SMALL PROBE REENTRY INVESTIGATION FOR TPS ENGINEERING (SPRITE)
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ABSTRACT

At the 7th International Planetary Probe Workshop a paper [1] was presented proposing a unique strategy for Thermal Protection Systems (TPS) testing designed to strengthen the ground to flight traceability of TPS qualification programs. The concept presented was to develop an inexpensive small scale test platform, i.e., small probes that are fully instrumented, that can be tested both on the ground (in arc-jet facilities) and in flight. This paper presents the results of a focused project that addresses this concept, showing how such small probes were designed and then tested at full scale in an arc jet. This is a paradigm shift from the traditional stagnation point testing to one of "test what you fly", not only enabling traceability from ground to flight, but also enabling the assessment of practices/margins policies used in the design of the TPS of large scale entry vehicles such as Orion or MSL.

This effort, called SPRITE (**S**mall **P**robe **R**eentry **I**nvestigation for **T**PS **E**ngineering) has demonstrated the feasibility of ground testing flight-sized (35 cm diameter) reentry bodies with two very successful tests of full-sized instrumented proof-of-concept articles in the NASA Ames Research Center Aerodynamic Heating Facility (AHF). The objectives of this effort were to design, manufacture and test the article, develop a flight-like data acquisition system, demonstrate data gathering capability, application of design tools and assessment of their fidelity.

The SPRITE probe (a 35 cm diameter, 45° sphere-cone, with a conical after-body) was designed to represent a vehicle that could be both an arc-jet test model as well as an actual reentry body. The probe was instrumented with TPS instrumentation plugs of the same design used on the MSL heat shield [2] as well a number of back-face and internal thermocouples. Strain gages were also mounted on the TPS-protected aluminum structure in an attempt to determine thermo-structural response. Data from the sensors was collected by a custom-designed internal data acquisition system [3] as well as by the arc-jet facility. While it was not the intent of these tests to represent a specific mission, the models were tested at a heat flux (approximately 170 watts/cm^2) representative of an Earth reentry.

This paper will present an overview of the SPRITE project including: overall design of the probe, thermal analysis of the probe, design of an internal Data Acquisition System (DAS), Computational Fluid Dynamic (CFD) simulation of the test conditions, thermal-structural analysis, and results of the arc-jet tests.

1. BACKGROUND

SPRITE was intended as a proof of concept of a small diameter (35 – 40 cm) probe that could be used to test TPS materials both on the ground and as an actual flight experiment. Figure 1 shows the initial concept of the SPRITE probe which is further developed as an arc-jet model in this paper.

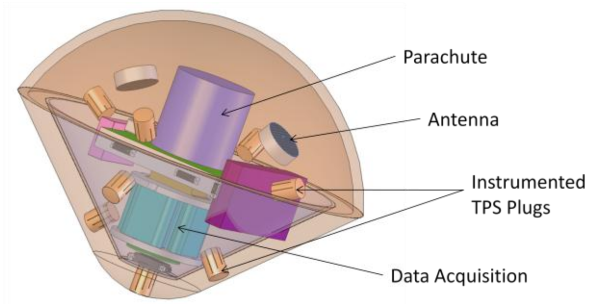

Figure 1 - SPRITE Concept

The 45° sphere-cone with hemispherical backshell configuration was initially chosen for SPRITE due to superior stability in all atmospheric flight regimes. Further background on the concept of operations, mission types and a discussion of using this concept for TPS testing can be found in [1].

In addition to the probe and mission design efforts it was necessary to verify the possibility of running such large models in existing arc-jet facilities. In 2009 and early 2011 a 36 cm (14 inch) diameter solid wood model of the 45° sphere-cone shape mentioned above was tested in the arc-jets at the NASA Ames Research Center. It was clearly demonstrated by these tests that a model of this size could be accommodated in both the 20 MW Aerodynamic Heating Facility (AHF) and the 60 MW Interaction Heating Facility (IHF).

2. MOTIVATION

The motivation for the SPRITE concept is the "Test-What-You-Fly" philosophy of being able to ground test a flight configuration test article; both mechanically and thermally. For the SPRITE project thermal testing was chosen to demonstrate the concept because arc-jet testing of large diameter models is technically challenging.

Since arc-jet testing is relatively expensive, the use of a large model maximizes the amount of information that can be gathered in a single test. Furthermore, the sphere-cone shape of the SPRITE enables simultaneously replication of flight-like heat flux, pressure, and shear over the acreage. Of course, the data obtained from testing SPRITE-like large geometries will have to be supplemented with "traditional" stagnation point or wedge tests, but fewer such supplementary tests will be required.

It is important to note that small earth entry probes are of great interest to the science community, both for return of small payloads from Low Earth Orbit (LEO) and as an enabling technology for return of samples from beyond Low-Earth Orbit. While samples have been returned in the past (Stardust, Genesis, and Hayabusa); there is not a standard approach to designing and recovering the reentry capsules. SPRITE and follow-on work will give insight into this activity as well. Furthermore, it is anticipated that with a large number (or statistically significant number) of flight tests of inexpensive small probes, risks for larger and costlier missions can be reduced considerably.

3. OBJECTIVES

There were three main objectives for the SPRITE project:

1. To demonstrate the feasibility of arc-jet testing flight articles at full scale – a required first step in the 'test what you fly' paradigm;
2. To demonstrate the feasibility of *in situ* measurements of temperature, strain and recession using a data acquisition system mounted inside the test article, i.e., to demonstrate gathering and storage of data acquired by sensors during an arc jet test; and
3. To demonstrate the ability of a combination of simulation tools – primarily *DPLR* [4], *FIAT* [5], and *Marc* [6] – in predicting material response and thermal environments in the interior of the test article during arc jet testing.

The sections below on the design of the hardware and experiment describe how it was planned to meet these goals and a summary of the results describe how well the goals were met.

4. EXPERIMENT DESIGN

One of the goals of the SPRITE project was to show that a flight-sized probe could be "flown" in an arc heater facility. From previous work using a solid wood model, [1] it was shown that a 36 cm diameter 45° sphere-cone body could be tested in the 20 MW Aerodynamic Heating Facility (AHF) at the NASA Ames Research Center.

Based on the tests with the solid wood model the decision was made to demonstrate a more sophisticated model of the same basic shape, but including many of the features of an actual flight probe. A hollow body with real TPS materials, flight-like TPS instrumentation based on the MSL Entry Decent and Landing (MEDLI) design developed for the Mars Science Laboratory (see [2]) and an internally mounted and powered data acquisition system were decided upon as the next steps in the development of this concept.

In order to validate the internal data acquisition system and avoid complete loss of experimental data due to a failure of the relatively untested internal system some thermocouple data were collected by the arc-jet facilities.

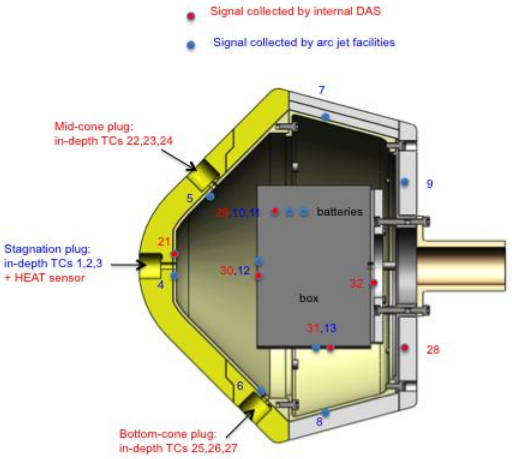

Figure 2 - SPRITE Probe Cross-section and Instrumentation

Due to the limited budget for this project some compromises had to be made that deviated from the flight-like aspects desired, however the overall design used flight proven TPS (PICA and Shuttle tile) and the above mentioned MEDLI instrumentation. Figure 2 shows a cross-section of the probe and location of the instrumentation. Details of the probe design, construction and testing are detailed below.

5. PROBE DESIGN

The development effort for the SPRITE probe consisted of the following aspects: mechanical design and fabrication, TPS design and fabrication, data acquisition system design and fabrication, computational fluid dynamics (CFD) analyses, thermal analysis and thermal-structural analysis.

5.1 Mechanical Design

Both the thermal protection system and the underlying structure needed to be designed for the SPRITE probe. From previous tests (see [1]) of wooden models it was know that a diameter of 35.6 cm (14.0 inches) would work for the arc heater configuration desired. This requirement and the desire to maximize the internal volume of the probe shaped the rest of the design.

For the TPS the first exercise was the choice of materials. In a real mission design reentry requirements, size, weight and other parameters would be used to choose the TPS material, for SPRITE the choice was made by what materials were easily available. This led to the choice of PICA (Phenolic Impregnated Carbon Ablator) as the forebody TPS material and Space Shuttle tile for the afterbody. In order to maximize the interior volume of the probe the thickness of the TPS was limited to 2.5 cm (1 inch) which meant the TPS thickness was dictated by the desired probe volume rather than sizing for a particular reentry or arc-jet condition, i.e., PICA was not sized to meet a bondline temperature constraint. Given the constraints to the design a very a robust and workable concept emerged.

Once the TPS was chosen the structure of the probe body, to which the TPS was attached and which contained the internal data acquisition system, was designed. Again cost and availability played a large role in the choices made. Composites, Titanium and spin-formed Aluminum were all briefly considered but in the end traditional CNC (computer numeric controlled) lathe machining from thick billets of 6061-T651 Machined Aluminum was determined to be the least expensive and shortest lead-time method available. Figure 3 shows the three main Aluminum pieces of the probe structure the forebody, afterbody and back cover.

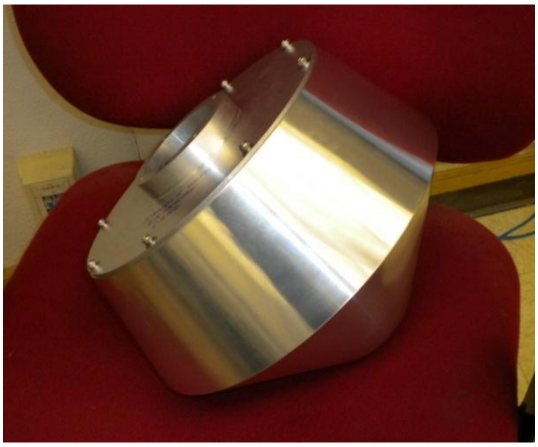

Figure 3 - Probe Aluminum Structure

For simplicity the Aluminum fore and aft bodies were kept the same diameter at the point where they joined. This joint was also a simple butt joint fastened with cap screws from inside the probe body.

In order to simplify the construction of the backshell of the probe the design was changed from hemispherical to conical. While that configuration might not be used on a flight vehicle it was deemed acceptable for a proof-of-concept arc-jet model. CFD analyses were conducted to verify the performance. Figure. 4 shows an exploded view of the probe assembly.

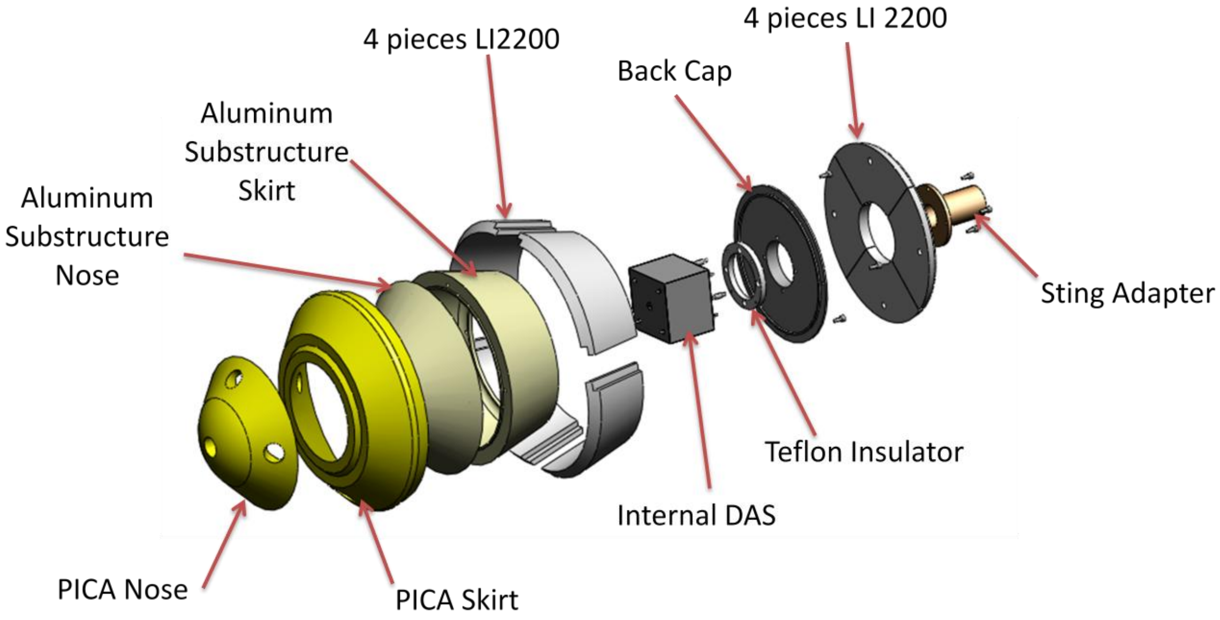

Figure 4 - Exploded View of SPRITE Probe Design

5.2 TPS Design

Many TPS materials could be used on an SPRITE type reentry probe; however a large quantity of PICA was available at no cost to the SPRITE project so this was chosen as the forebody TPS. CFD analyses indicated that afterbody heating at the arc-jet conditions being considered was fairly low (on the order of 10 watts/cm^2) and a lightweight refractory insulation such as any one of the materials developed for tiles on the Space Shuttle Orbiter could likely be used. A number of billets of 22 lb/ft^3 "Shuttle tile" (LI2200) material were also available to the SPRITE program and this material was used as the afterbody TPS.

Because the billet of PICA available for the forebody was 13 cm (5 inches) thick and the required thickness for the forebody was approximately 14.6 cm (5.75 inches) the PICA had to be made in two concentric pieces, likewise the billet size of the Shuttle tile required that the backshell TPS be made in four pieces.

As mentioned above the PICA thickness was arbitrarily (from the thermal protection standpoint) set to 2.54 cm (1.0 inch) on the frustum of the cone. This dimension effectively set the thickness of the backshell tiles at about 1.8 cm (0.70 inch).

5.3 Data Acquisition System Design

One of the other main objectives of the SPRITE project was to show that the data from TPS sensors could be collected from a small and inexpensive data acquisition system (DAS) mounted and powered internally to the probe.

A DAS was designed and fabricated at Ames using off the shelf commercial components and powered by a Lithium-Ion battery. Because the SPRITE probe was not going to be space qualified or thermal-vacuum and vibration tested, ordinary (inexpensive) commercial grade components were used. The system was designed to collect data from 20 type K thermocouples, five HEAT sensors (Hollow aEro-thermal Ablation and Temperature Detector – a TPS isotherm detector [2]). Not all channels were utilized. At the last minute an attempt was made to add two strain gages to the channel count. While the circuitry was in place for the tests the results were not very good, reflecting the hurry of the design and installation.

The system was designed to fit in an (approximately) 1U CubeSat (10 cm x 10 cm x 10 cm) form factor and mounts via a Teflon insulator to the back cover of the probe. This arrangement was not flight-like as the center of gravity of the probe was not considered important for the arc-jet test.

The use of commercial components in the electronics for the DAS (and in particular the battery) limited the allowable internal temperature to 60 °C the maximum allowable battery temperature. Because the lithium-Ion polymer batteries used can fail catastrophically if they are exposed to excessive temperature it was felt that is was particularly important to meet this constraint.

Fig. 5 shows the nearly complete SPRITE model with DAS just prior to final assembly.

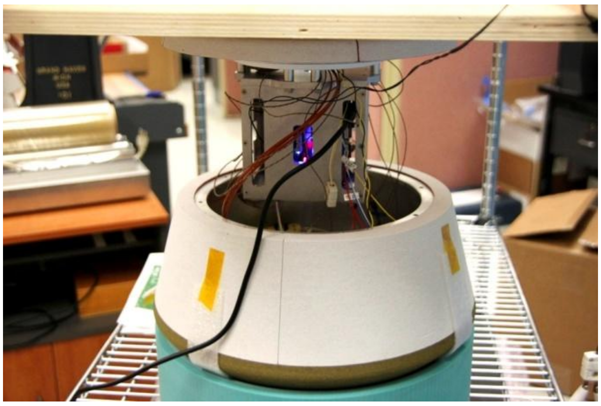

Figure 5 - DAS and Probe Prior to Final Assembly

5.4 Computational Fluid Dynamics

In order to assess the conditions being imposed on the SPRITE model in the arc-jet facility a CFD model of the probe in the AHF was run using the *DPLR* (Data Parallel-Line Relaxation) code [4]. The results of this simulation were used to guide the design of the experiment and as the input to the FIAT calculations and the thermal structural analysis.

DPLR was also used to evaluate the as-tested conditions based on readings from several different calorimeters inserted into the plasma flow before and after model insertion. Ideally a copper calorimeter of the exact size and shape of the test article would be use, however such a device of the size and shape of the SPRITE probe was prohibitively expensive for this small project. The *DPLR* results agreed well with the calorimeter readings as can be seen in Fig. 6.

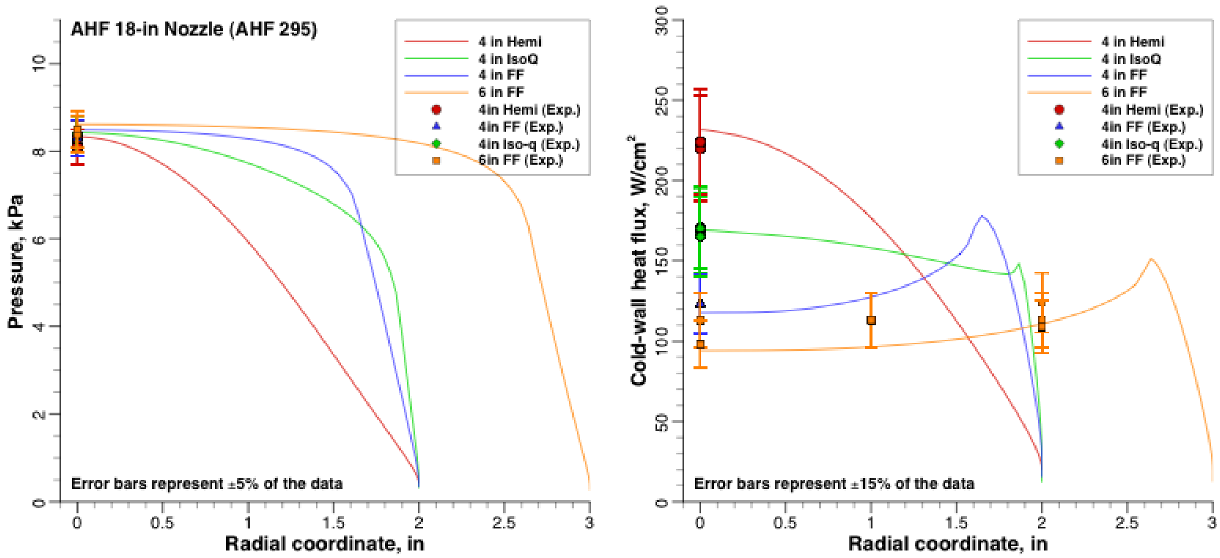

Figure 6 - Comparison of DLPR and Experimental Results

5.5 Thermal Analysis

Two types of thermal analyses were carried out as part of the SPRITE effort: Ablation analysis of the PICA using the FIAT (Fully Implicit Ablation and Thermal response) code and thermal analysis of internal temperatures using the MSC Marc-Mentat [6] implicit nonlinear Finite Element Analysis (FEA) code.

5.5.1 FIAT Analysis

Using the a priori PICA thickness of 1", and flow field predictions for the 18" nozzle of the AHF (at arc-heater conditions) as inputs, FIAT and TITAN (Two-dimensional Implicit Thermal Response and Ablation program – a 2-dimensional version of FIAT) were used to predict the heating at the bond between the PICA and the Aluminum structure. This modeling indicated that the SPRITE model could be run in the AHF for up to 100 seconds before the allowed bond-line temperature of 290 °C was exceeded. Based on this analysis 100 seconds was set as the upper limit for the exposure to the plasma flow. It will be shown next that other factors limited the exposure to a shorter duration.

5.5.2 Marc-Mentat (Thermal) Analysis

For the thermal Finite Element Analysis using MSC Marc-Mentat, a 2-D axisymmetric model of the SPRITE probe was developed. The 2-D model was very detailed and included the internal DAS structure and batteries as well as the Probe structure and TPS. Heat flux distribution from *DPLR* was directly imposed as boundary condition to the FE model. The conduction re-radiation based analysis in Marc-Mentat lead to conservative results (pyrolysis and ablation ignored). Figure 7 shows an example of the results from the thermal model.

The Marc-Mentat analysis predicted that the temperature of the battery enclosure would reach ~90 °C if the probe was exposed to the flow for 100 seconds, significantly higher than the maximum rated temperature of 60 °C. In view of this result further FIAT/Marc-Mentat calculations were run for an exposure time of 50 seconds. This analysis predicted the DAS enclosure would reach ~60 °C. While 60 °C was the absolute maximum temperature allowable, for the reasons mentioned above it was felt that this analysis was conservative, so an exposure time of 50 seconds was set as target for the arc-jet tests. References [7,8] have details of this analysis and the results. Subsequently, a higher fidelity thermal analysis was conducted by integrating TITAN temperature maps after exposure to the finite element models and modeling the thermal soak. The temperature history predicted by this analysis for metal container box and batteries were in very close agreement with the experimentally obtained results.

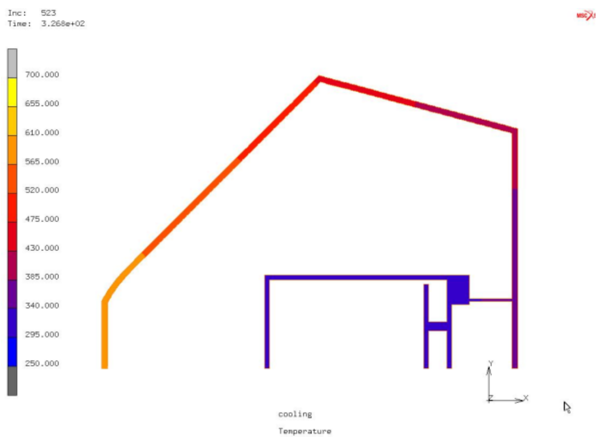

Figure 7 - Marc-Mentat Thermal Model

5.6 Thermal-Structural Analysis

In order to assess the impact of the thermally induced stresses on the SPRITE probe a fully coupled "90 degree" Marc-Mentat model of the probe, including PICA, LI-2200 tile, RTV adhesive and the Aluminum structure was developed (see Fig. 8). Using the heating predicted by the CFD modeling as the heating input the model was used to predict the in-plane (IP) and through-the-thickness (TTT) stresses in the PICA (by far the weakest of the materials used to make up the probe).

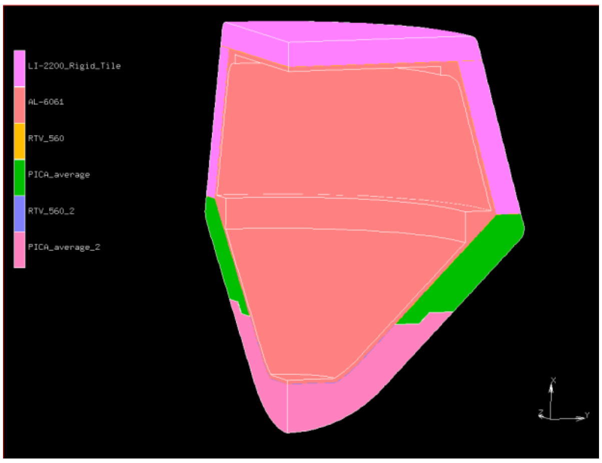

Figure 8 - Marc-Mentat Structural Model

While an extensive discussion of the modeling results is beyond the scope of this overview paper a brief discussion will be presented. The IP stress were predicted to peak very slightly over the 99% allowable stress, but the material allowables for PICA are calculated on a very conservative basis and therefore the peak stress from this calculation was considered to be acceptable. On the other hand the peak TTT stress peaked well over the average stress (a number significantly higher than the 99% allowable) and there was concern that the PICA would fail locally either at the joint between the two pieces or near the change in curvature of the aluminum structure at the nose radius. However, since this failure was likely to occur during the soak-back period and not during the exposure to the plasma flow it was deemed non-critical to the success of the test.

6. SOME EXPERIMENTAL RESULTS

Two identical SPRITE models were built and tested, as nearly as possible at the same arc heater conditions. The first test was run in December of 2010 and the second test in February of 2011. Figure 9 shows the probe mounted to the sting just prior to testing and Fig. 10 shows the first model in the plasma flow. Testing at two different arc-jet conditions was initially considered. However, due to some interesting behavior observed in the PICA, it was decided to run the second model at the same arc heater conditions as the first. The TPS anomaly is discussed in section 6.2, below.

Figure 9 - SPRITE Model on AHF Sting-arm

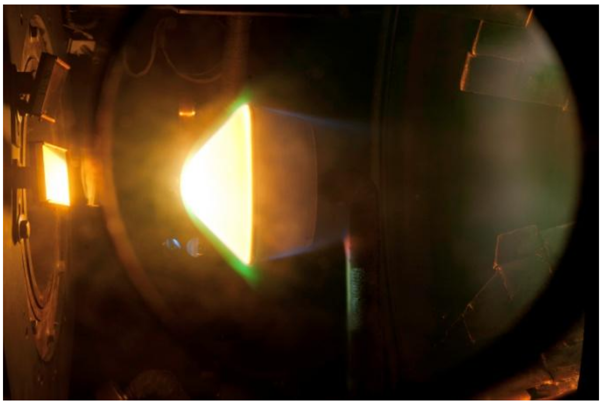

Figure 10 - SPRITE Model in Plasma Flow

6.1 Internal DAS Performance

There was very good agreement between the internal data system and the facilities, as well as good agreement between the data and pre-test predictions. A few minor issues were encountered, including premature clipping of some temperature traces, and poor performance of the strain gage measurements. The clipping of the TC traces was easily correctible, however some redesign is indicated in the case of the strain gage measurements (and perhaps the gauging strategy as well). Figure 11 shows a comparison of the in-depth TPS temperatures as measured by the internal DAS compared with the predicted temperature (this trace shows the clipping mentioned above). Figure 12 shows two traces from internal thermocouples mounted next to each other, one trace recorded by the internal DAS and one by the arc-jet facility. The noise on the internal DAS data was corrected for the second test.

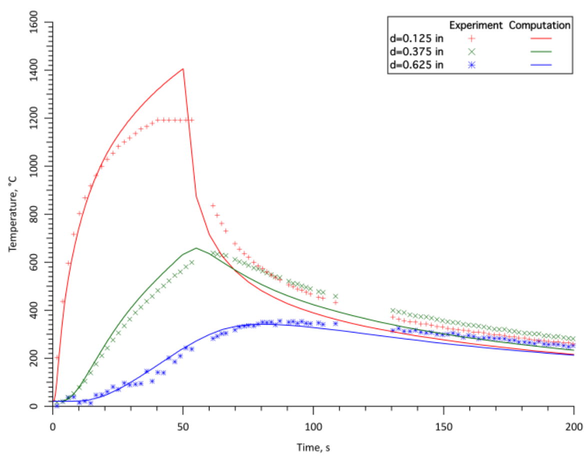

Figure 11 - In-depth Temperatures - Measured vs. Predicted

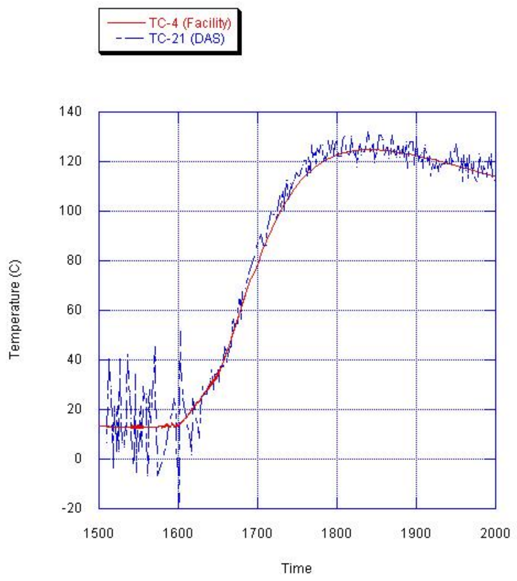

Figure 12 - Comparison of Internal DAS and Facility Temperature Measurements

6.2 TPS Performance

The PICA and LI-2200 tile performed as expected with the exception of a circumferential crack which appeared near the nose as shown in Fig 13. This crack occurred on both models in almost exactly the same place and during the second test (since it was specifically being watched for) was observed to occur about a minute after the model was removed from the plasma flow. There are several possible explanations for this behavior; it is in the weak (TTT) direction of the PICA material and it starts (and stops) at the cylindrical cutout for one of the instrumentation plugs. The crack is also near an "edge" in the Aluminum structure which was predicted to be a stress concentrator. This behavior is of great interest to the TPS community and is currently being investigated by post-test X-ray inspection and possibly cross-sectioning or coring the model. Since the crack seems associated with a known weak point in the TPS (the instrumentation cutout) and it was observed to occur on cool-down, the cracks have not been classified as failures and in fact should help us better understand how to design heat shields using PICA.

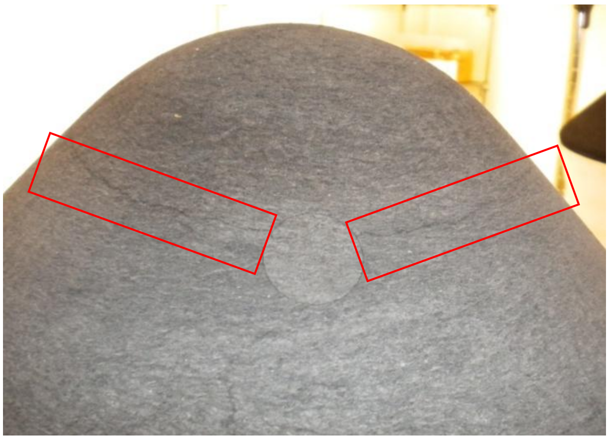

Figure 13 - TPS Cracking

6.3 Internal Temperatures

In Section 5.5.2 there was a short discussion of the internal temperature predictions. The SPRITE team was very gratified to see the measured internal battery temperature only 7 °C below the predicted value. This was an important result as it validated the approach to modeling the heat flow and temperatures throughout the probe and provides a good tool for modeling future flight probes where internal temperatures after reentry will also be of concern.

7. CONCLUSIONS AND FUTURE WORK

The SPRITE project was a success and proved that one can certainly "test-what-you-fly". The project exercised all the analysis tools that were initially identified and showed that (very) good predictions of environments, and structural and thermal behavior could be made using those tools.

There is still a significant amount of work left to complete before an actual test flight can be considered. From the SPRITE testing itself the following work is suggested:

- Investigation of the PICA cracking and structural design of the probe
- Additional maturation of the internal electronics
- Development of a better system of measuring and recording strain

In addition to the above several other aspects of a flight design should be pursued, including: packing of parachute to maintain the proper center of gravity, inexpensive recovery of the probe once it has landed, and design of the spacecraft to support the probe in space and provide the proper ΔV and targeting for reentry.

8. ACKNOWLEDGEMENTS

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