, LMA (Denver, Colorado) to determine the thermal-optical properties of the carbon-carbon samples discussed above. A program of fabrication and testing (Ref. 11) was initiated at NASA's Langley Research center to determine the strength and internal properties of the carbon-carbon samples.

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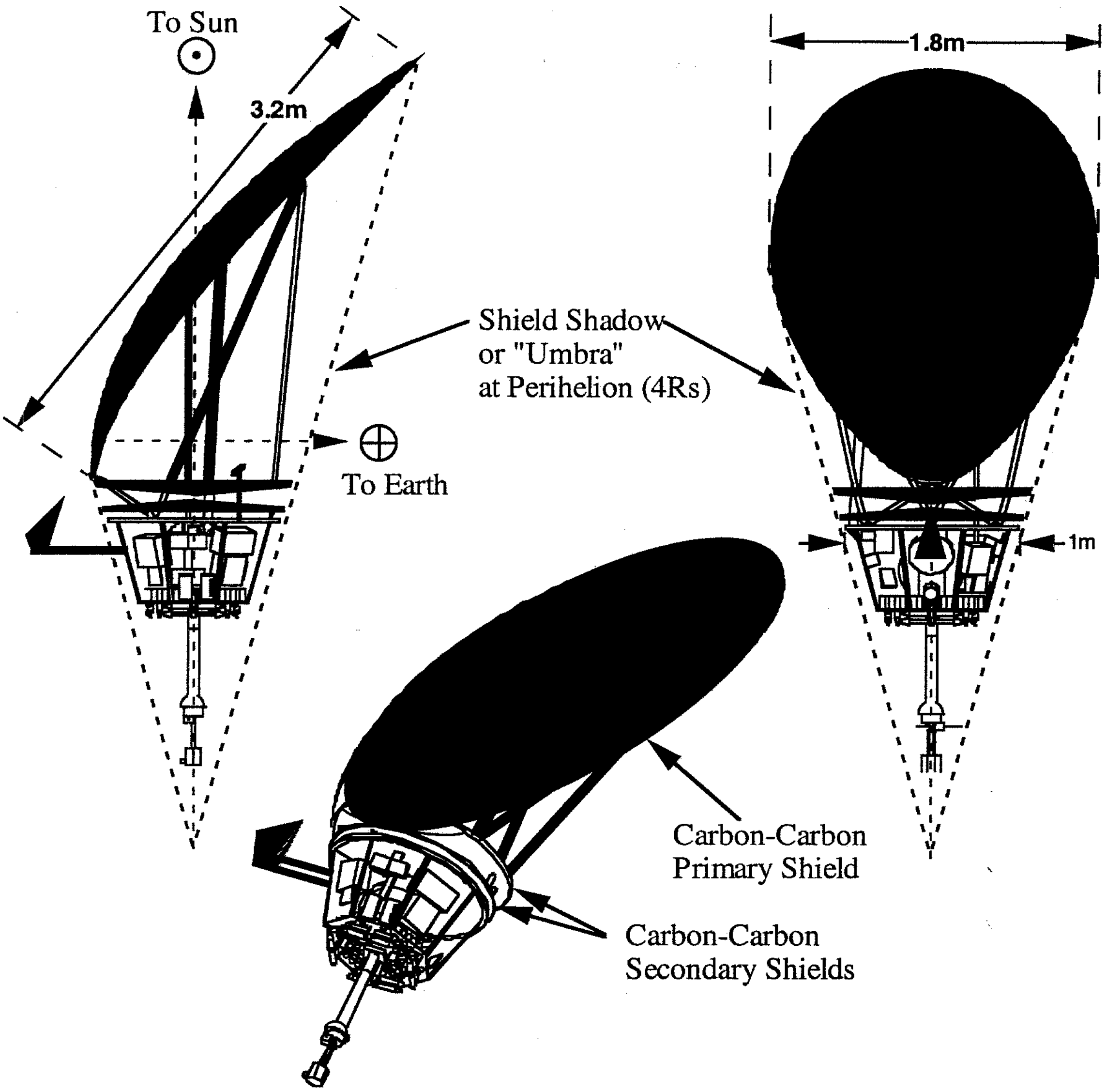
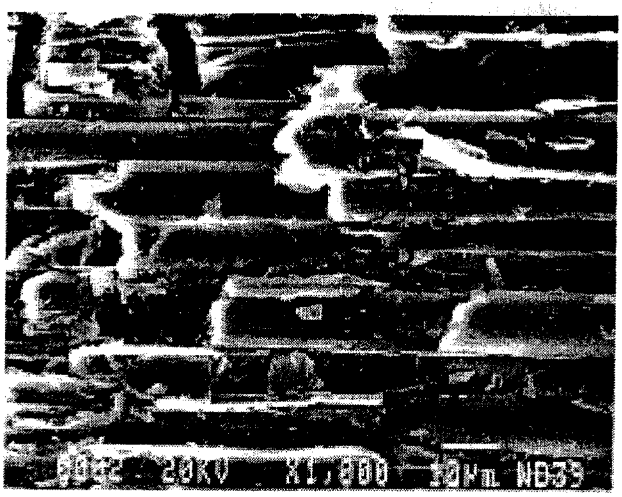
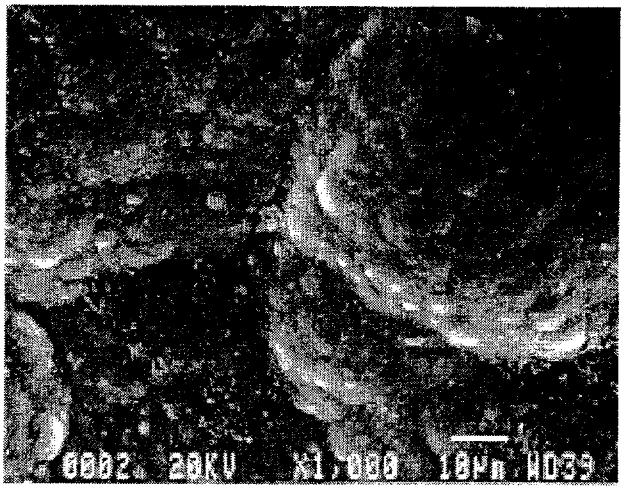


Figure 2 The Solar Probe Configuration at Perihelion



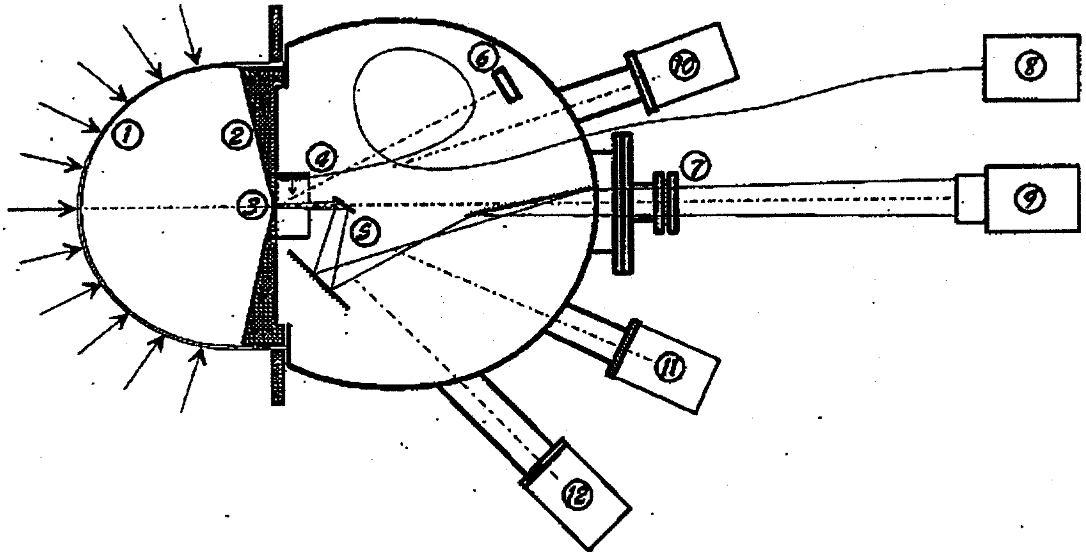
a. FMI Sample #5 (P55 - Pitch/Pitch - 8 HS-Machined)



b. SAIC Sample #6 (T-300HT - Phenolic/CVI+Sealcoat - 8HS)

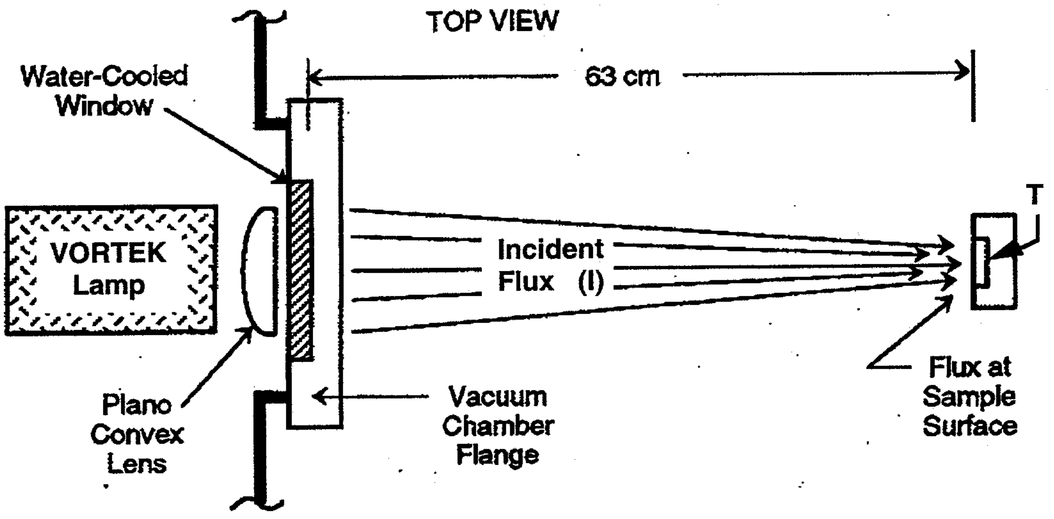
Figure 3. Scanning Electron Micrograph of Two C-C Samples (from Ref. 3).

Two test facilities were used for the thermal optical properties testing in the U.S. A laboratory at Lockheed Martin Astronautics (LMA) in Denver, Colorado uses a high intensity halogen lamp ("VORTEK") beam that passes through a window into a vacuum chamber containing the sample. Figure 5 is a schematic image of the LMA facility. The measurements are primarily temperatures acquired using thermocouples in contact with the carbon-carbon sample. Knowing the flux input (I), the test data allows the direct determination of the ratio of solar absorptance (α) to hemispherical emittance (ε) using the classic equation shown in Figure 5. Thus, by measuring the I and T values, the α/ε ratio can be determined in a well calibrated environment.



1: hemispherical silica glass window, 2: water-cooled shield and sample holder, 3: specimen, 4: optical fiber probe, 5: 3-mirrors goniometer, 6: microbalance, 7: measurement window, 8: two-color pyrometer or pyro-reflectometer, 9: radiometer or spectroradiometer, 10: mass spectrometer, 11, 12: UV and ion sources.

Figure 4. Schematic of MEDIASE Testing Facility at the CNRS-IMP Solar Furnace



α_S = Solar Absorptance / ε_h = Hemispherical Emittance

σ = Stephan-Boltzmann constant

$\alpha_S / \varepsilon_h = \sigma T^4 / I$ T = Temperature

I = Incident Flux (from Vortek)

Figure 5. Schematic Drawing of LMA VORTEK Testing Facility and Analytical Solution for α/ε

4.0 TESTING RESULTS

In a separate facility at the Thermal Properties Research Laboratory (TPRL), the emittance was determined separately (Ref. 10) in a laboratory that measures emittance using Joule heating of the sample. Figure 6 illustrates some of the emissivity results. The solid curves are the results of the TPRL testing for the samples shown in the legend. Note the similarity of the three samples (BFG-1, BFG-4, and C-CAT) and the significantly higher emittance in the FMI sample. This sample was pitch densified and suggested, early in the program, that this technique could be a key result. The dashed line shows early results from a testing program using the MEDIASE facility at the CNRS-IMP.

The results of the LMA measurements are shown in Figure 7. These results include the determination of the temperatures of the samples and the calculation of the (α/ε) ratio using the equation in Figure 5. Note that the BFG-5 and the SAIC sample results suggest a nearly flat or even decreasing function as temperature increases. Also, the FMI sample, which had such a high emittance (see Figure 7) at high temperatures, has the highest (α/ε) ratio at high temperatures. These results suggest some significant trends that depend on the fabrication processes although the data is quite sparse. If these trends are correct, the combination of phenolic pre-pregnation and CVI final densification suggest that the α/ε ratio is nearly a constant (or decreasing) function as temperature increases. This is very desirable for the Solar Probe to minimize the shield temperatures (and mass loss) at the high flux at perihelion. The solar absorptance (α) has not measured directly but can be inferred from the TPRL results and the LMA results using equation shown in Figure 5.

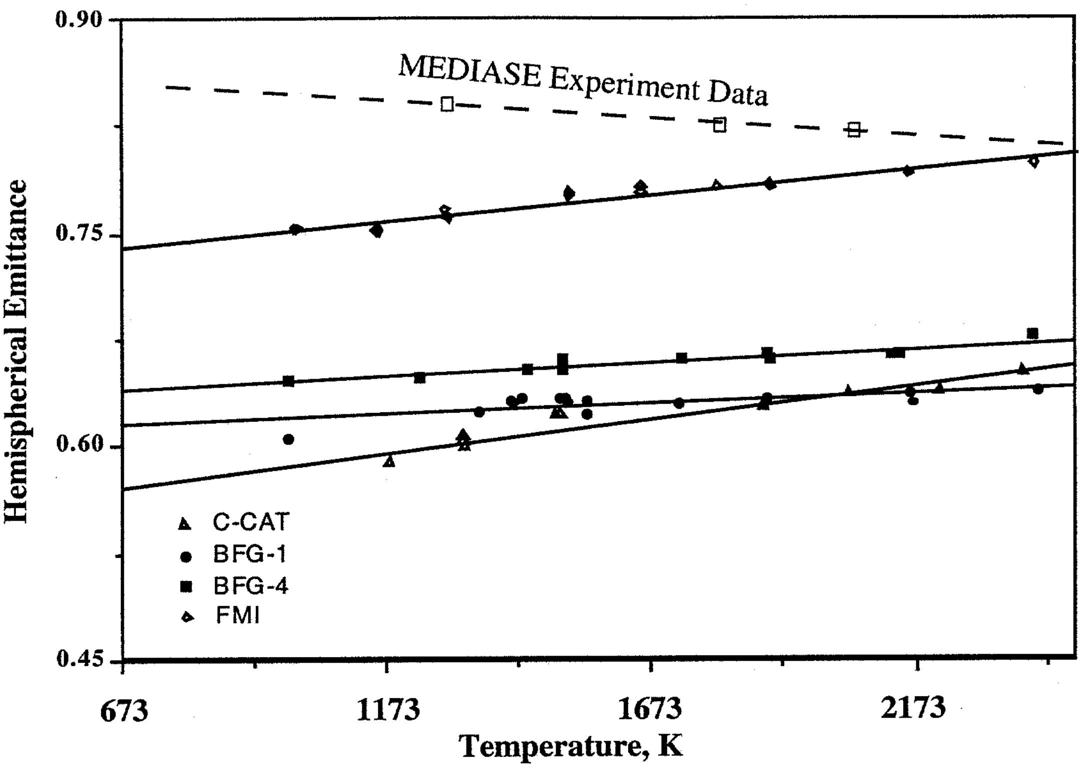


Figure 6. Emittance of Selected Samples vs. Temperature

5.0 CONCLUSIONS

The test results suggest that a shield fabricated from a carbon-carbon material that uses a phenolic pre-pregnation and a CVI final densification can perform well at perihelion. The new results allow the determination of a design space for the Solar Probe shield as shown in Figure 8. Here the shield temperature and mass loss are plotted against the α/ε ratio. The preliminary mass loss requirement specified by the science team is less that 2.5 mg/sec at perihelion and is the key design parameter. Prior to the testing program the design value of the carbon-carbon was assumed to be 1.1. As can be seen from Figure 8, the peak shield temperature (~ 2350 K) and the mass loss (~0.6 mg/sec) are below the requirement for this α/ε ratio and the minimum solar incidence angle of 35° (See Figure 2). (The data of Figure 7 is for an 0° incidence angle.) If the material has the properties of the CVI sample, or $\alpha/\varepsilon = 0.7$, as shown in Figure 8, the temperature and mass loss drop significantly to to ~ 2100 K and ~ 0.006 mg/sec. This drop of almost two orders of magnitude in mass loss suggests that this scientific concern is no longer an issue.

With these results the confidence of fabricating a full scale shield is improved. In the future, a program to revalidate these results is planned and new tests in the U.S. and in France will be conducted using new materials specifically fabricated for the Solar Probe shield.

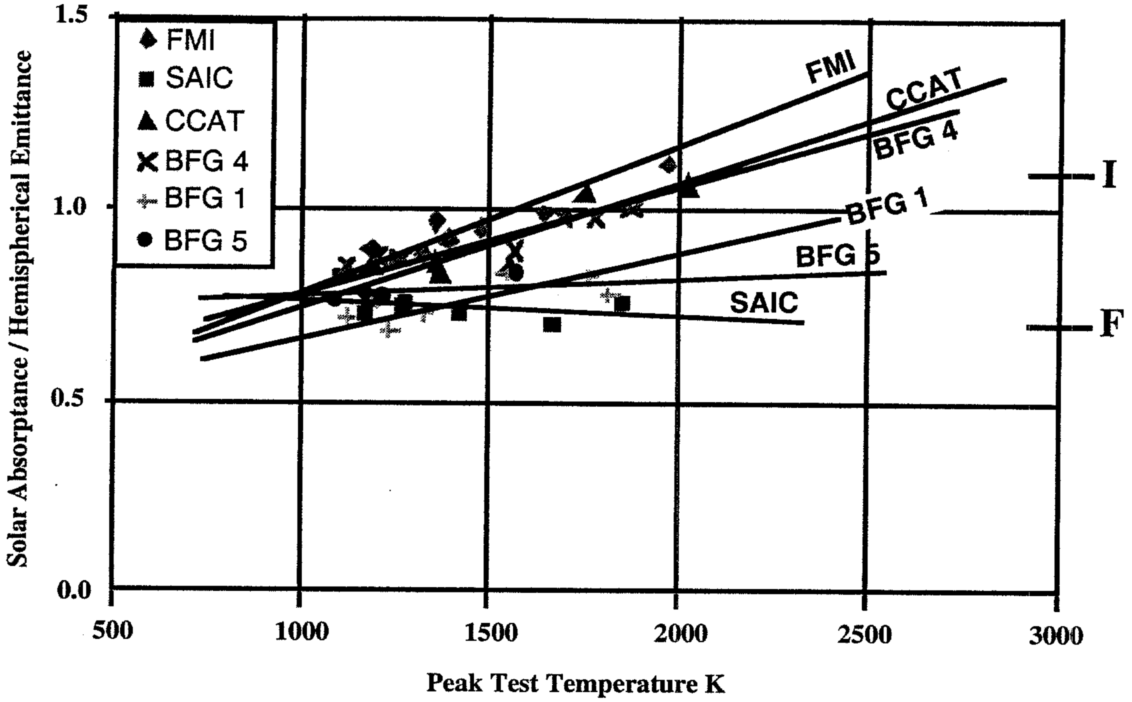


Figure 7. Ratio of Solar Absorptance to Hemispherical Emittance vs. Temperature for the U.S. Test Samples (zero degrees incidence angle)

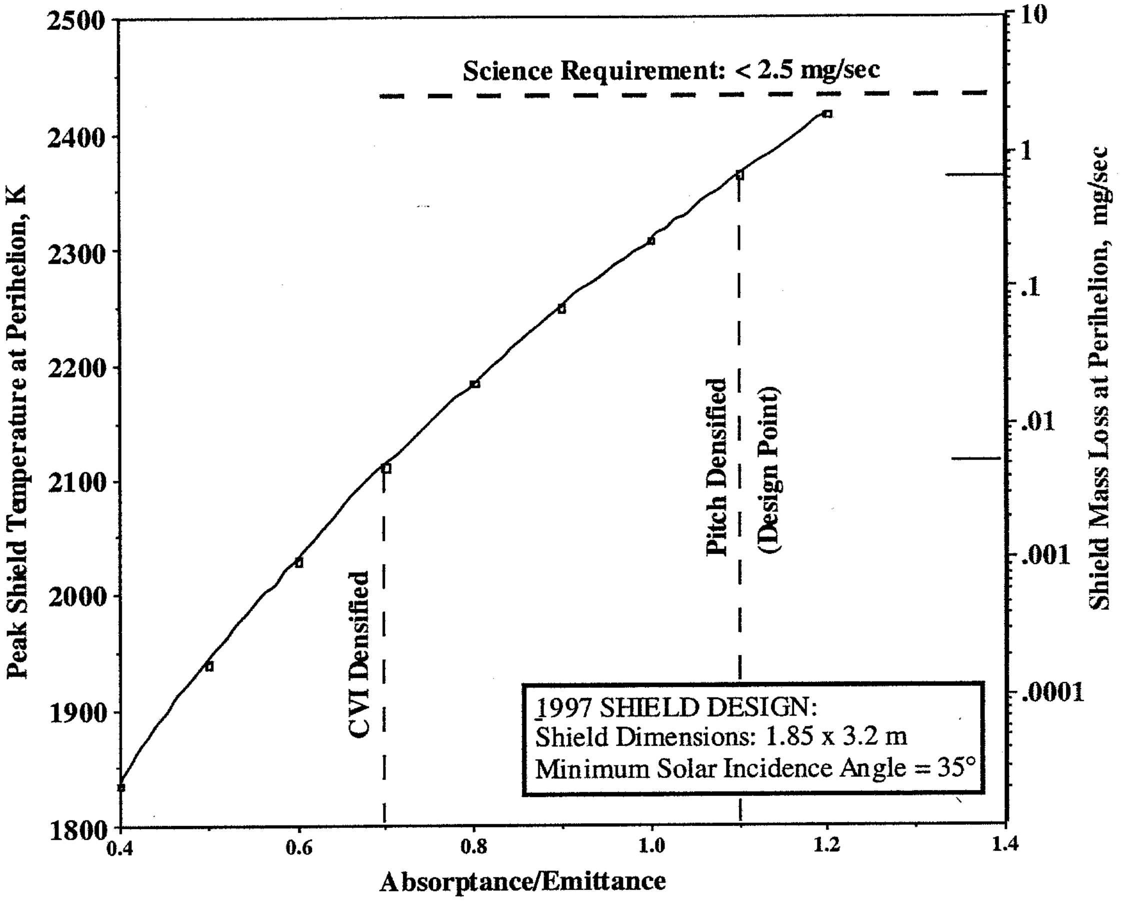


Figure 8. Shield Peak Temperature and Mass Loss vs. α/ε ratio

6.0 ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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