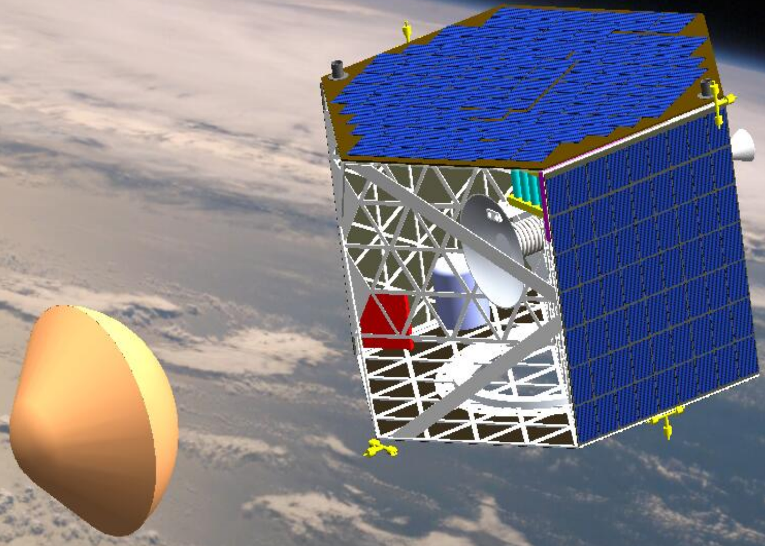
SPRITE: A TPS Test Bed For Ground and Flight

D. Prabhu, P. Agrawal, K. Peterson, G. Swanson, K. Skokova, N. Mangini
ERC, Inc.

D. Empey, S. Gorbunov
Sierra Lobo, Inc.

E. Venkatapathy
NASA Ames Research Center



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Outline

- TPS Design Process
- Current Arc Jet Philosophy for Testing & Qualifying TPS Materials
- Motivation for SPRITE
- SPRITE as a Flight-Test Paradigm
- SPRITE as a Ground-Test Paradigm
- Lessons Learned
- The Next Steps

What does SPRITE stand for?

Small **P**robe **R**e-entry
Investigation for **T**PS
Engineering

TPS Design Process

- **The current *TPS design process* much more sophisticated than before**
  - Reliance on improved/calibrated *modeling and simulation* procedures
  - Fewer, but focused, experiments (ground or flight, esp. flight)

- ***Predict aerothermal environments* for a given geometry and ref. trajectory(ies)**
  - Trajectory dispersions
  - Shape change
  - Uncertainties in aerothermal environments

- ***Select and size TPS materials for a margined bondline temperature constraint***
  - ***Heritage, i.e., TRL of TPS material, is important!***
  - Choice of materials (nonablative, or ablative: Carbon- or Silicon-based)
  - Material stack up
  - Choice of bondline adhesives
  - Uncertainties in materials properties
  - Material thermal response model and its uncertainties

Response models for TPS anchored to arc jet tests & *not flight experiments!*

Test & Qualification of TPS Materials: Arc Jets

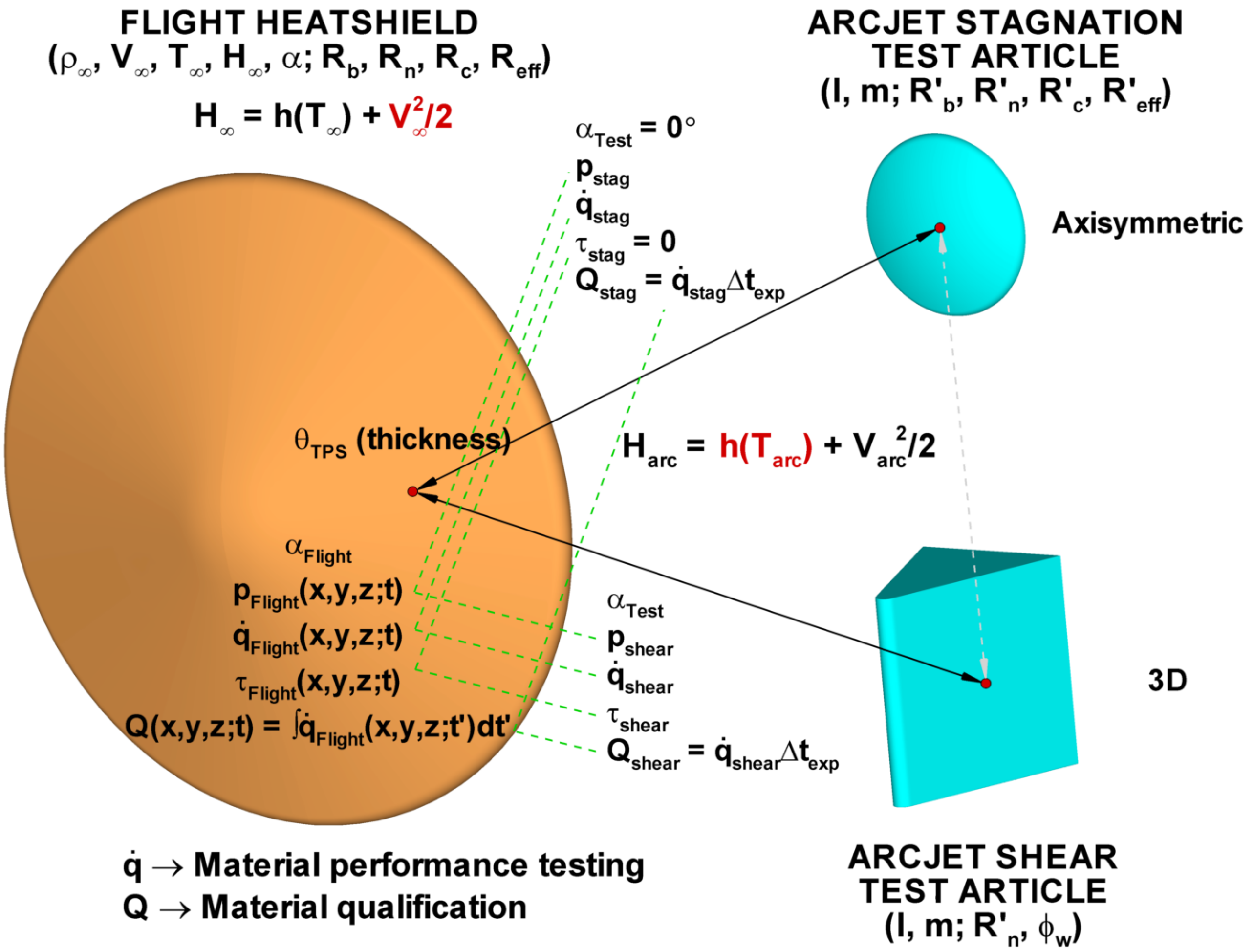
- **Arc jet test gas (usually air, sometimes N_2) not necessarily representative of the planetary atmosphere**
  - For Mars entries – enriching air with additional O_2 is one alternative

- ***Geometric similitude*** **is not demanded**
  - Flight and arcjet test articles need not be geometrically related (by scale or shape with surface features)

- ***Dynamic and boundary layer similitude*** **between ground and flight is not demanded either.**
  - TPS response history or "memory" not considered
  - Attempt to replicate flight-like enthalpy levels
  - Ground tests are "point tests"
    - Usually a single combination of **heat flux-pressure**
    - For glassy ablators a single combination of **heat flux-pressure-shear** is important

Arc jets at ARC and JSC currently cannot replicate radiative heating environments, and have limited turbulent flow capabilities

“Point Test” Approach to Materials Test & Qual: TRL Elevation (to 5, if no flight heritage for material)



FLIGHT HEATSHIELD
$(\rho_\infty, V_\infty, T_\infty, H_\infty, \alpha; R_b, R_n, R_c, R_{eff})$

$H_\infty = h(T_\infty) + V_\infty^2/2$

ARCJET STAGNATION TEST ARTICLE
$(I, m; R'_b, R'_n, R'_c, R'_{eff})$

$\alpha_{Test} = 0°$
p_{stag}
$\dot{q}_{stag}$
$\tau_{stag} = 0$
$Q_{stag} = \dot{q}_{stag} \Delta t_{exp}$

Axisymmetric

θ_{TPS} **(thickness)**

$H_{arc} = h(T_{arc}) + V_{arc}^2/2$

α_{Flight}
$p_{Flight}(x,y,z;t)$
$\dot{q}_{Flight}(x,y,z;t)$
$\tau_{Flight}(x,y,z;t)$
$Q(x,y,z;t) = \int \dot{q}_{Flight}(x,y,z;t')dt'$

α_{Test}
p_{shear}
$\dot{q}_{shear}$
τ_{shear}
$Q_{shear} = \dot{q}_{shear} \Delta t_{exp}$

3D

$\dot{q}$ → **Material performance testing**
Q → **Material qualification**

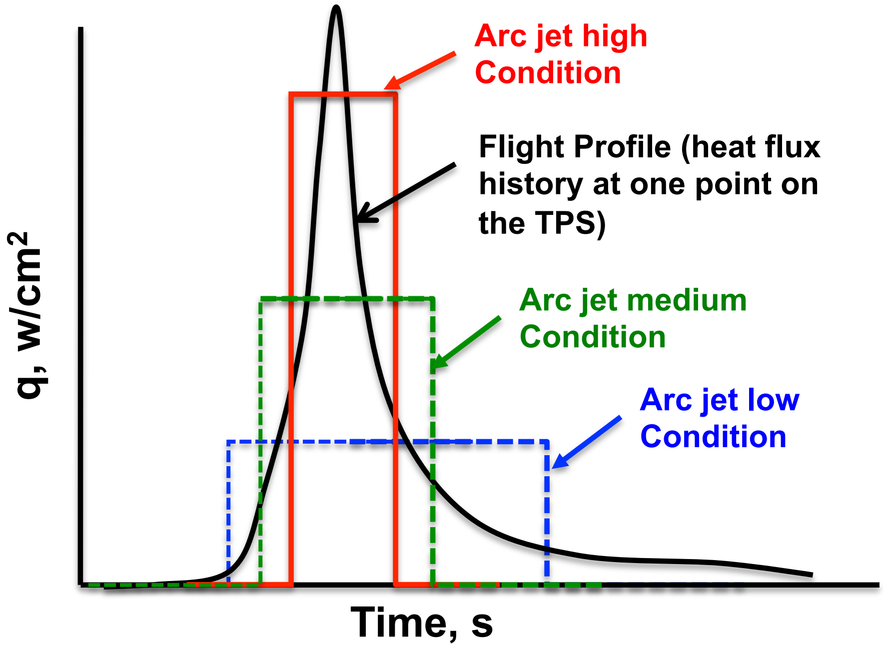
ARCJET SHEAR TEST ARTICLE
$(I, m; R'_n, \phi_w)$

Matching flight enthalpy in an arc jet means trade between chemical energy (T_{arc} ➔Current/Flow) and kinetic energy (V_{arc} ➔Nozzle Size)

The “Test Like You Fly” Paradigm

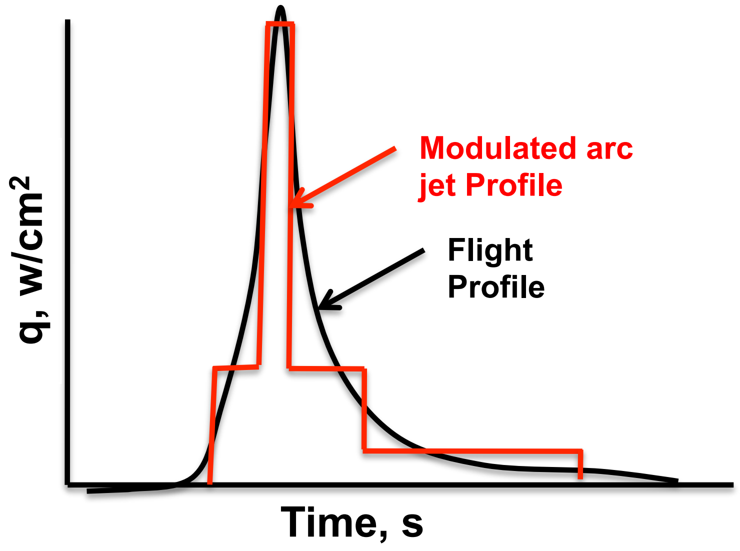
Traditional

(Same heat load at different heat flux levels)



Desirable

(Stepped/Piecewise constant heat load)



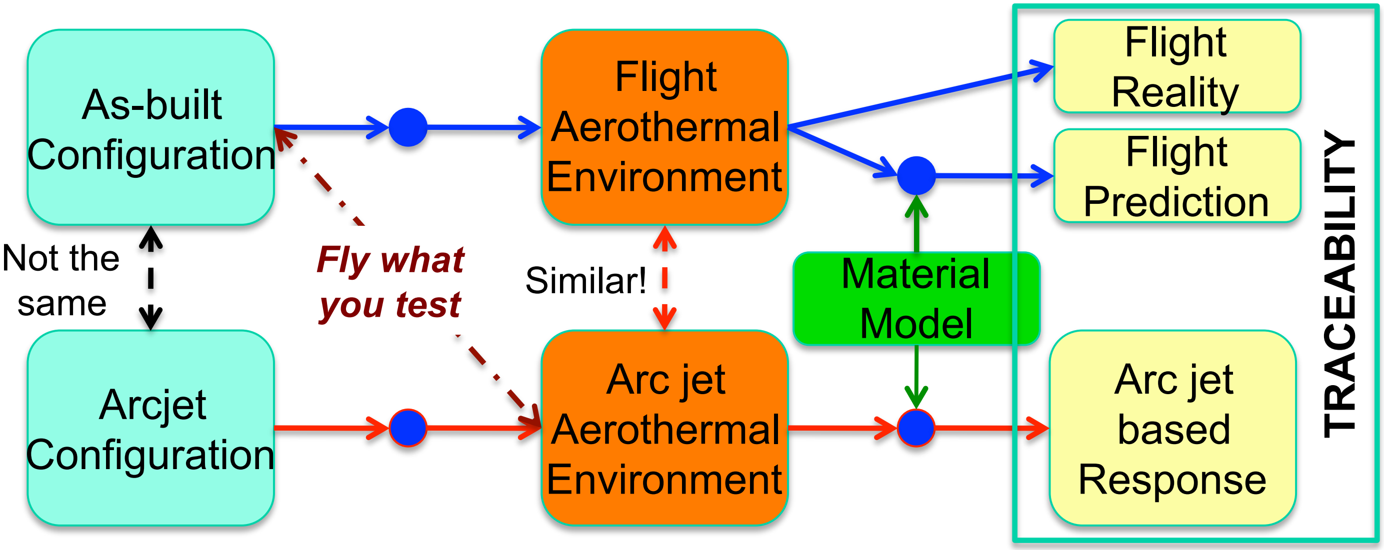
- **Freestream conditions time-varying in flight, but held constant in arc jet test**
- **Heat flux modulation is difficult from a facility operations view point**
  - **Attempted during TPS development program for MPCV**

Motivation

- **Do we know how well we have designed the TPS of the flight vehicle**
  - Do we have a clear understanding of the *'conservatism' in the design*?
- **Can we develop a *low cost flight experiment* to address this 'conservatism'**
  - Can we *replicate the design environments* around a concept flight vehicle?
- **Can the low-cost configuration be tested in a *ground-based facility*?**

- ***Three immediate advantages* of a low cost flight experiment:**
  - **Significant reduction in the number of ground-based arc jet tests?**
  - **A *TPS test bed* that provides actual flight environment exposure to candidate materials**
    - **Reference for future TPS designs**
    - **Risk reduction in technologies**
    - **TRL elevation of materials**
  - **The flight experiment(s) can enable/evaluate *S&MA* aspects of *COTS* missions**
    - PICA-X and gap fillers on Dragon.

Paradigm Shift: “Fly What You Test”



As-built Configuration

Flight Aerothermal Environment

Flight Reality

Flight Prediction

Not the same

Fly what you test

Similar!

Material Model

Arcjet Configuration

Arc jet Aerothermal Environment

Arc jet based Response

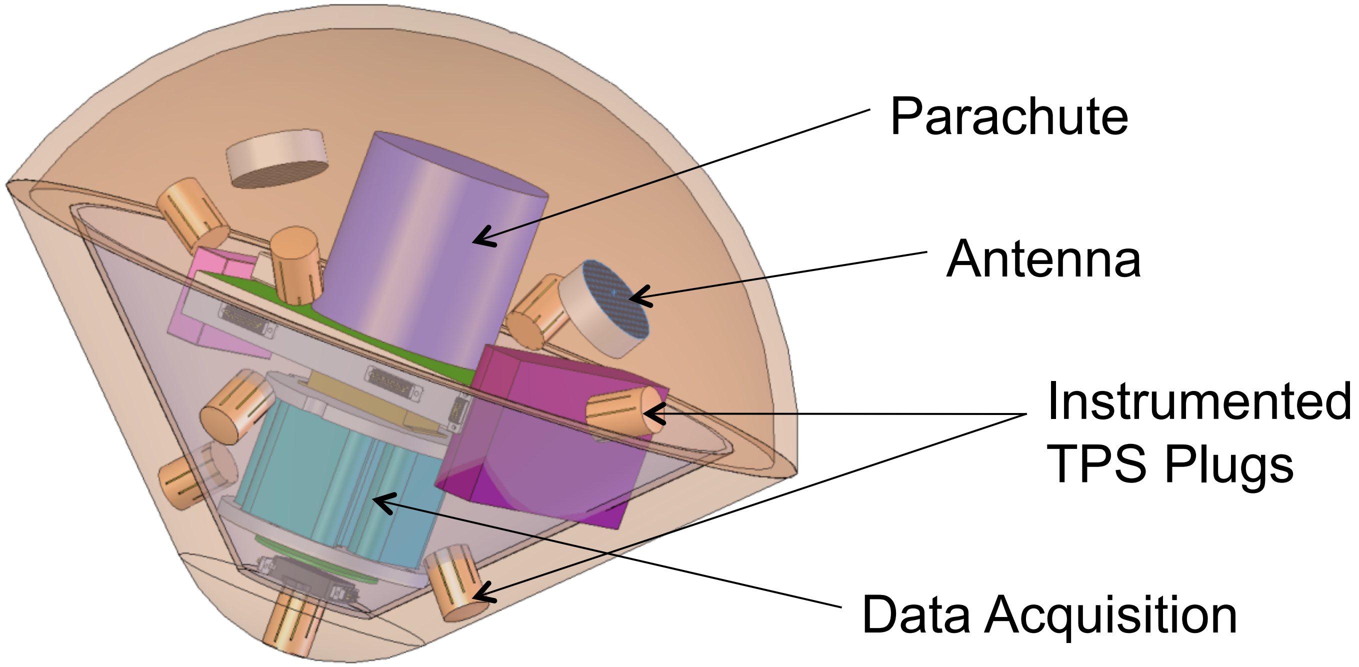
TRACEABILITY

- **For the case of ablative TPS, material response is the major feedback mechanism**
- **Arc jet conditions are usually held constant, but imposed flight aerothermal environment and ablator response “memory” can affect flight reality**
  - Example: Apollo flight data showed “coking” of char, but coking not observed in accepted pre-flight arc jet results

A flight experiment with capsule recovery back on Earth can help anchor/validate the material model calibrated to arc jet tests

SPRITE as a Flight-Test Paradigm

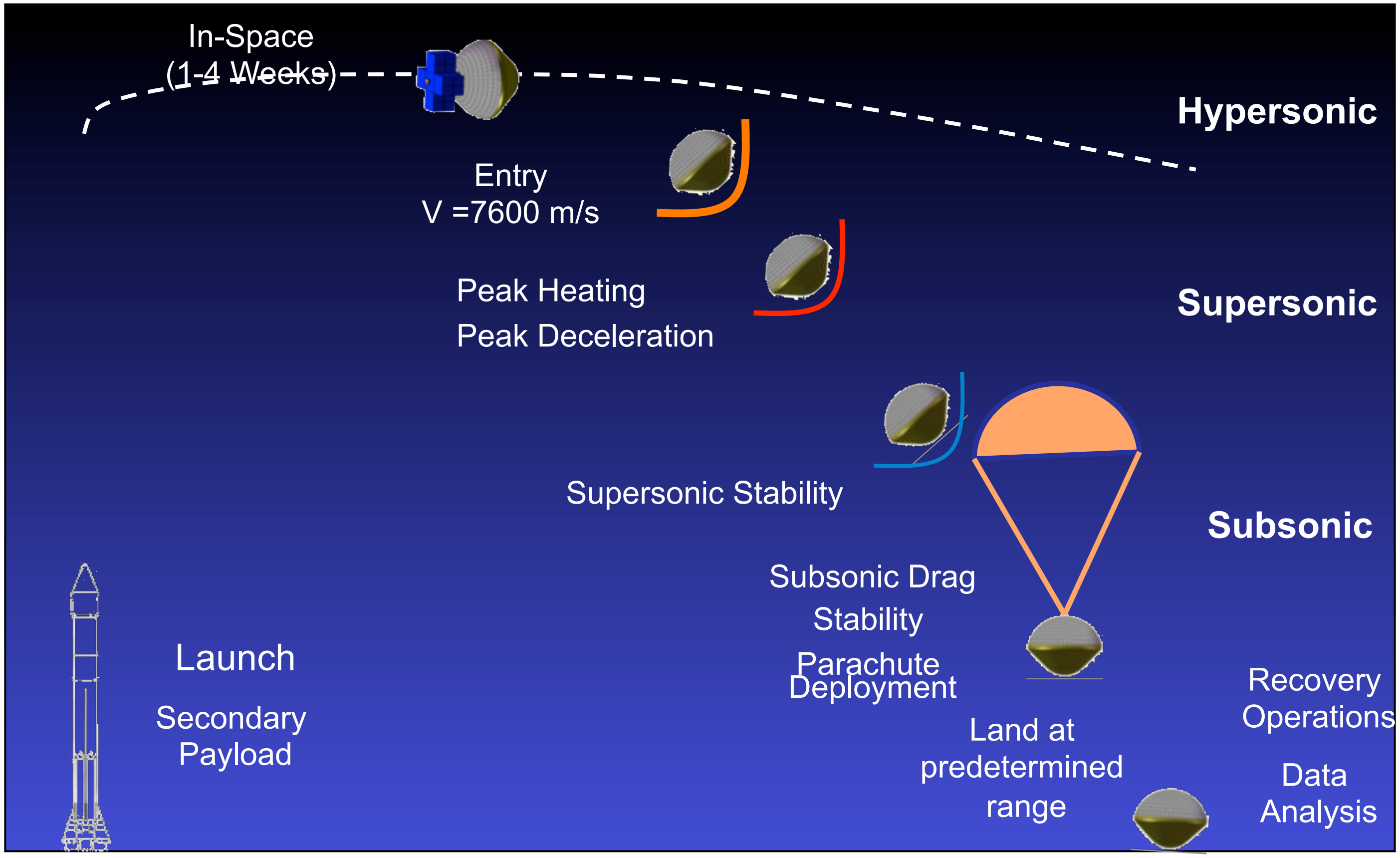
SPRITE Concept Geometry



- **Initial SPRITE geometry modeled along lines of Deep Space 2 (DS-2)**
  - 14-inch dia 45° sphere-cone body with rounded back shell for aerodynamic stability
- **Test-what-you-fly paradigm**
  - Test at flight-scale (geometric) in a ground-based facility
  - Attempt to replicate aerothermal environments along portions of the actual flight trajectory by testing in an arc jet

SPRITE Concept of Operations (Con-Ops)

Flight System Design



In-Space
(1-4 Weeks)

Entry
V =7600 m/s

Peak Heating

Peak Deceleration

Supersonic Stability

Subsonic Drag

Stability

Parachute
Deployment

Land at
predetermined
range

Launch

Secondary
Payload

Hypersonic

Supersonic

Subsonic

Recovery
Operations

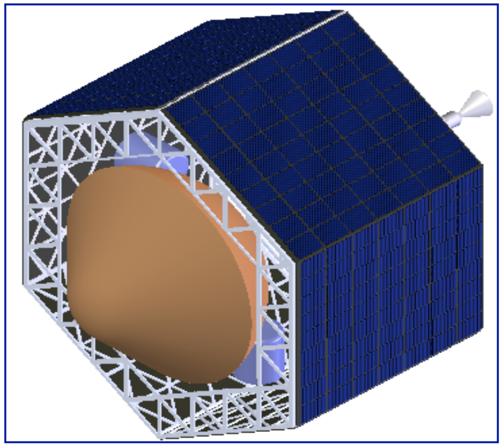
Data
Analysis

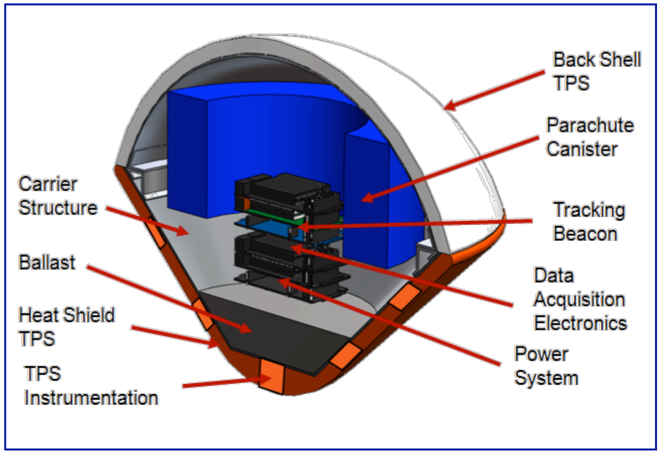
Mission System Design

Concept of Operations

Deorbit, Descent & Landing, and Recovery as important aspects the remain to be addressed

SPRITE (As Secondary Payload) Systems Analysis



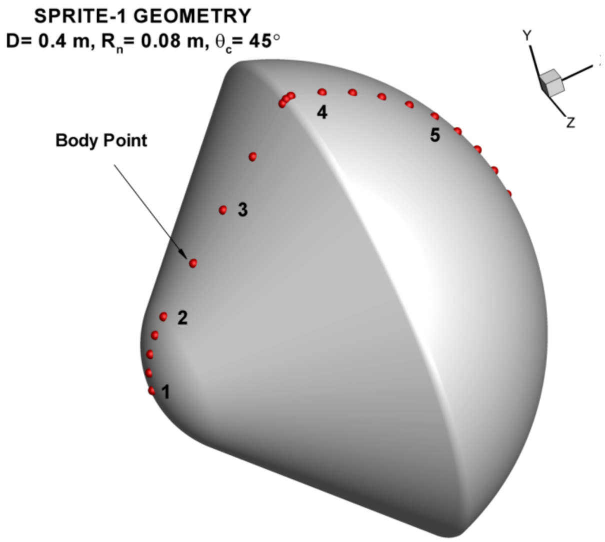


Subsystem	w/ Margin (kg)
Flight Instrumentation	1.807
Communication	0.913
Command & Data Handling	0.480
Electrical Power System	0.922
Recovery System	1.300
Aeroshell	2.909
Structures	2.990
Totals	**11.322**

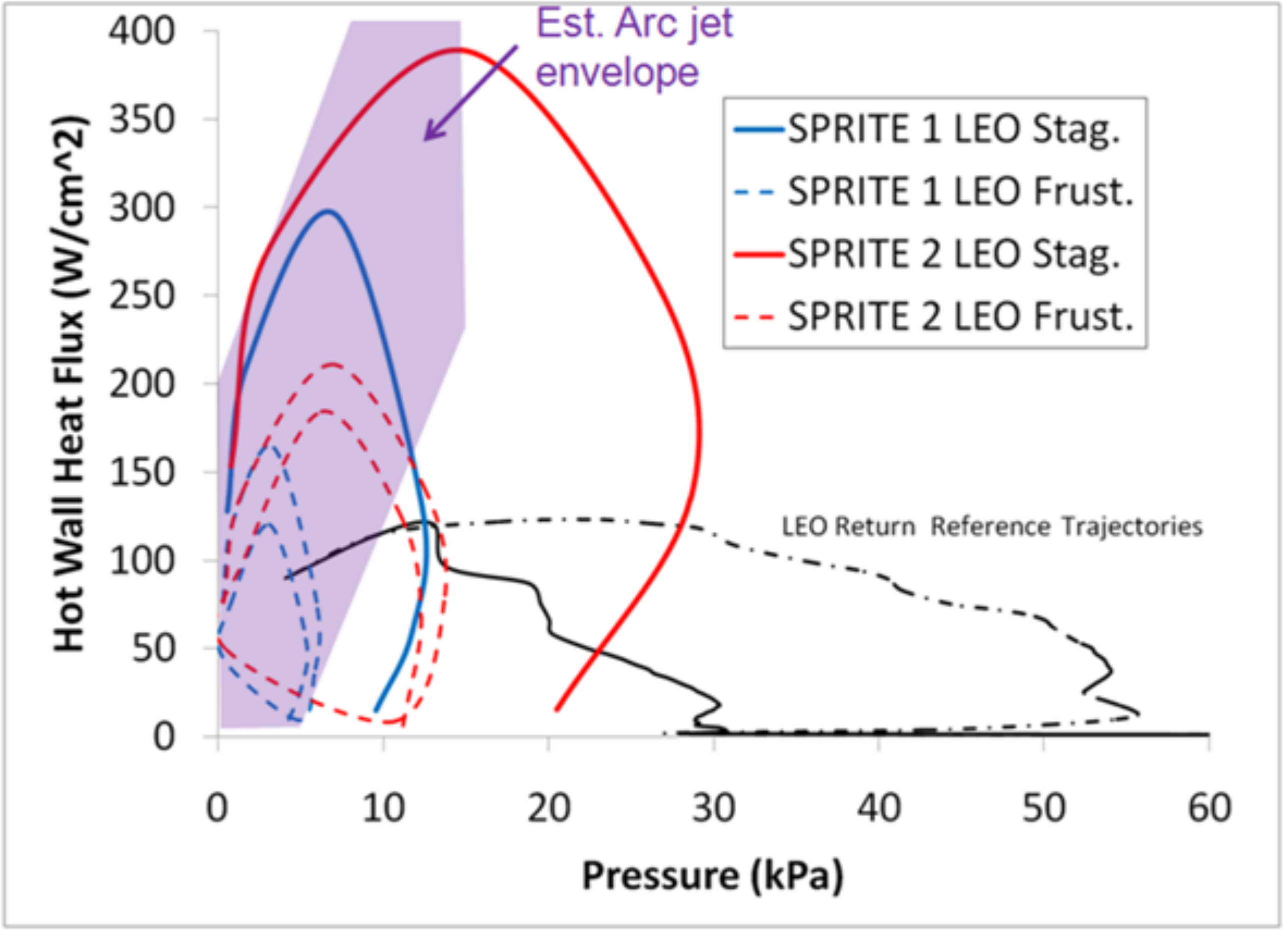
	Ground Test	Sub Orbital	LEO	GTO
Entry Velocity, km/s	N/A	2 to 5	7 to 8	9 to11
Estimated De-orbit ΔV, m/s	N/A	N/A	200-300	<50
Est. Environments Q = Heat flux, W/cm^2 P = Pressure, kPa S = Shear, Pa	Q:50-400 P:0.1-12 S:50-250	Q: 100-200 P: 15-35 S:100-200	Q: 100-400 P: 10-25 S:100-300	Q: 800-1000 P: 20-50 S:300-600

- **No choice of orbit as a secondary payload**
- **Requirements might be imposed by the primary payload**

Example: SPRITE Applicability to Orion



- Body points shown on centerline only
- Body is axisymmetric and the trajectory is ballistic
  - Body points can be distributed over the acreage (consider as sensor locations)



Partial coverage of CEV ISS heat flux-pressure space can be achieved

SPRITE as a Ground-Test Paradigm

Engineering of a Small Probe: The First Steps

- **Mechanical Design and Fabrication (TPS and Structure)**
- ***In situ* Data Acquisition System Design and Fabrication**
- **Thermal Analysis**
  - ***FIAT* and *TITAN* for the TPS materials**
  - ***MARC* for Internal Temperatures**
- **Thermal Structural Analysis (*MARC* and *NASTRAN*)**
- **CFD (*DPLR)* for predicting aerothermal environments**

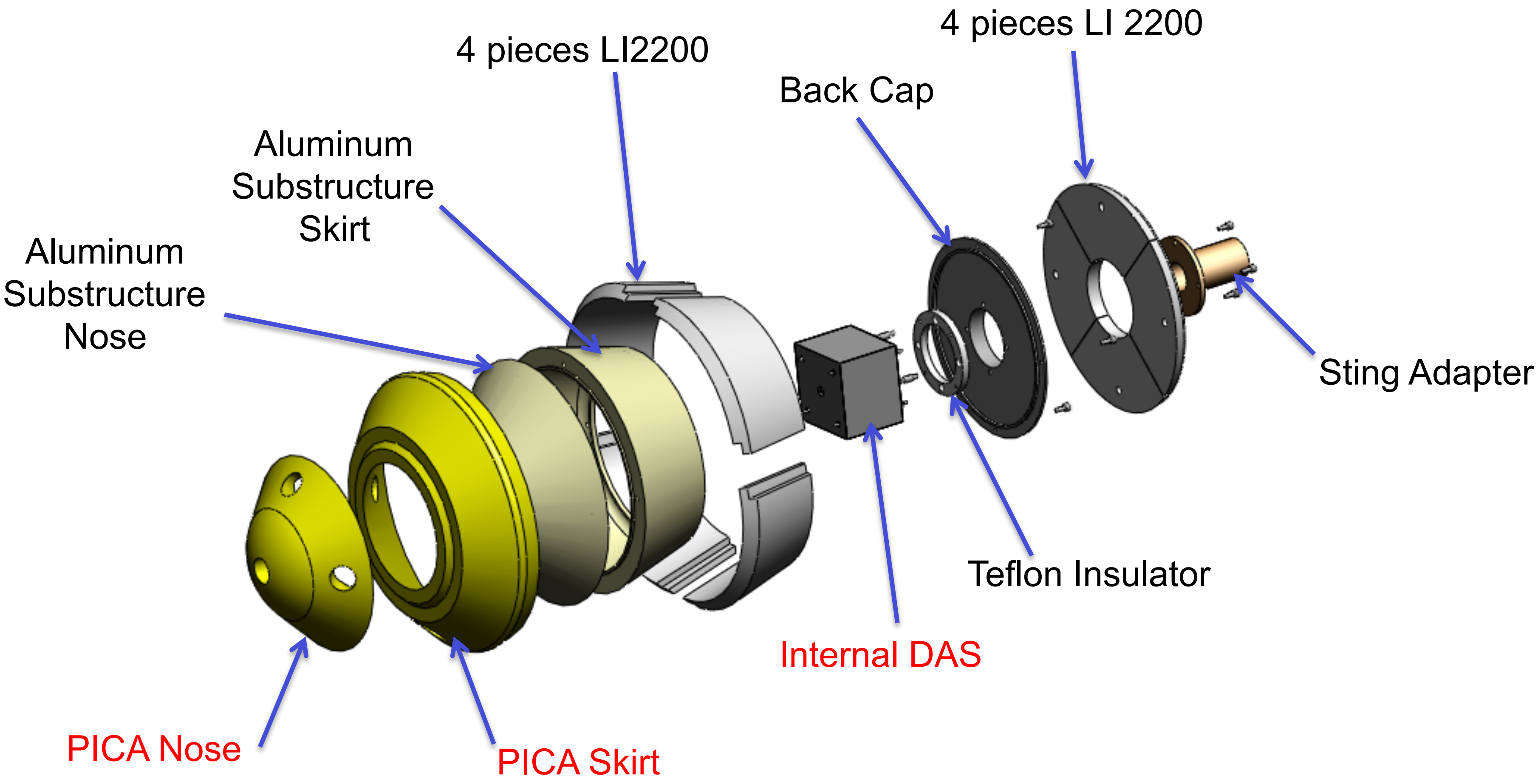
• No particular flight profile targeted for first ground test of probes
• TPS materials not sized for any specific heat load
• Backshell geometry different from that of flight test for test design simplicity

Objectives of the Ground Test

To demonstrate:

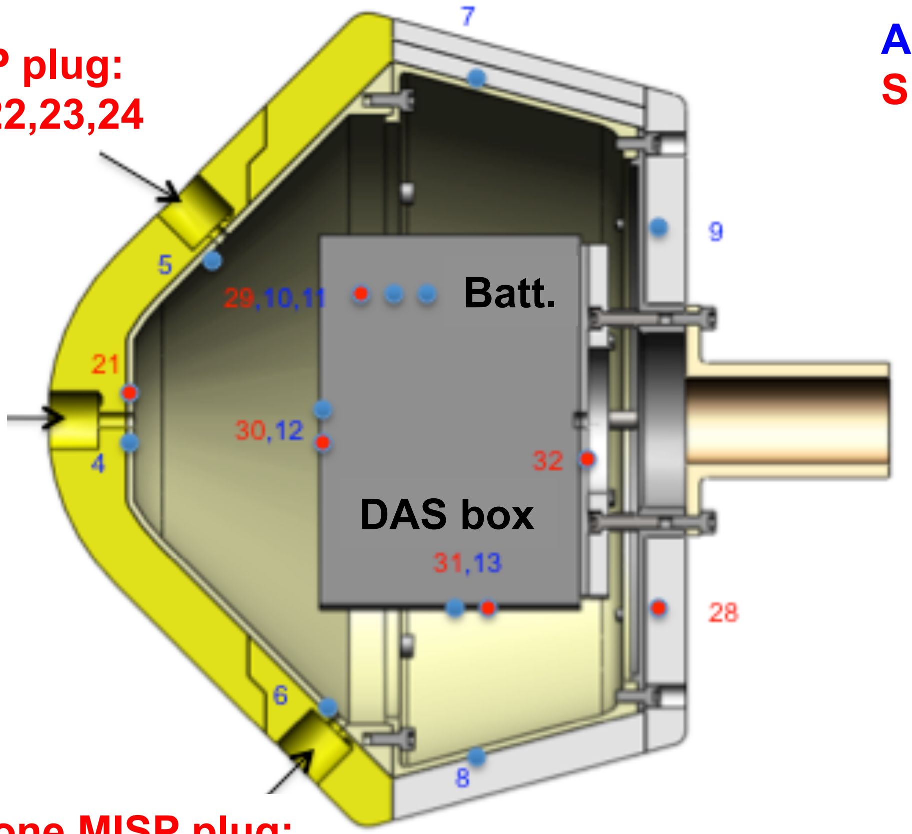
- **Feasibility of arc-jet testing flight articles at full scale**
- **Feasibility of *in situ* measurements of temperature, strain and recession using a data acquisition system mounted inside the test article**
- **That a combination of simulation tools – primarily *DPLR*, *FIAT*, and *MARC* – can be used to predict material response, thermal environments and thermal structural behavior**

Final Design of Small Probe for Arc Jet Tests



- **TPS selected by availability: PICA for heatshield and LI-2200 for aft**
- **TPS materials not sized for any specific heat load**

Distribution of Sensors (K-Type Thermocouples)



Mid-cone MISP plug:
In-depth TCs 22,23,24

Stagnation MISP plug:
In-depth TCs 1,2,3
+ HEAT sensor

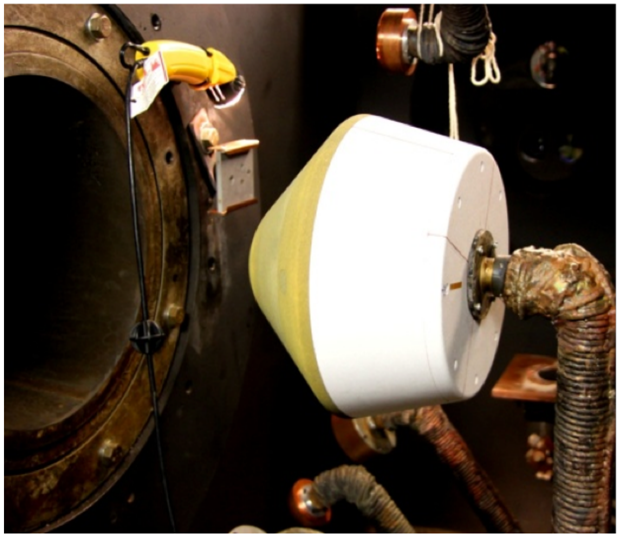
Bottom-cone MISP plug:
In-depth TCs 25,26,27

Arc jet Facility DAS
SPRITE Integrated DAS

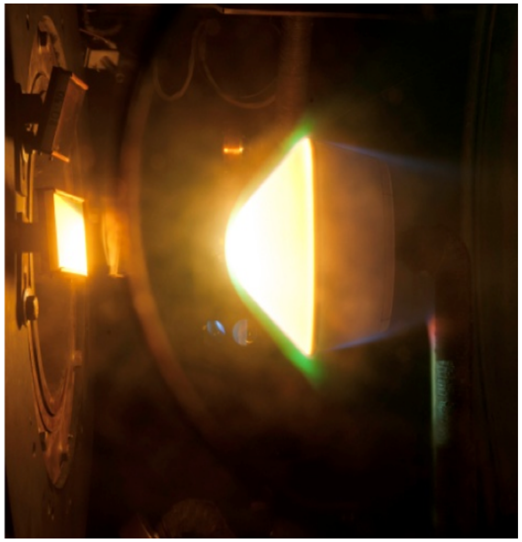
- **MEDLI-type MISP sensors used (SPRITE is the Maid of the MISP?)**
- **Thermocouple signals acquired by internal DAS and facility DAS, with overlap**

Arc Jet Tests

Pre-Test
(18-in nozzle AHF)



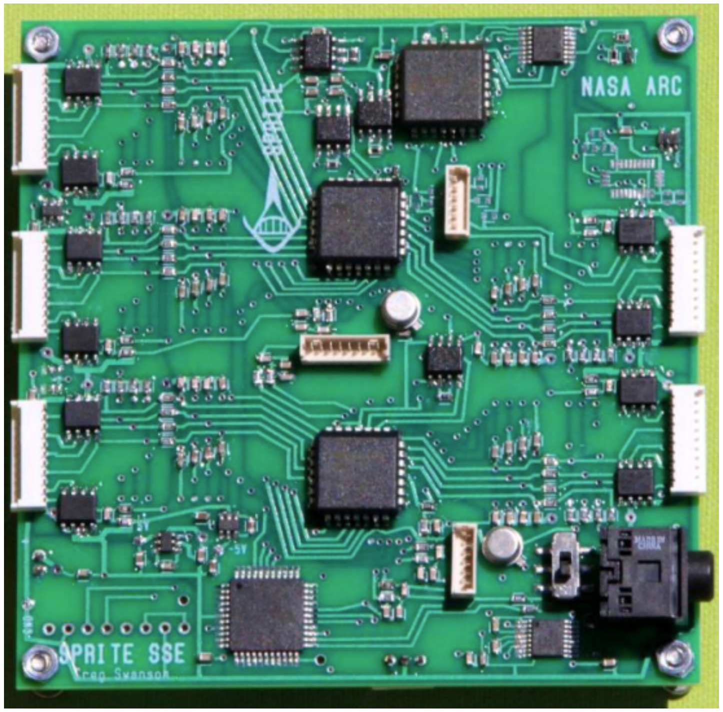
During Test
(Test AHF 295)

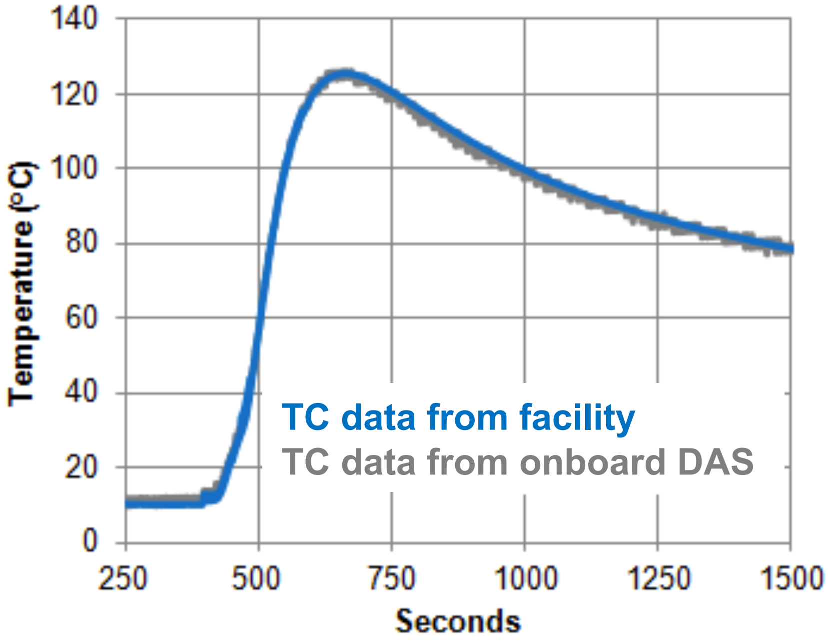


Post-Test
Charred PICA Heatshield

- **Two 14-in (36 cm) SPRITE probes designed & tested in AHF (20MW arc jet)**
- **Demonstrated ability to build a small probe within a small budget**
- **Demonstrated the survivability of payload**
- **Demonstrated the ability to obtain data for validation & verification**

In situ Data Acquisition System



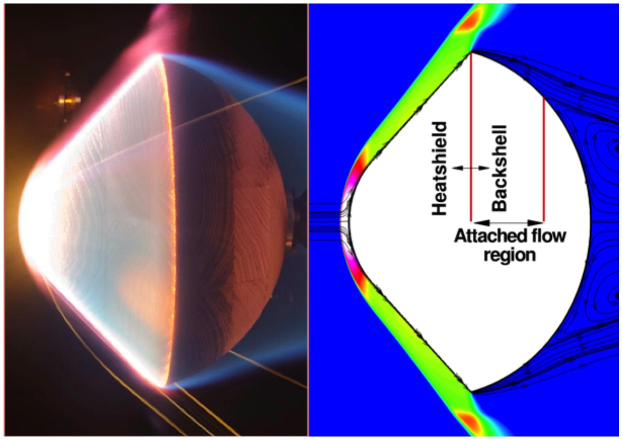


- **A custom Data Acquisition System (DAS) designed & built using COTS components**
- **Successful data collection and verification during the tests established the capability for *in situ* flight data measurement, that could be a powerful tool for future flights.**

Analysis

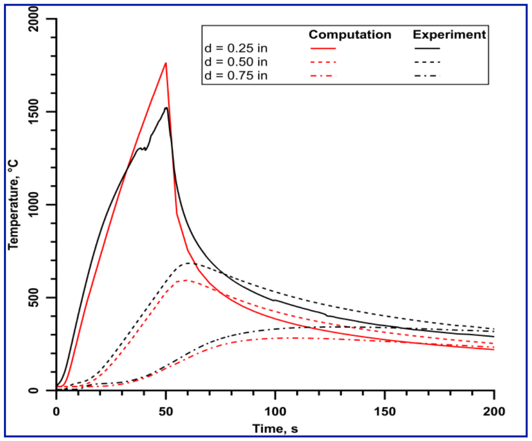
FLOWFIELD SIMULATION

DPLR



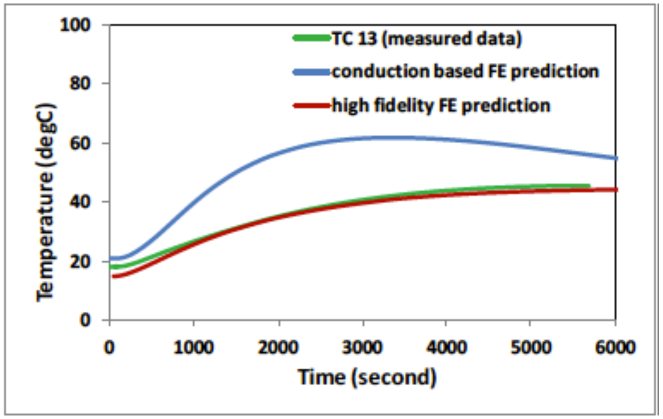
MATERIAL RESPONSE

FIAT



THERMAL ANALYSIS

MARC

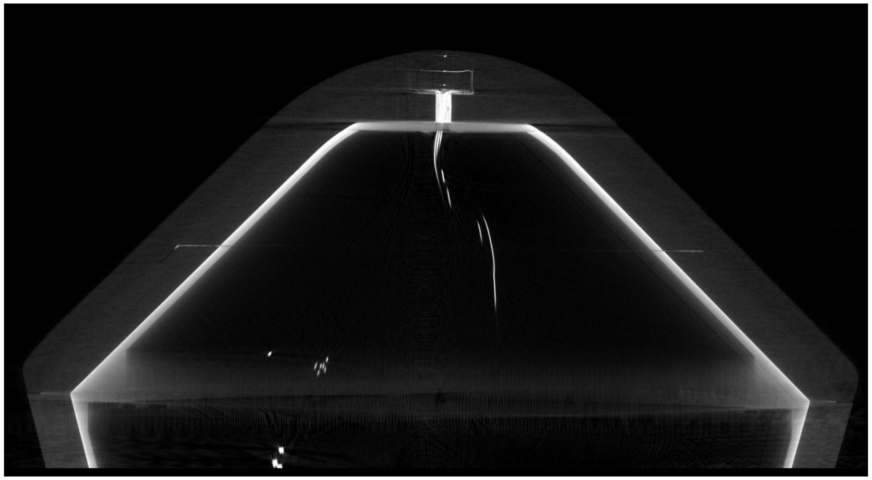


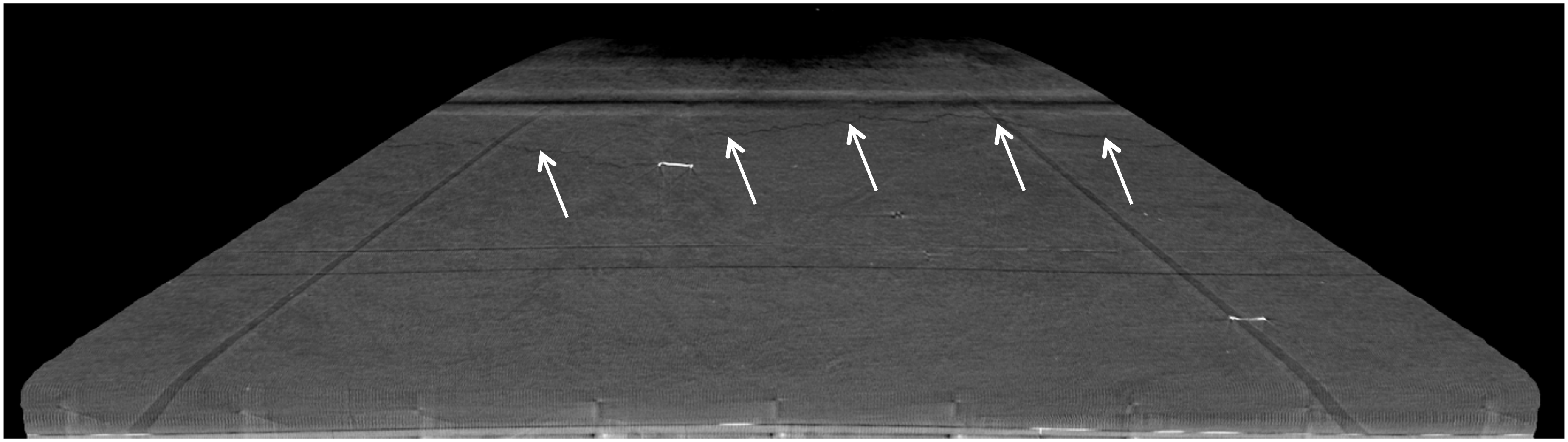
- **Proved the predictive capability for aerothermal environments during entry**
  - **V&V of flowfield simulations with DPLR (Design/Analysis code)**

- **Established a good approach for thermal soak analysis for sample return missions**
  - **V & V of thermal predictions for aeroshell, interior and payload with a combination of *MARC* and thermal response tools**

NDE of Test Articles: X-Ray CT of SPRITE

- "Shell Extraction" of a layer of the SPRITE PICA
- Analysis of the CT data indicated the maximum depth of the crack to be 1.5 cm out of 2.5 cm
- From the CT data recession appears to be ~3.1 mm





Lessons Learned

- We can test a probe of a size that could also fly in space and reenter the atmosphere;
- Data can be collected reliably in a small probe by a data acquisition system in the plasma flow;
- The project exercised all the analysis tools that were initially identified; and
- Showed that good predictions of environments, structural and thermal behavior could be made using those tools

The Next Steps

- **Converting SPRITE to an arc jet test paradigm which will supplement traditional stagnation and shear (wedge or swept cylinder) testing of materials**
  - **Leverage the ability to achieve combination of pressure, heat flux *and* shear in a single test**
  - **SPRITE will prove useful in testing new flexible or conformable ablative materials for which performance under shear loads is important**
  - **Smaller scale versions of the geometry can be tested safely at angle of attack for back shell materials**
  - **Cavities representative of MMOD damage can be instrumented and tested**

- **Build a flight (-like) test article for high-altitude balloon drop or suborbital flight**
  - **Parachute (or not)**
  - **Flight data acquisition**
  - **Locator beacon**
  - **Validate recovery operations**

- **Design a flight article & excute a atmospheric re-entry flight test**