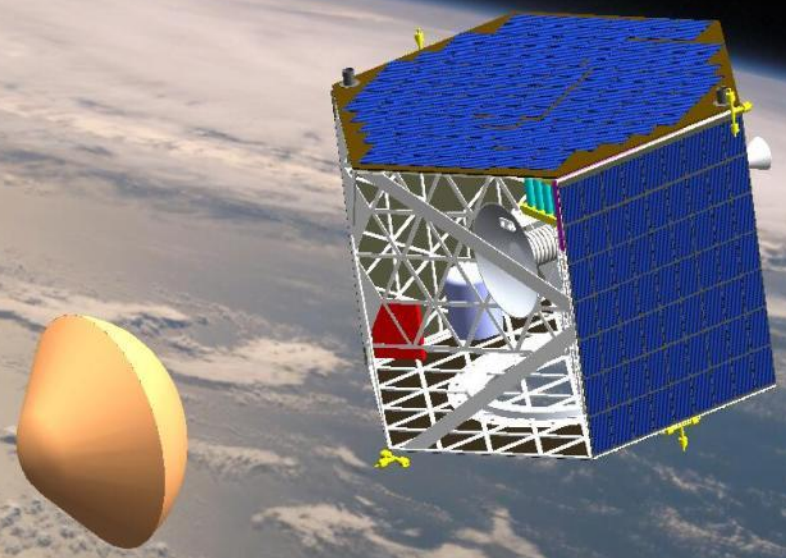
# SPRITE

**S**mall **P**robe **R**eentry **I**nvestigation for **T**PS **E**ngineering



Daniel M. Empey
Sierra Lobo, Inc., NASA Ames Research Center
8th International Planetary Probe Workshop
June 7th, 2011

# Acknowledgments:

Co-Authors:

Kristina Skokova, Parul Agrawal, Keith Peterson, Dinesh Prabhu, Gregory Swanson

*ERC, Inc., NASA Ames Research Center*

And

Ethiraj Venkatapathy

*NASA Ames Research Center*

Special Thanks To:

Alan Cassell

Y-K Chen

Don Ebaugh

Johnny Fu

Sergey Gorbunov

Austin Howard

Hiep Khuc

Joe Mach

Matt Switzer

Imelda Terrazas-Salinas

This work was made possible by the MMEEV, Orion and MEDLI Projects as well as the TS Division @ the NASA Ames Research Center

# Outline

- Background
- Motivation
- Objectives
- Probe Design
- Test Design
- Test Results
- Conclusions

# Small Probe Programs: SPRITE and SPORE

**QUESTION**: Is there commonality in small reentry probe systems designed for:

A) Entry Technology Development and
B) Space Science/Biological Sample Return.

Can a common architecture serve both needs? If so, can a capability be developed at a cost that would draw in a variety of users? We propose that the answer is yes to both questions.

**APPROACH:**

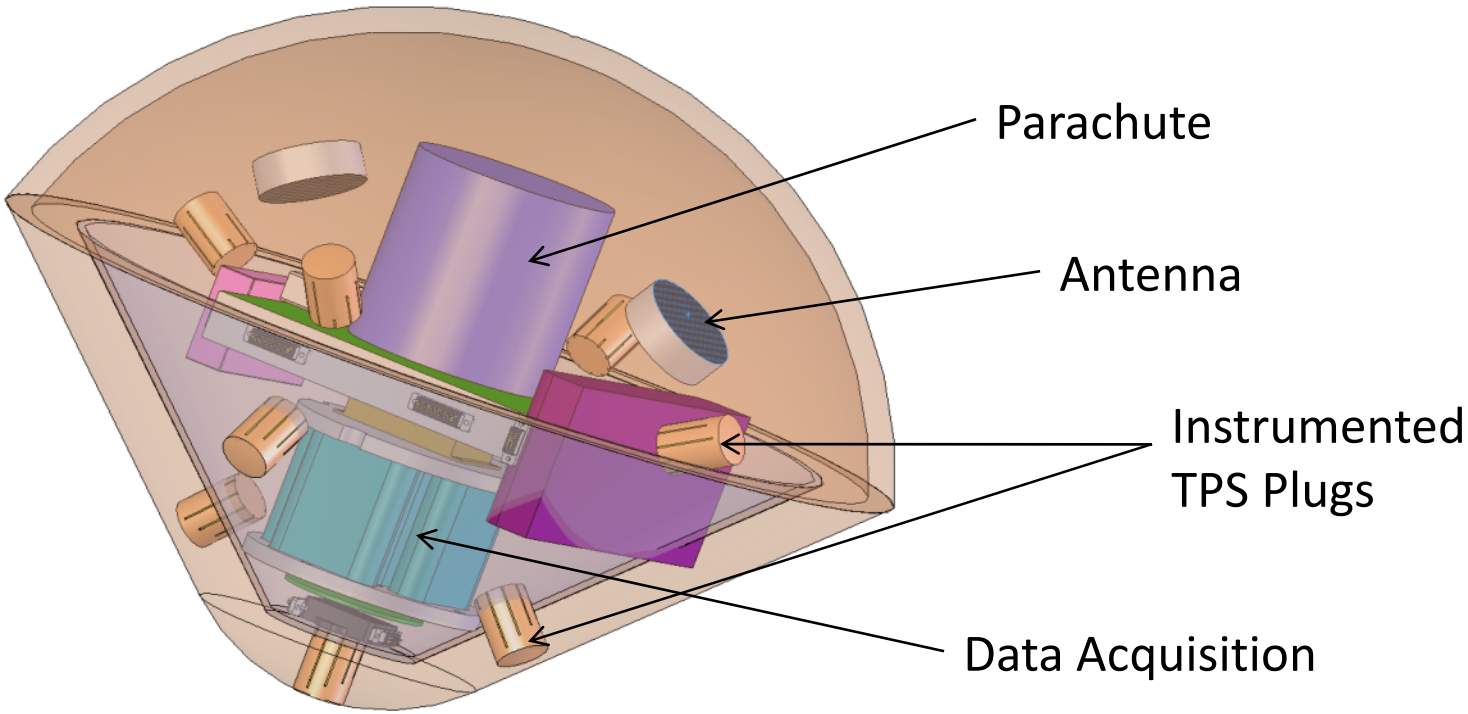
**Georgia Tech** to lead effort to design small entry probe for biological sample return from small orbital free flyer: Small Probe for Orbital Return of Experiments (SPORE)

**NASA Ames Research Center** to lead effort to design small entry probe system with the objective of assessing TPS performance: Small Probe Reentry Investigation for TPS Engineering (SPRITE)

# What is SPRITE?

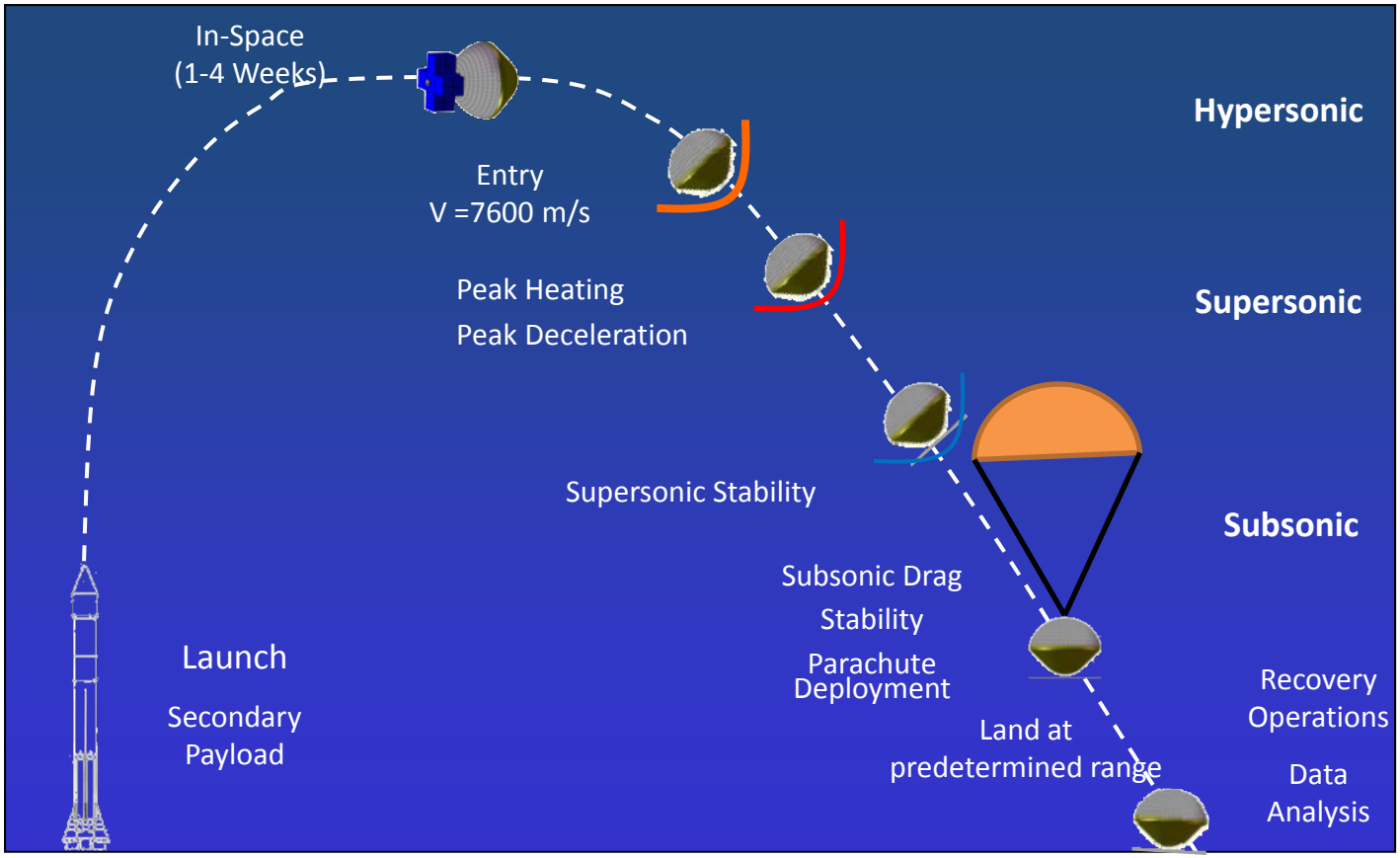
- Small reentry probe ~14 inches (35 cm) diameter
- Test full-size in arc-jet and fly in space
- The concept is fully described in the IPPW7 Paper:

  *"Small Probes As Flight Test Beds For Thermal Protection Materials"*



# SPRITE ConOps Overview

Flight System Design




Mission System Design

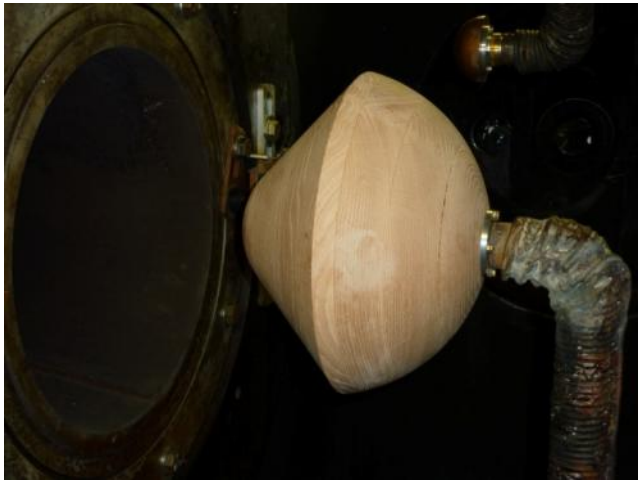
Concept of Operation

# Motivation

- The ultimate in ground-to-flight traceability "test-what-you-fly"
- One low cost TPS flight test could be worth many arc-jet tests
- Could be a model for future arc-jet testing (alternative to Iso-Q or wedges – "two-for-one"?)
- Other uses such as CubeSat return
- SPRITE models intended as proof-of-concept for all of the above

# Background – InSPIRe (Sept - 2009)

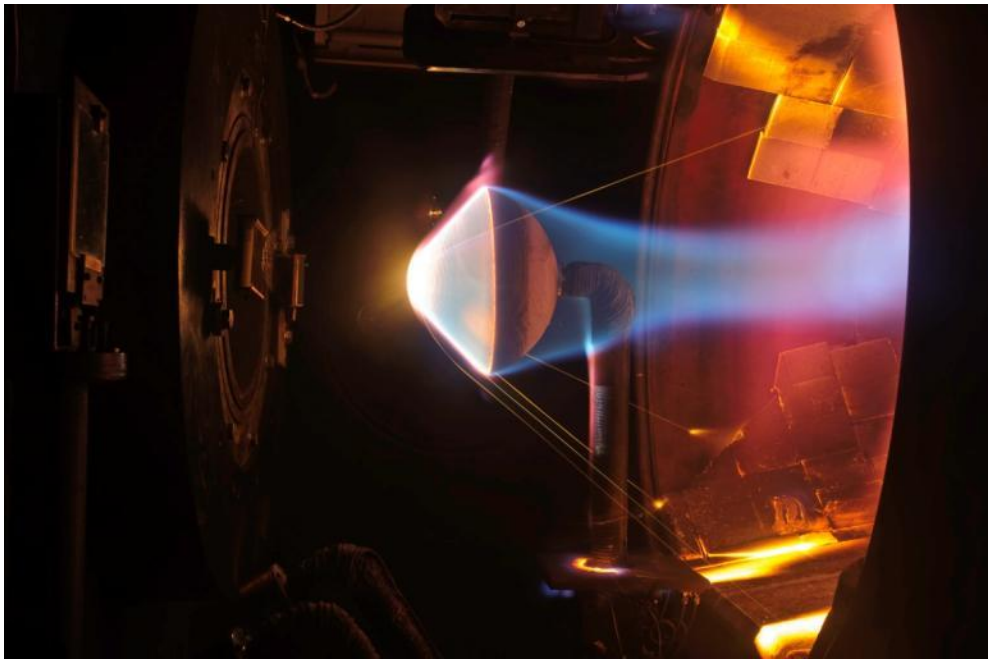
## (**In**novative **S**mall **P**ayload **I**n-space **Re**trieval Probe)

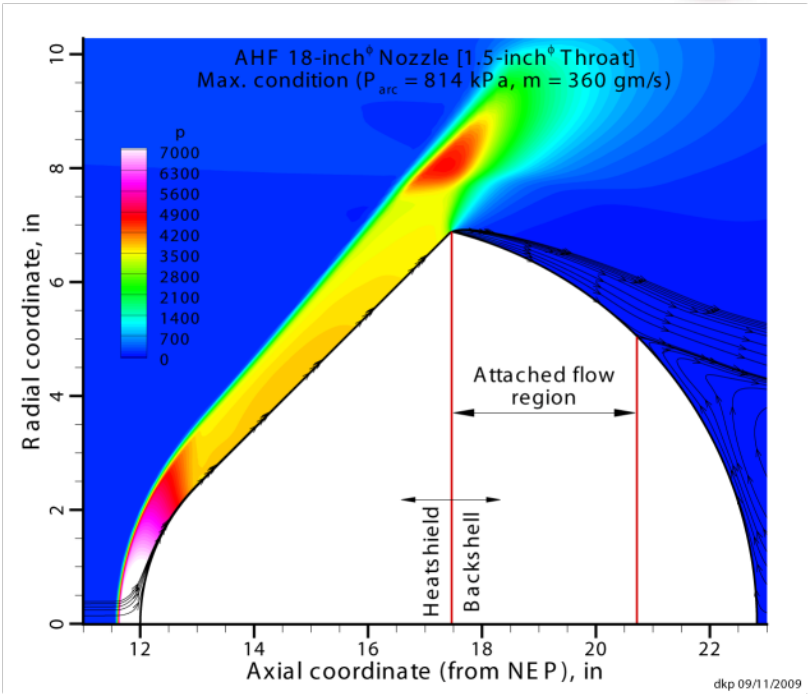


1:1-scale red oak replica of the Deep Space 2 entry probe shown mounted on a sting arm of the AHF (18-inch nozzle)

- Explored the possibility of testing/qualifying an entry microprobe at full scale in an arc jet
  - Included both heatshield and backshell
- Establish blockage limits for safe operation of arc jet with full-scale models
  - Wood (red oak) replica of flight article was used
  - Deep Space 2 configuration (≈14-inch diameter, 45° sphere-cone heatshield with spherical aftshell) considered as representative

# AHF999i Test Summary






- Test AHF999i performed at facility max conditions (I = 2200 A, and m = 352 gm/s with 1.5-inch throat)
- Test article exposed for 20 seconds in the arc-heated stream
- Calorimeters also included in test
- Interaction of expansion fan and bow shock seen (but small influence)

# Test Objectives

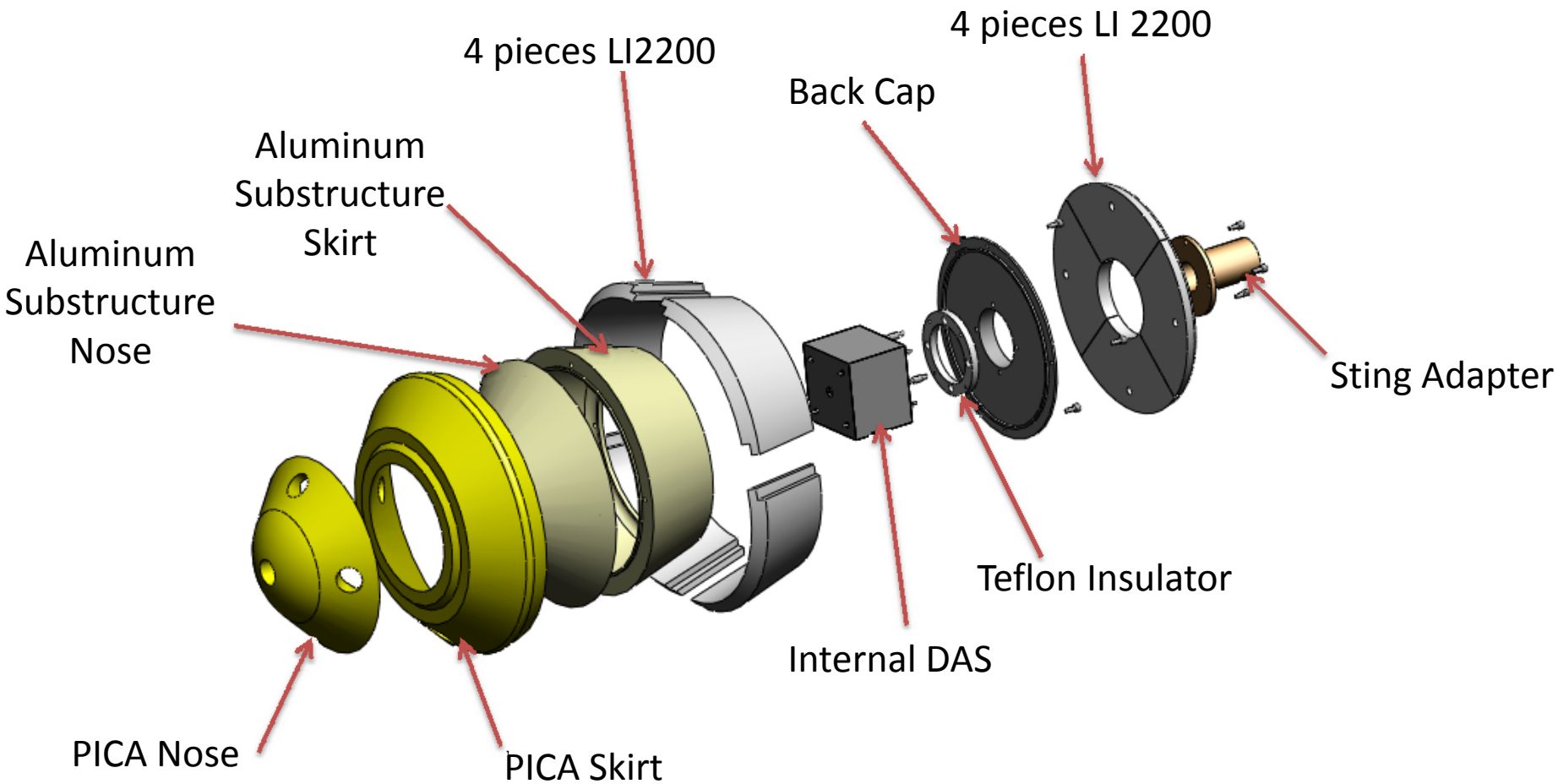
- To demonstrate the feasibility of arc-jet testing flight articles at full scale – a required first step in the "test-what-you-fly" paradigm
- To demonstrate the feasibility of *in situ* measurements of temperature, strain and recession using a data acquisition system mounted <u>inside</u> the test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

# Design Effort

- Mechanical Design (TPS and Structure)
- Data Acquisition System (DAS) Design
- Thermal Analysis
  - *FIAT*/*TITAN* for PICA (and bond-line temperatures)
  - *MARC*-*MENTAT* for Internal Temperatures
- Thermal Structural Analysis
- Computational Fluid Dynamics (CFD)

Note: All of the above work done in-house at NASA Ames Research Center by the authors of this paper.

# Design of the 14” Diameter SPRITE Probe



# Design Issues

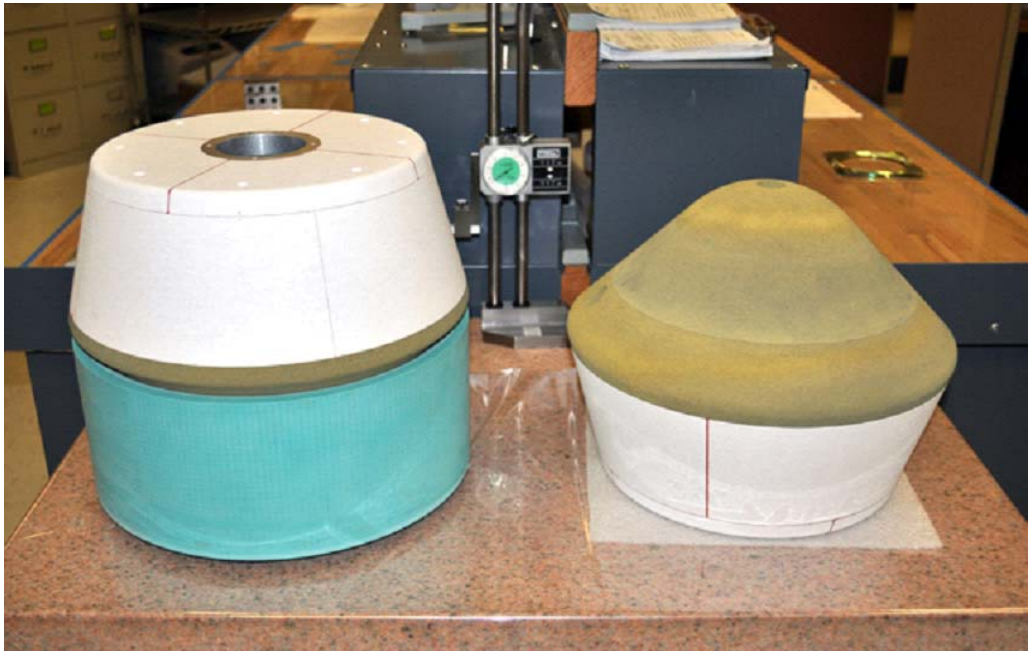
- From previous work (InSPIRe) 14” diameter considered max size for AHF 18” nozzle
- Need to leave sufficient room inside probe body for data acquisition system
- No particular flight profile being tested
- TPS selected by availability (PICA and LI2200)
- In order to maintain maximum internal volume 1” thick PICA chosen for forebody (based on prior experience)
- For expediency aluminum chosen for structure (inexpensive, available and parts easy to machine)

# Fabrication

- Machine TPS
- Machine aluminum structure
- Assemble probe
- Assemble and install instrument plugs
- Assemble DAS
- Integrate probe
- Pre-test X-ray CT scan

# SPRITE Assembly

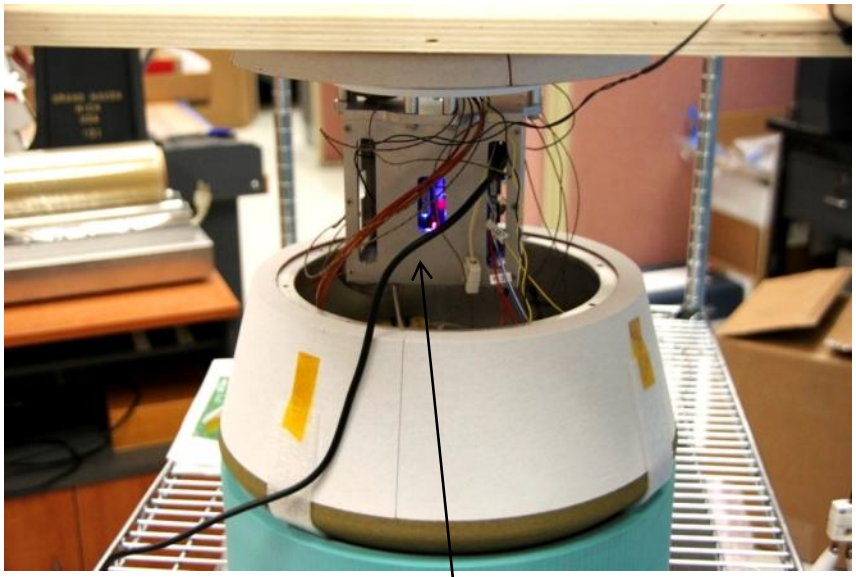
Aluminum Structure



Assembly Nearly Complete

# Data Acquisition System

- The DAS consists of three main components:
  - Custom designed Sensor Support Electronics board,
  - SparkFun Logomatic data recording board,
  - Lithium Polymer batteries that provide power to the system.
- Placed in an aluminum electronics box inside the SPRITE probe
- Condition sensor data from the test model
- Record it to on-board memory
- Serially transmit it to the outside of the test chamber.
- Data from 12 TCs, 2 strain gages and one HEAT sensor were collected by DAS.



Note that the electronics box is approximately the same size as a CubeSat.

# Test Design

- *FIAT* analysis indicated 1 inch thick PICA could be exposed for 100 seconds at AHF facility max conditions and still maintain 200° C bond line temperature
- Thermal analysis *(MARC-MENTAT)* showed the maximum allowable battery temperature (60° C) to be the driving requirement and suggested 50 seconds was a more prudent exposure time

# Test Conditions

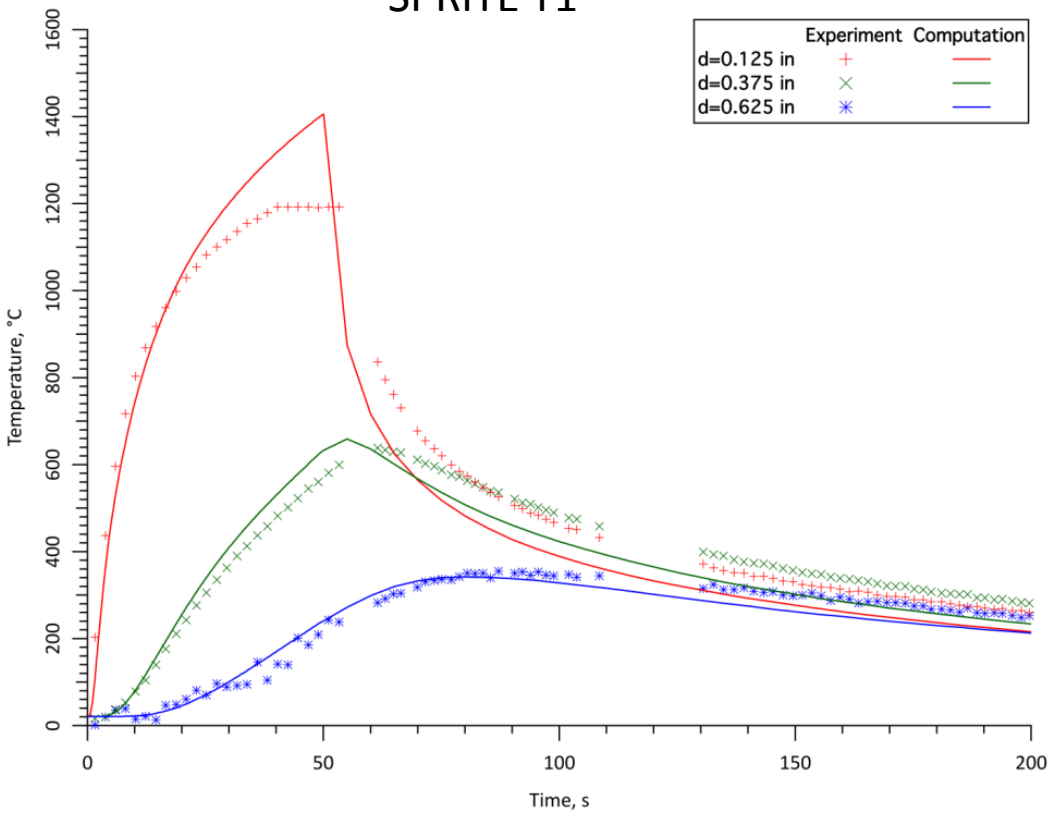
- Test AHF 295 conducted in the 18-inch nozzle
- Single arc-heater setting in AHF 295
  - *Arc current of 2000 A, mass flow rate of 388 g/s (including Ar)*
  - *Bulk enthalpy measured via energy balance (EB2)*
- Different slug calorimeters used
  - *4-inch iso-q (primary, single slug)*
  - *4-inch hemispherical (single slug)*
  - *6-inch flat-face (multiple slugs)*
- Test article and calorimeters tested at 12 inches from nozzle exit plane
- Heat flux of approximately 170 watts/cm$^2$

# SPRITE T1

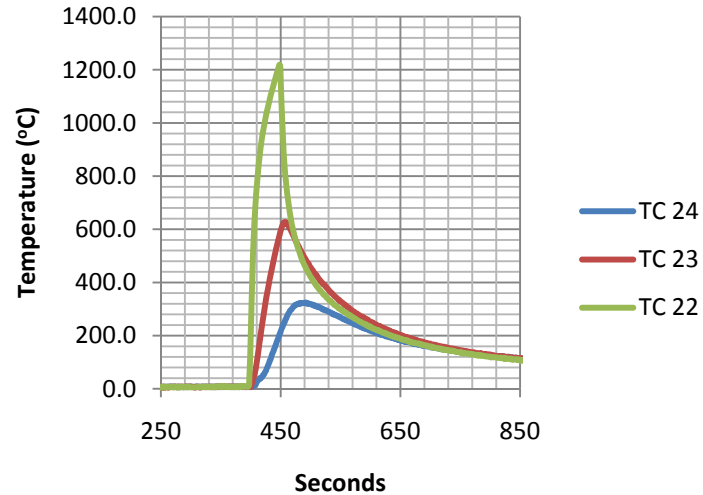
# Some Results from the Arc-jet Tests

# Predicted vs. Measured Temperatures (SPRITE Mid-cone Plug)

SPRITE T1

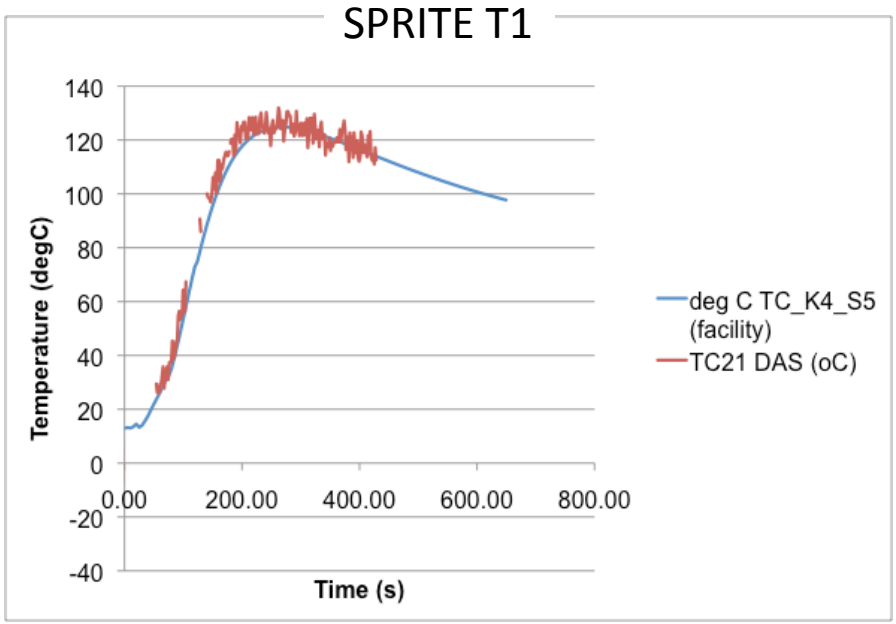


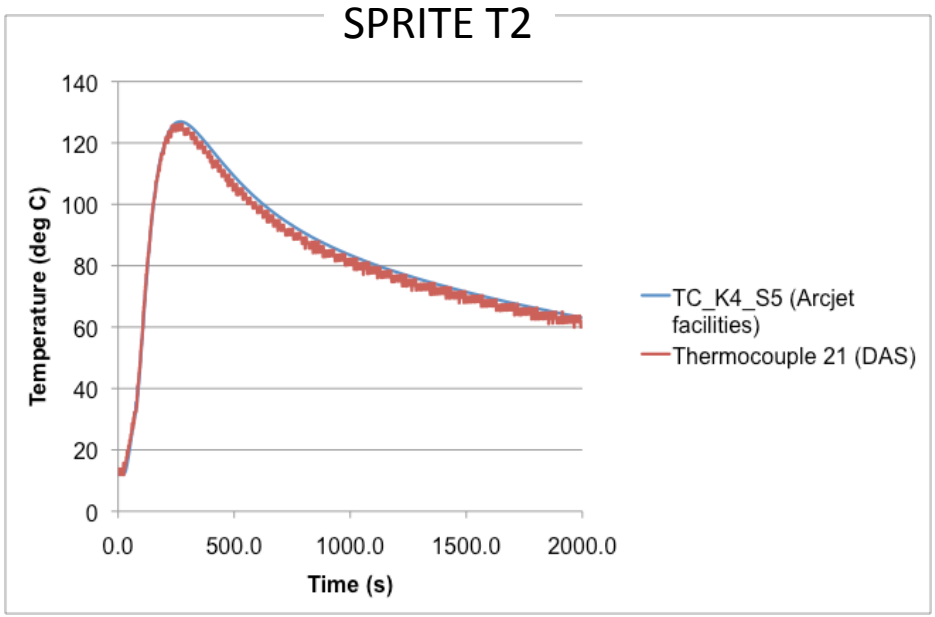

SPRITE T2




Measured data from internal DAS

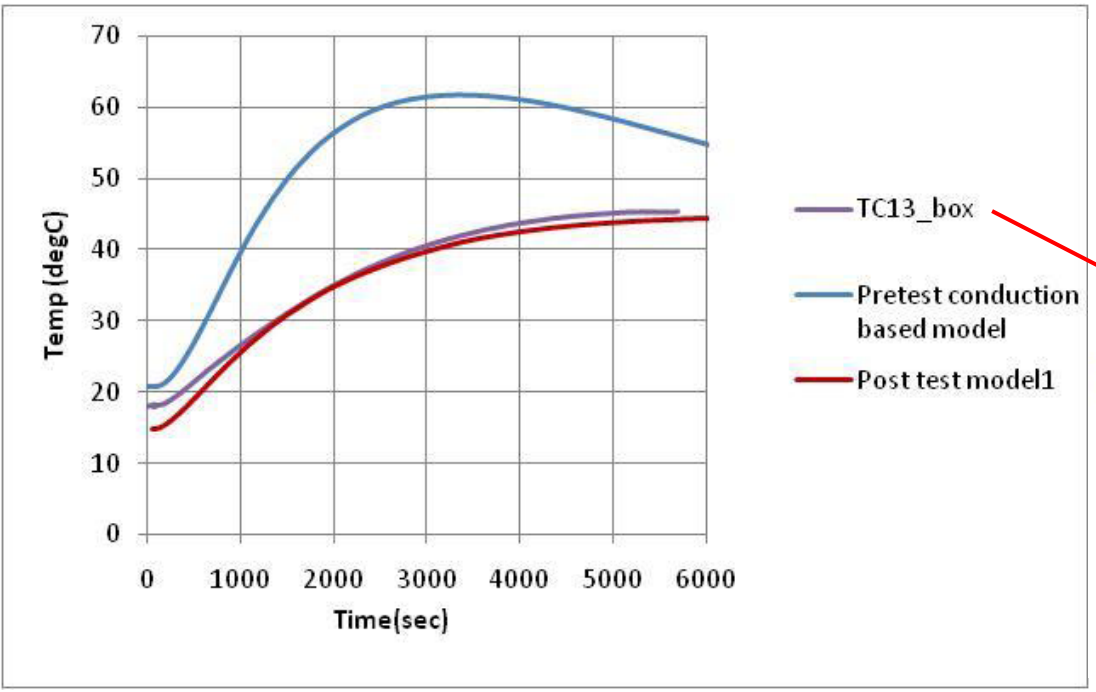
# DAS vs. Facility TC data for TC4 (Al below stagnation plug)

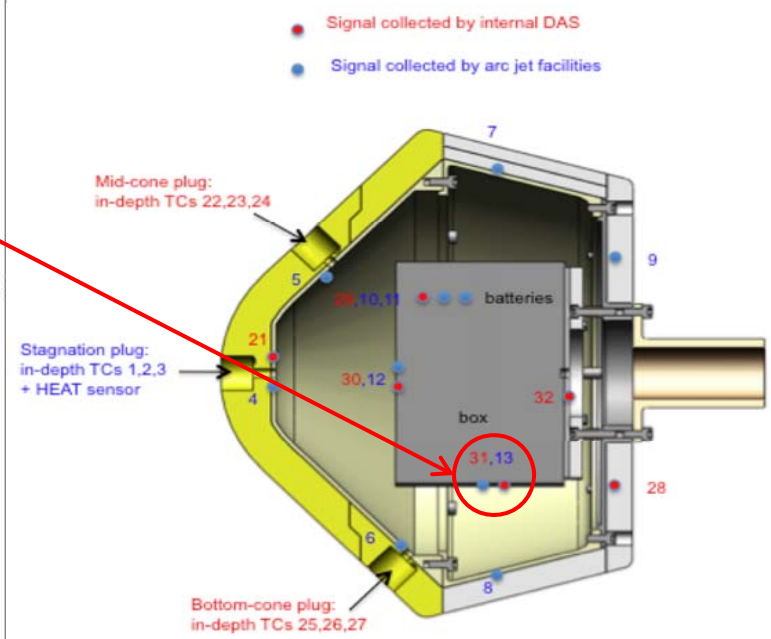



Note that the noise and data drop-outs from the first run have been eliminated in the second run.

# Thermal Modeling: Prediction vs. Measured




- The pretest prediction was considered conservative because it did not include pyrolysis or ablation.
- The posttest prediction used a more sophisticated model, but otherwise could have been run pretest.

# PICA Cracking

# Issues Raised by Testing

- PICA cracking (structural design)
- Thermal-structural analysis indicated potential failure point of PICA (the analyst said “I told you so” when the PICA cracked!)
- Electronics need additional maturation
- Strain Gauging needs work
- Internal thermal predictions were very good

# Conclusions and Future Work

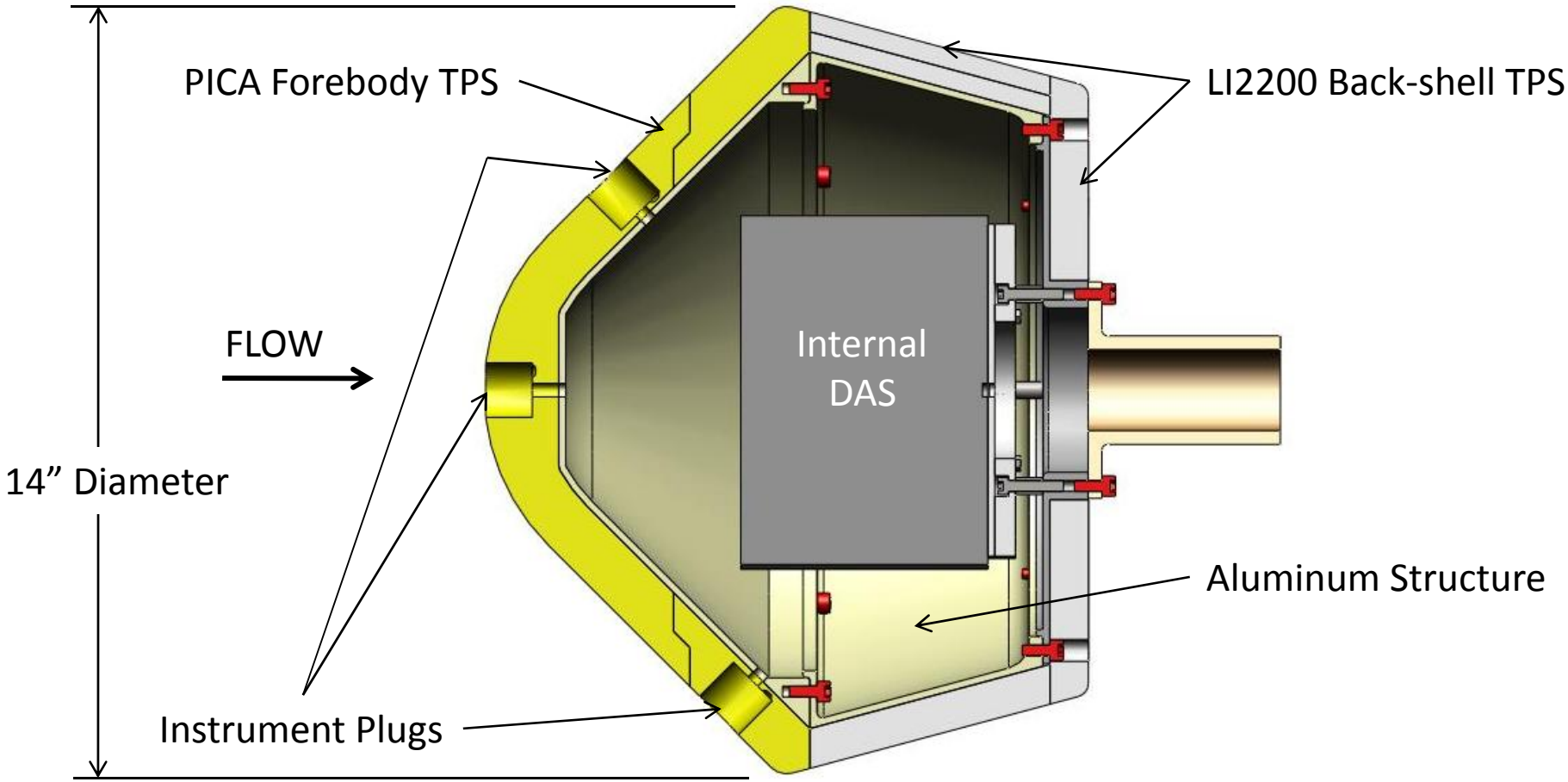
- The SPRITE Project Showed:
  - We can test flight-sized articles
  - We can record TPS instrumentation measurements Internally during an arc-jet test
  - Our analysis tools work well at predicting behavior
- Forward Work:
  - Investigate PICA cracking
    - Post test CT scan
    - Additional structural analysis
  - Develop parachute and recovery plan
  - Design a flight article

# Backup

# Small Earth Entry Probes: Why Now?

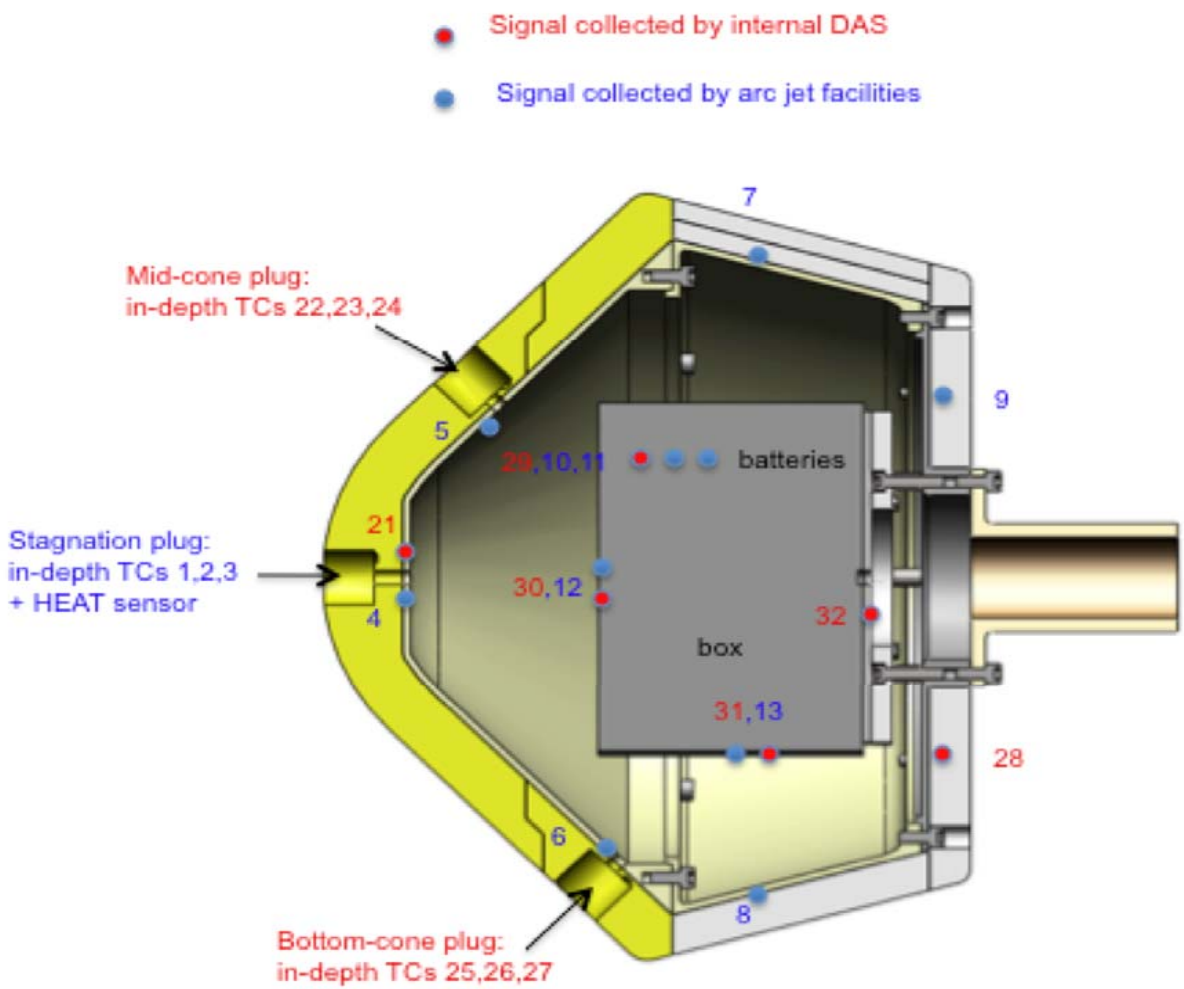
- Cube-sat community has established ability to launch and fly scientifically valuable missions at low cost.
- Next step is to recover the payload, so that high-precision, earth-bound lab instrumentation and scientists can be engaged to further science.
- NASA has proven experience in exploiting secondary payload opportunities.
- Accumulating demand for 100kg to LEO launch vehicle, which would enable dedicated low-mass, low-cost missions.
- Shuttle retirement and gap of 4-5 years presently limits flight opportunities to/from LEO or Station.
- High confidence in NASA entry system design and recent proven capability in systems engineering.
- **New NASA emphasis on technology development.**

# SPRITE Cross-section



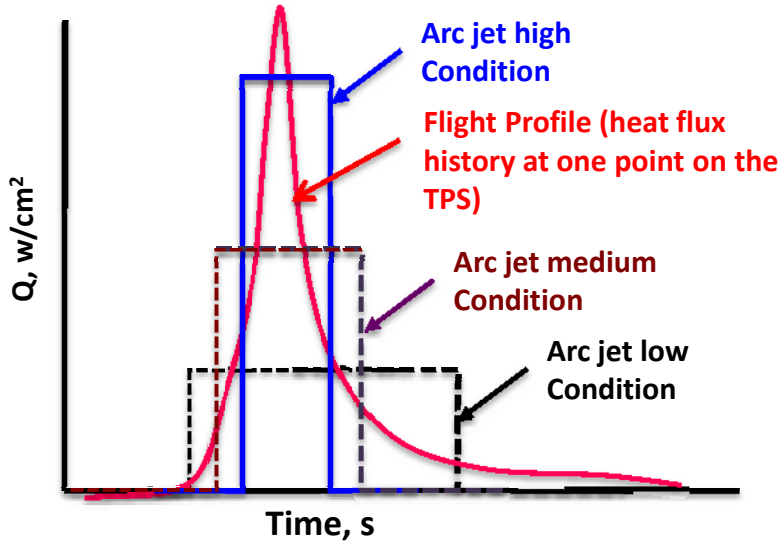
# SPRITE Arc Jet Model Instrumentation

-3 Instrumented PICA plugs with 3 TCs in each plug
-HEAT sensor in stagnation plug
-Strain gages on aluminum shell
-TCs on aluminum shell at various locations (8 TCs)
-TCs on the electronic box and DAS components (8 TCs)

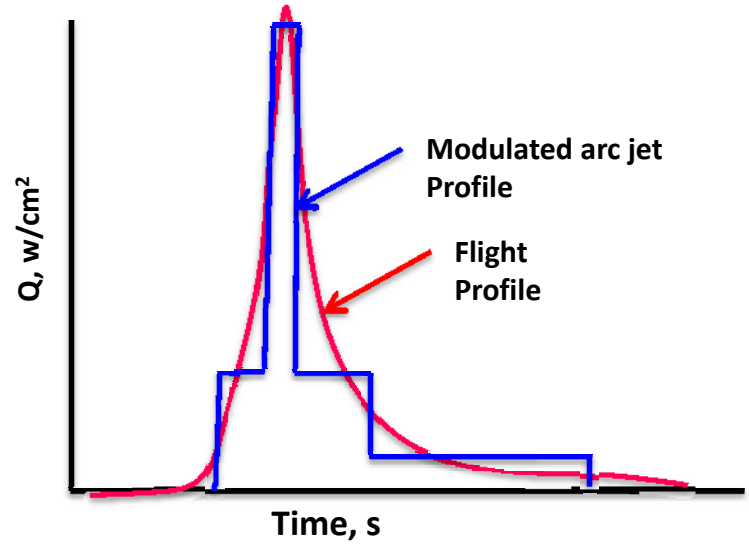


# Can we test like we fly?

**Traditional**
**(Same heat load at different heat flux levels)**

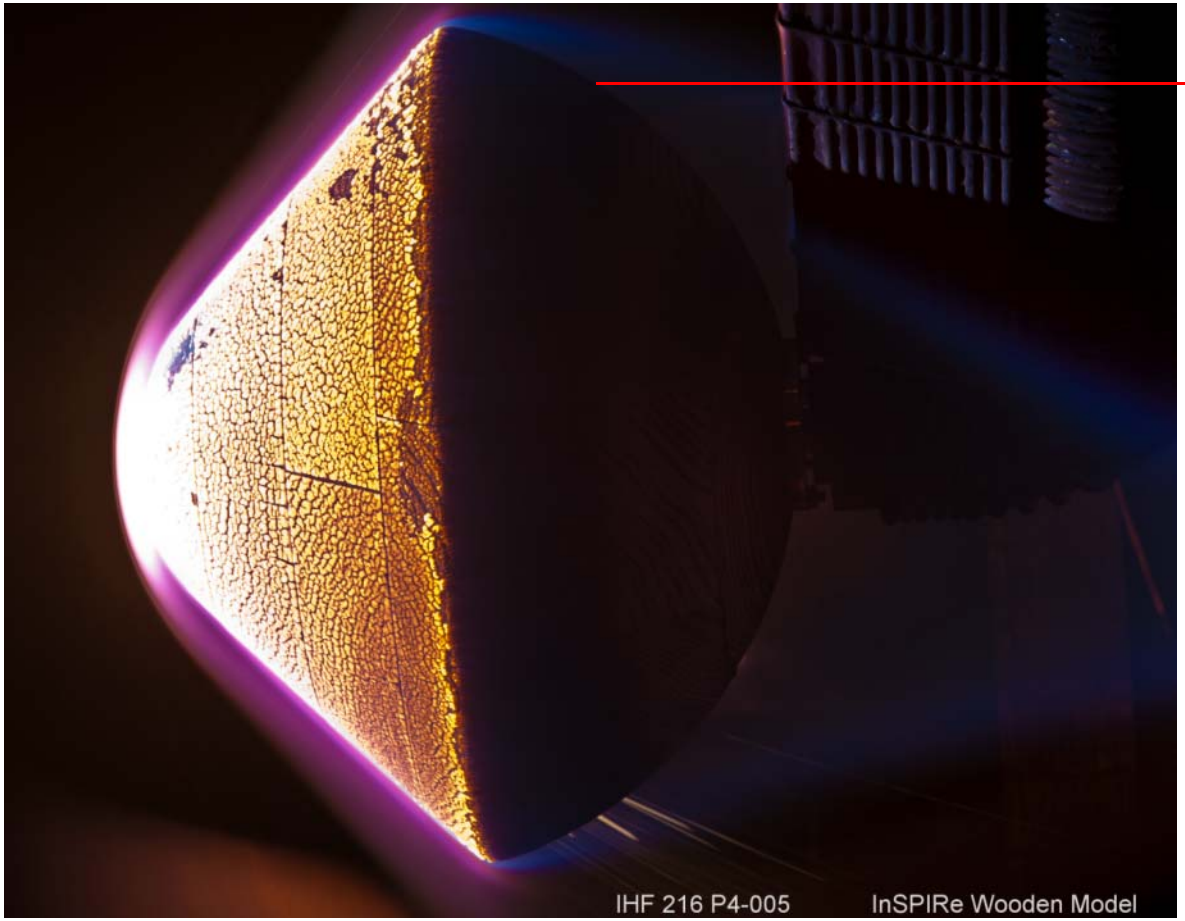


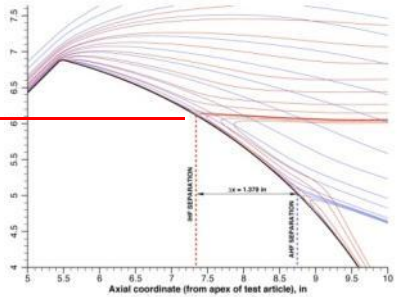

**Desirable**
**(Stepped/Piecewise constant heat load)**




- Freestream conditions (hence the aerothermal environment) are time-varying in flight, but usually held constant in an arc jet test
- For glassy ablators, modulation of heat flux, and measurement of shear, are not only desirable, but important to understand glass melt failure
  - Modulation is difficult from an facility operations view point
  - One attempt at modulating arc jet conditions to match the flight has been done (JSC)
  - Even with modulation, the arcjet test is still a “point test”

# IHF216




InSPIRE red oak model reused in IHF

Tested 2/7/11 in 21” nozzle as part of a facilities test

Two insertions

# Market for Small Probes

| Small Probe Customer Base vs Affordability | | |
|---|---|---|
| **Customer** | **Objective** | **Typical Budget** |
| University Scientists | Space / Bio /material science | $2-$5M |
| NASA CEV TPS | TPS Material Characterization | $5-15M |
| Constelation Program | Sustained Engineering and Program Risk Reduction | $15-100M |
| | | |
| **Dedicated Flight Test Cost Comparison** | | |
| LEX | TPS and Entry System Risk Reduction | ~ $300M |
| ST-9 | Aerocapture Entry System Concept Demonstration | ~ $150M |

Small Probes in the $15M-$30M range would be attractive to technology development programs and to operational programs for risk reduction.

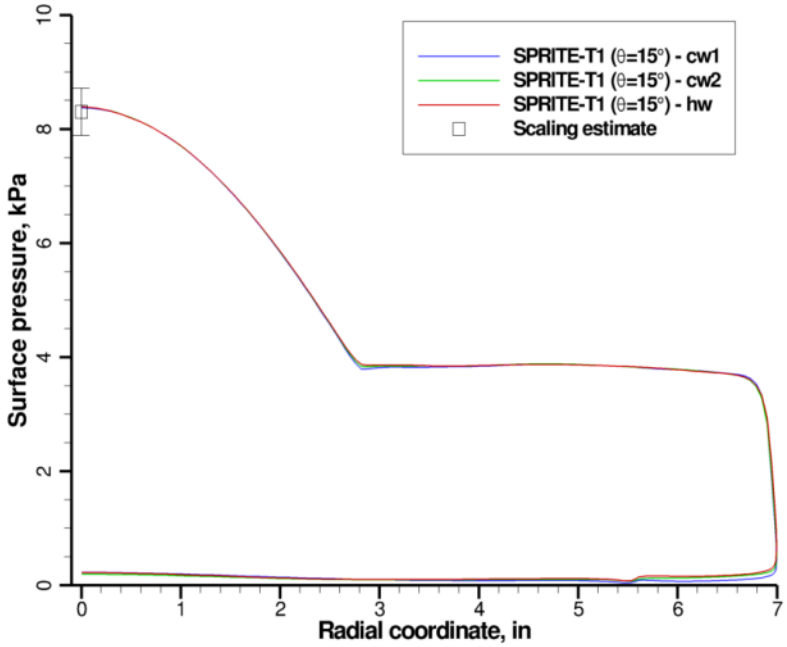
Small Probes in the $5M-$20M range would be attractive to University space science programs.

# SPRITE's Added Value

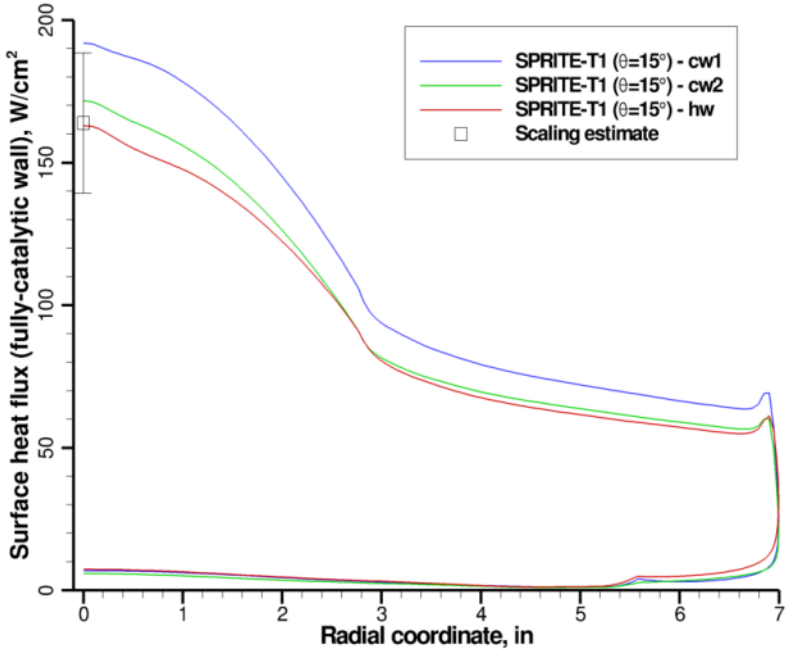
- Reference data from flight that can be used to challenge confidence in the thermal models that were derived primarily from steady state ground test data
- Investigate governing physics currently modeled as well as the phenomena that are absent from the current models (e.g. glass melt, coking and mechanical erosion)
  - Investigate transient response of materials in a flight profile test
  - Directly challenge ground test facility's ability to represent flight environments for material response
- Platform to investigate failure mechanisms in flight environment that are difficult to model and/or test on the ground
- Use knowledge of flight performance to increase confidence in TPS downrange capability

# Test Article: CFD Results

**Pressure**




**Heat flux**




- For cold-wall 1 – $T_w$ = 400 K, fully catalytic wall
- For cold-wall 2 – $T_w$ = 1073 K, partially catalytic wall
- Test article material assumed fully catalytic and in radiative equilibrium ($\varepsilon$ = 0.85)