NASA Application of TPS Instrumentation in Ground and Flight

Daniel M. Empey
Sierra Lobo, Inc.
&
Edward R. Martinez
NASA Ames Research Center

Moffett Field, CA 94025

Lecture for IPPW9 Short Course
June 16th 2012

Contributors

- Jose Santos (Sierra Lobo, Inc./NASA ARC)
- Tomo Oishi (Jacobs Technology/NASA ARC)
- Sergey Gorbunov (Jacobs Technology/NASA ARC)
- Anuscheh Nawaz (Sierra Lobo, Inc./NASA ARC)
- Joseph Mach (Sierra Lobo, Inc./NASA ARC)
- Mike Wright (NASA ARC)
- Michael Winter (UARC/NASA ARC)

Outline

- Introduction
- Recession
- Temperature
- Plug Design
- Heat Flux
- Pressure
- Future Technology

Introduction

- Purpose is to give a ***condensed overview*** **of the current practice for measurement of TPS surface and in-situ basic quantities during ground testing and reentry.**

- **Basic methods will be discussed, and examples given to demonstrate our current uncertainties.**

- **References for further reading**

- **Emphasis is on temperature, pressure, and recession.**
- **Radiation methods are briefly discussed.**
- **There are many other methods that will not be covered in this talk.**

Benefits of TPS Instrumentation

- **TPS Design Verification**
  - Ensure that flight design and thermal margin determination are correct
  - Requires data from several flights to build up a statistical database
  - Identify areas with excess or reduced margin due to insufficient data during design
- **Operational Vehicle ISHM / Forensics**
  - Pre-entry assessment of overall TPS “health”
  - Real time analysis of TPS performance for detection and root cause determination of off-nominal performance events
- **TPS/Aerothermal Modeling Tool Validation**
  - Data from multiple flights will provide much better statistical basis for uncertainty quantification and reduction of: surface and in-depth material response as well as incident aerothermodynamics predictions
- **Design and Performance Data for Second Generation Heatshield**
  - Reassessment of overall TPS margin may result in a lighter, more efficient 2nd generation ISS-return heatshield
  - Performance data from ISS return missions will have some benefit for Lunar return as well, but will not reduce design margin until data are returned from lunar return missions

The Details

- **TPS Margins & Tool Validation**
  - Can a transitional aerothermal database be employed on the HS and/or BS?
  - Are the liens on thickness due to mechanical erosion justified?
  - Does the TPS material coke, thus improving overall performance?
- **Detailed Design Feature Verification**
  - Does the gap design maintain integrity and adequately protect bondline during a range of entry conditions?
  - Is the compression pad design, including possible downstream recession mitigation, performing as desired?

How will instrumentation on the flight vehicle be an improvement over a dedicated flight test?

- Data volume and statistics. A single flight can never exercise or validate reliability estimates, which require that the vehicle operate in off-nominal conditions

What Has Been Measured on NASA Flights

Mission	Instrumentation	TPS Mass Fraction	Observations	Benefits
Apollo 2 & 3	36 Pressure Sensors 35 Calorimeters	13.7%	- Reliable data (early in the trajectory) at orbital entry velocities	- Provided data to improve reliability of entry capsule
Apollo 4 & 6	17 Pressure Sensors 23 Calorimeters Stagnation and offset radiometers Heat shield recovered and sectioned	13.7%	- Reliable data (early in the trajectory) at super – orbital (trans – Lunar) entry velocities - Reliable radiation data - In-depth characterization of ablating TPS material – lack of recession due to "coking"	-Flight data available basis for quantifying uncertainty in afterbody heating predictions for lifting entry - Allowed for optimizing heat shield mass performance
Fire II	3 forebody calorimeters Stagnation and offset radiometers 12 Afterbody thermocouples 1 Afterbody pressure sensor Rear-facing calorimeter	- Flight Experiment - Heat Shield Ejection	- Surface total heating during portion of reentry -Total and spectrally resolved incident radiation to surface - Afterbody heating for entire entry - Confirmed lack of neck radiation at super-orbital velocities in air	-Provides validation data for aerothermal/air radiation models - Helps quantify uncertainty in afterbody heating predictions
Pioneer Venus (4 probes)	2 Thermocouples in each heat shield	12.9%	- Massive ablation in the shoulder region (as was the case with Galileo)	- Provided data for design of TPS in the shoulder region

What Has Been Measured on NASA Flights

Mission	Instrumentation	TPS Mass Fraction	Observations	Benefits
PAET	-Forebody pressure and heat transfer - Thermocouple in TPS near shoulder - Narrow – band radiometers	13.7% (FB) 3.5% (AB)	- Spectrally-resolved radiation over several discrete regions	-Validating data for radiation band models - Data for improvement of heating predictions
RAM-C	-Microwave receiver/transmitter - Langmuir probes	Flight Experiment	-Electron number density and temperature in flight - Quantification of radio blackout – cause and effect	- Validation of CFD models
Viking I & II	-2 Backshell thermocouples - Afterbody pressure sensors – limited data	~3.2%	-None	-Provided basis for Mars Pathfinder TPS design - Provided confirmatory data for CFD – afterbody pressure
Galileo	-Forebody recession sensors -Afterbody thermocouples	45% (FB) 5% (AB)	-Largest heat flux and heat load of all planetary missions - Successful demonstration of the ARAD sensor – recession data - Lower than expected recession in the stagnation region - Larger than expected shoulder recession	Provides the basis for design of heat shields for gas giant entries

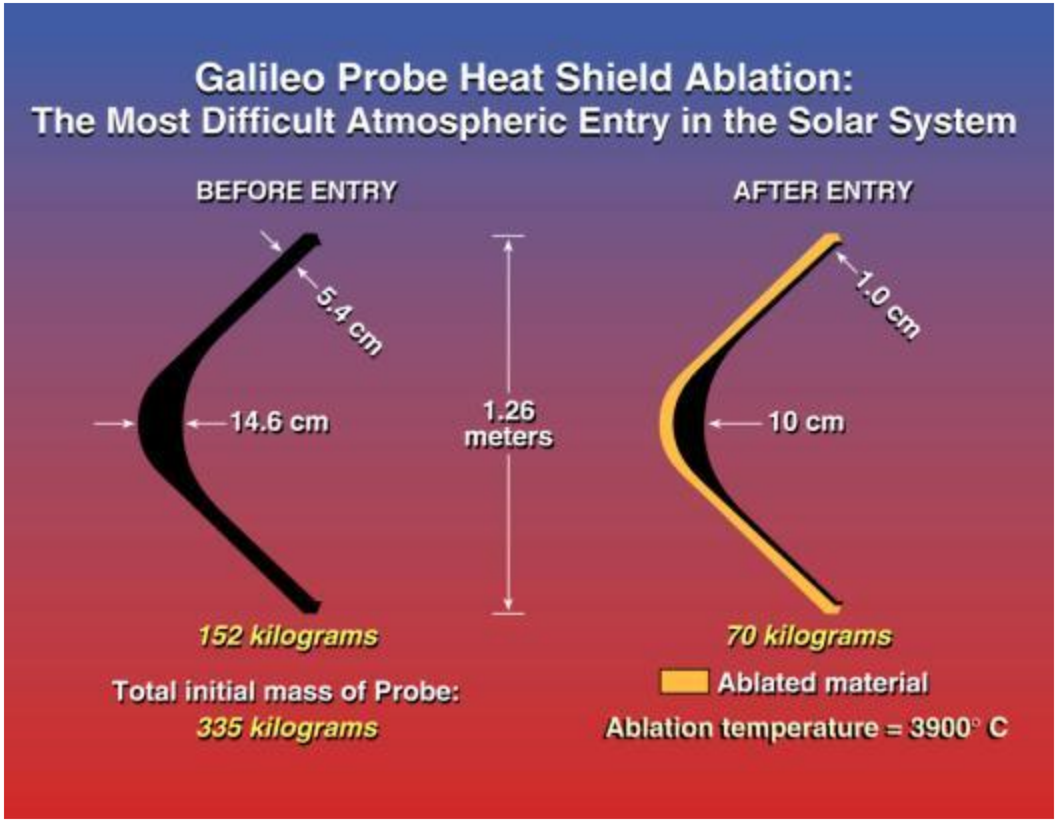
What Has Been Measured on NASA Flights

Mission	Instrumentation	TPS Mass Fraction	Observations	Benefits
Space Shuttle (STS 1 – 4)	-Pressure and heat transfer sensors (wind and lee side) - Accelerometers and gyroscopes	~16%	-Global and control surface aerodynamics - Demonstration of real gas effects on vehicle aerodynamics	- Provides data for validation of CFD analysis tools
Mars Pathfinder	-9 in-depth thermocouples in TPS - 3 resistance thermometers	6.2% (FB) 2% (AB)	-6 functional TC's including only on the afterbody - 2 functional RTD's	- Provided a rationale for MER afterbody heat shield optimization
MER	- None	8.0% (FB) 7.8% (AB)	- Heat shield visually inspected by rover	-None
Stardust	- None	~22%	- Heat shield recovered and inspected - Recession and char measured	-TBD
MSL (in < two months!)	- 7 Heat shield thermal plugs - 7 forebody pressure sensors		-Entry Aug 5, 2012 - Other talks at IPPW	
Orion EFT-1	- 19 Heat shield thermal plugs - 15 Aerothermal plugs - 9 Forebody pressure sensors - 2 Forebody radiometers - Afterbody thermocouples		-Launch 2014 - Orbital reentry	
Orion EM-1	- Similar to EFT-1		-Launch ~2017 - Lunar reentry velocity	

Outline

- Introduction
- **Recession**
- Temperature
- Plug Design
- Heat Flux
- Pressure
- Future Technology

NASA Galileo Jupiter Probe Recession Sensor



Analysis of Galileo Probe Heatshield Ablation and Temperature Data, Milos, et. al, Journal of Spacecraft & Rockets 1999

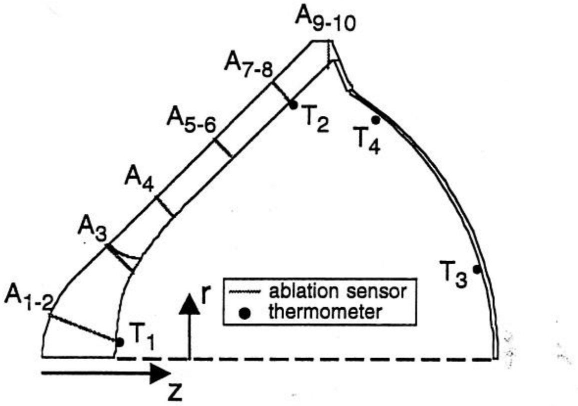


Fig. 2 Locations of 10 ablation sensors (A_1–A_{10}) in heatshield and four resistance thermometers (T_1–T_4) inside structure; sensors are not coplanar.

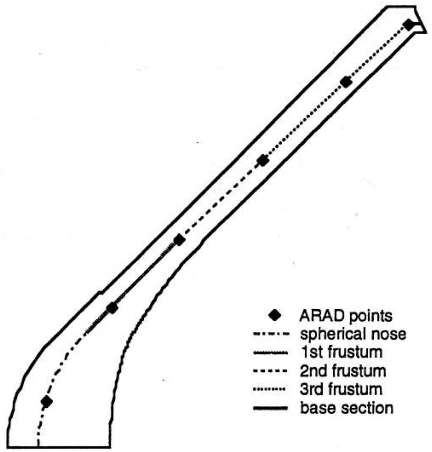
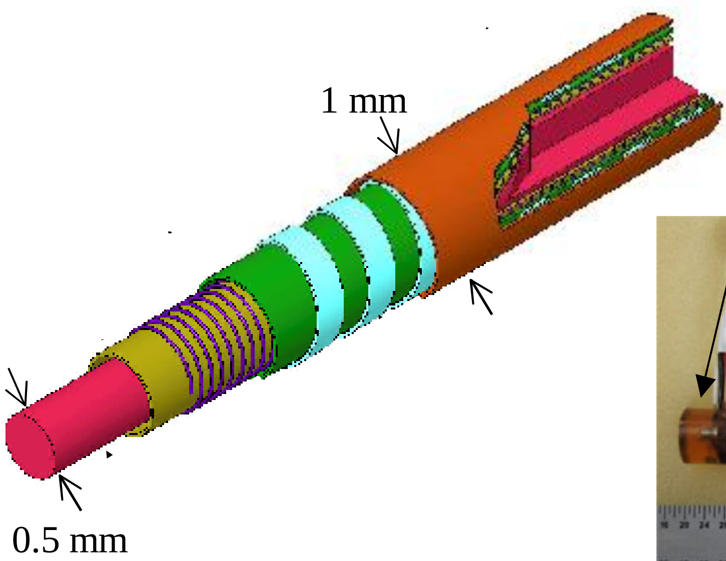


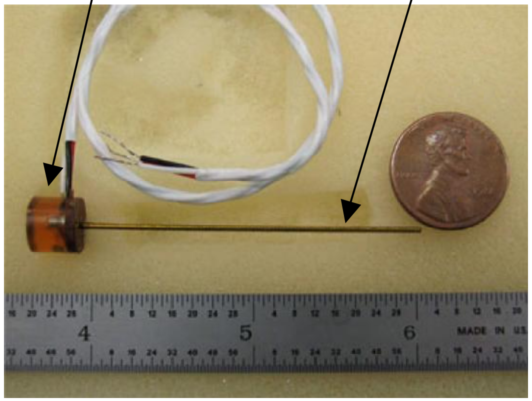
Fig. 5 Reconstruction of heatshield final shape (to scale with initial centerline thickness of 14.6 cm).

Heat Shield Recession Sensor
ARAD Construction

Entry Systems and Technology Division

- Three coaxial conductive elements: Pt-W winding; Nickel ribbon; graphite core
- Kapton/epoxy provides a tenacious, electrically conductive char
- Measures a char zone - following a ~700 C isotherm
- Uncertainty of ~ +/- 0.2 mm - based on current source uncertainty of ~10 mV (0.91mm for Galileo)
- Flight heritage for carbon-phenolic TPS

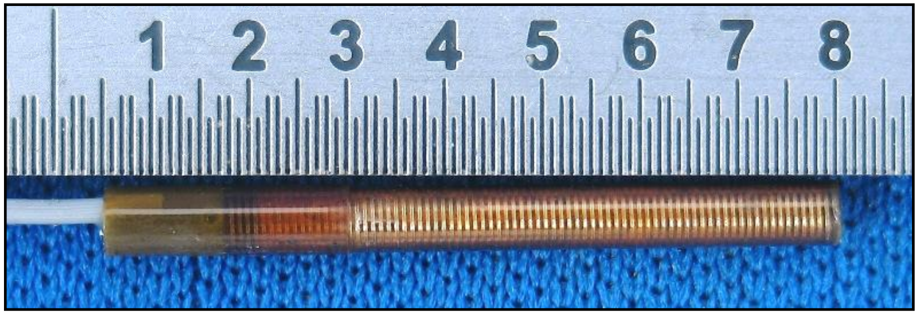


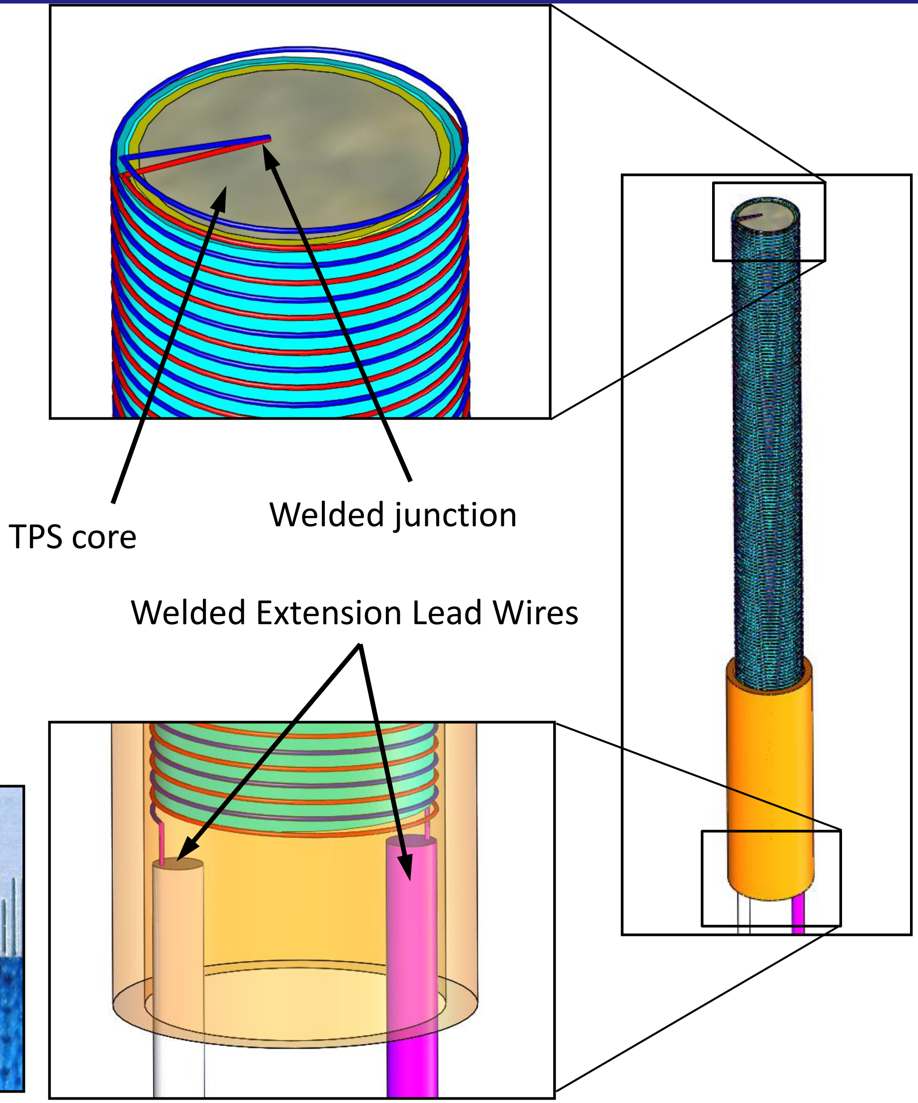


HEAT* Sensor

(*<u>H</u>ollow a<u>E</u>rothermal <u>A</u>blation <u>T</u>racking)

- The HEAT sensor is a resistance measurement based sensor that measures the depth and rate of an isotherm as it moves through the thickness of the heat shield material during entry
- Utilizes a dual winding of 0.001-in. dia. platinum wire wrapped around a polyimide tube
- A core of the acreage TPS is inserted into the HEAT to reduce the sensor's disturbance to the local material
- AIAA-2008-1219 and AIAA-2011-3955 papers provide more details





Outline

- Introduction
- Recession
- **Temperature**
- Plug Design
- Heat Flux
- Radiation
- Pressure
- Future Technology

Thermocouple Application: Uncertainty

- **Reversible Effects**
  - Magnetic Fields: reentry
  - Elastic Strain
  - Pressure: reentry
- **Irreversible Effects**
  - Plastic Strain
  - Metallurgical phase change
  - Transmutation: out-gassing
  - Chemical Reaction: with TPS atmospheric elements

Table 1 Thermocouple Calibration Tolerances

Type	Temperature Range	Standard Tolerance	Special Tolerance
K	0 — 1250 C	Max: –2.2 C or –0.75%	Max: –1.1 C or –0.4%
S	0 — 1450 C	Max: –1.5 C or –0.25%	Max: –0.6 C or –0.1%
C	32 to 4200 F	Max: –8.0 F or –1.0%	Not established.

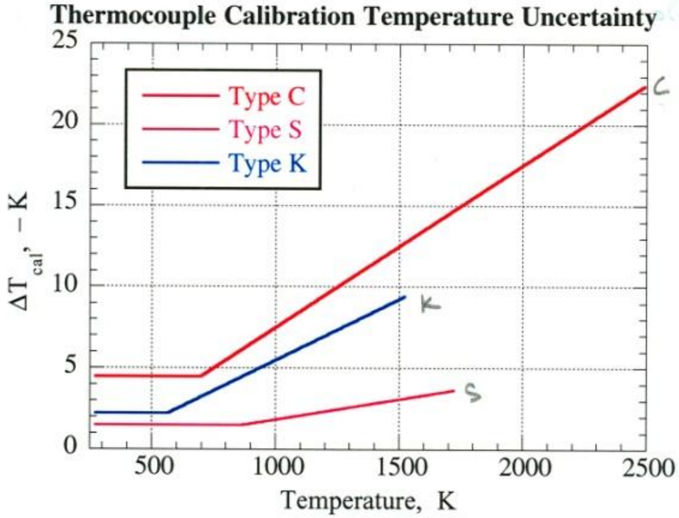
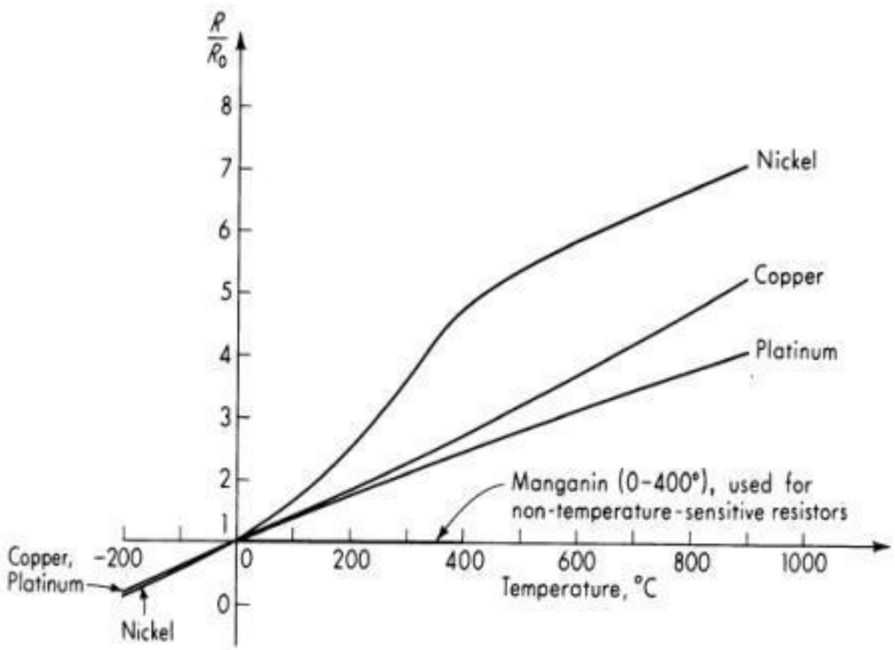


Fig. 1 Temperature uncertainty introduced by the thermocouple calibration tolerances.

Conventional Temperature Sensors (RTD)

Platinum Resistance Thermometers (PRT)

- 4 wire device, 2 to measure, 2 to bring known current
- Platinum wire resistance changes with temperature, measure voltage drop across this resistance given a known current input



Platinum is linear +/- 1.2% from 260 to 815 C

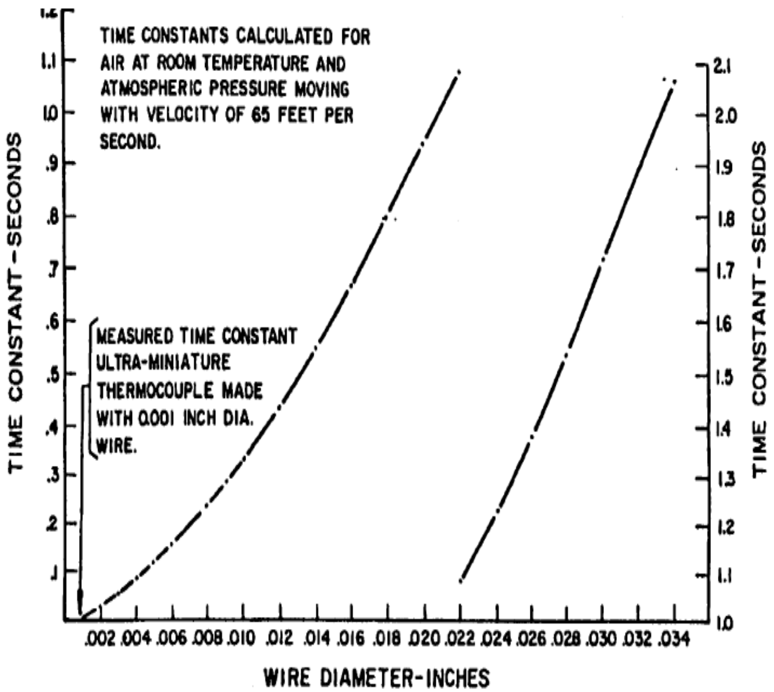
Example PRT: ceramic wire wound

Error Sources

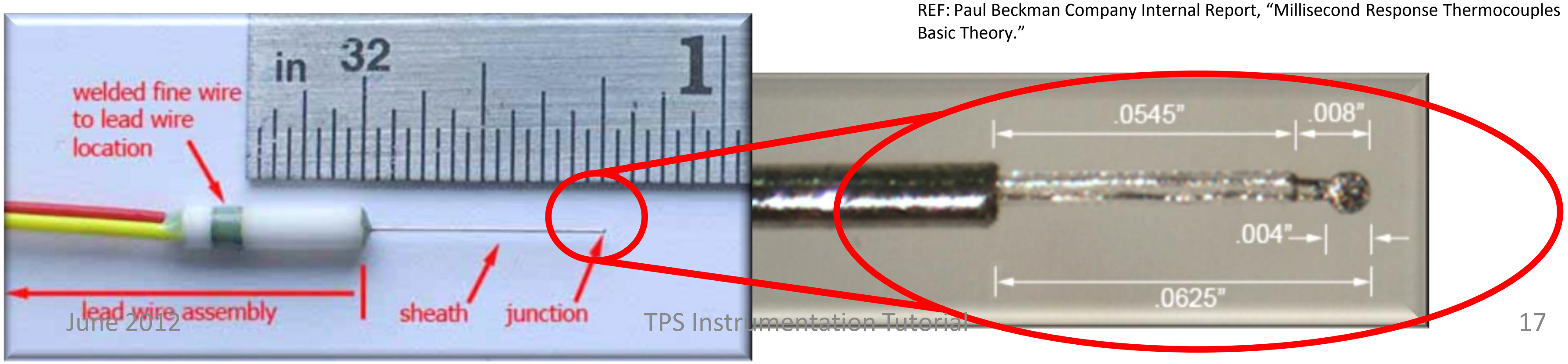
- Strain of surface
- Heating of RTD due to current flow through the element
- Transmutation of element

Sheathed Probe Overview

- Paul Beckman Company (PBC) heritage
- Ames SMART sensor (Sheathed Miniature Aerothermal Reentry Thermocouple)
- Fine wire at 0.0005-0.0008" dia. vs. 0.003-0.020" conventional wire dia.
  - Faster response time to temperature
- Fine wire junction 0.003 – 0.004" dia.
- Double Bore Quartz tube 0.004" dia.
- Sheath 0.008" dia. vs. conventional 0.020" dia.



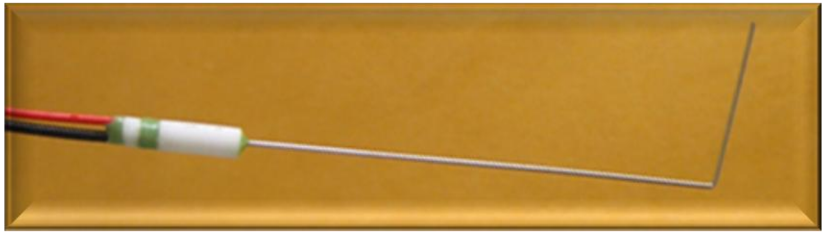
REF: Paul Beckman Company Internal Report, "Millisecond Response Thermocouples Basic Theory."



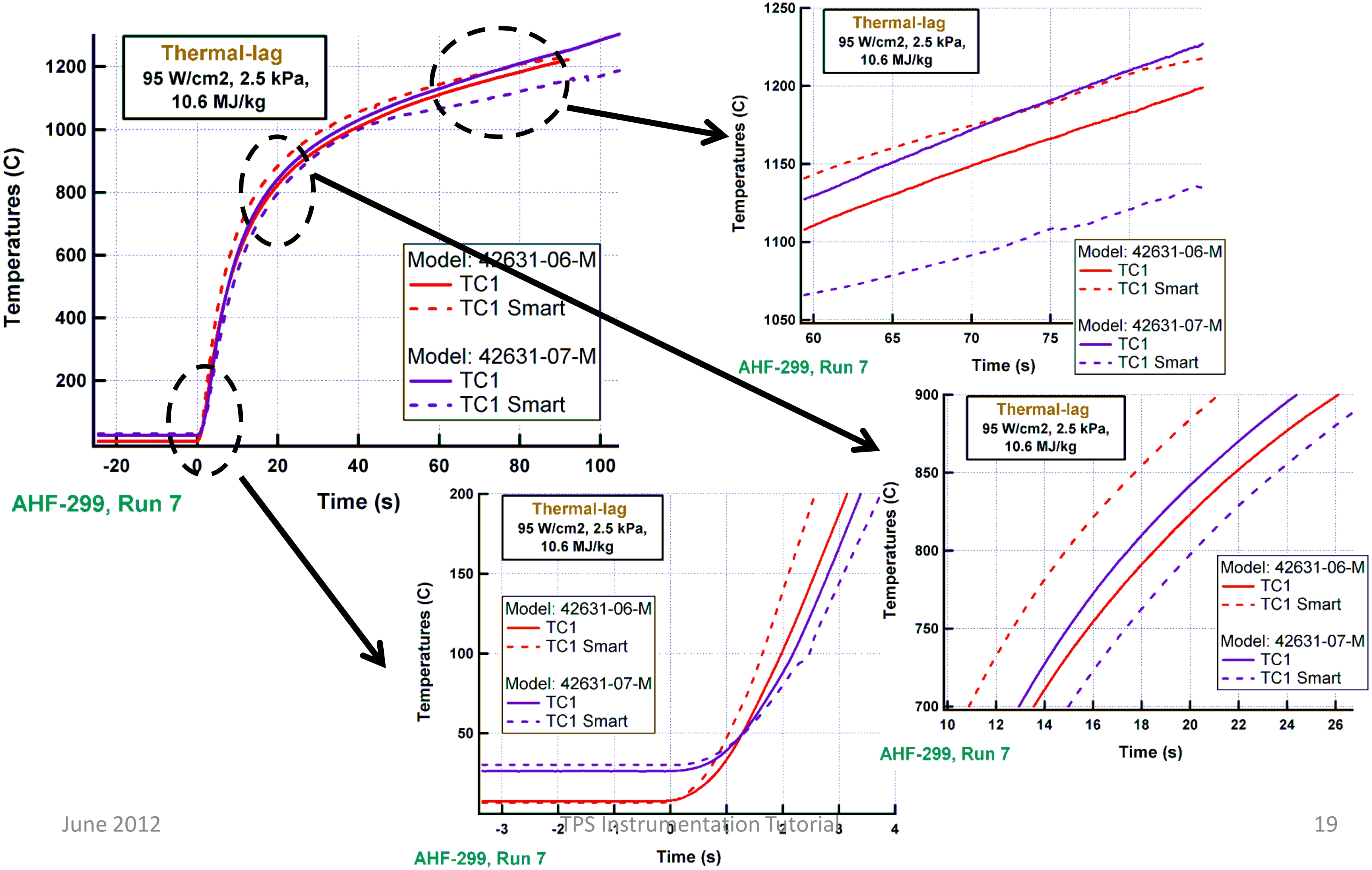
Benefits

Design Feature	Implication
Thermoelement fine wire diameters between 0.0005-in and 0.001-in	• Response time constants on the order of tenths of a millisecond
Quartz tube (0.004-in outer diameter)	• Provides electrical insulation • Wires remain slack inside the quartz for strain relief • No need for ceramic powder filling
Metal sheath (0.008-in outer diameter) – Stainless steel or tantalum	• Provides resistance to corrosion • Several different probe tip configurations may be implemented • Can be bent 90° for installation into a TPS sensor plug

- Completed probe is one modular unit with “plug-n-play” characteristics once lead wires are terminated.



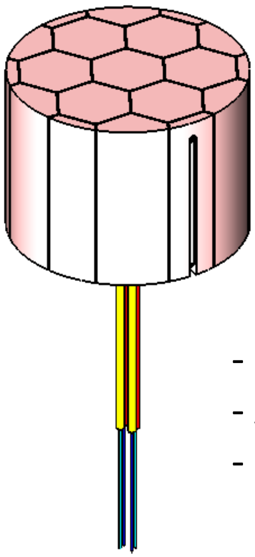
Near surface Type K compared with “SMART” Type-K

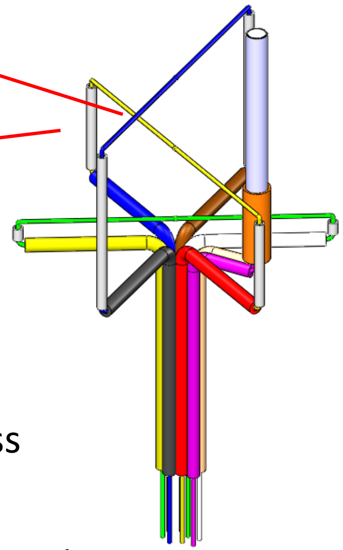


Outline

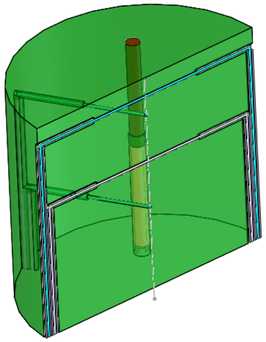
- Introduction
- Recession
- Temperature
- **Plug Design**
- Heat Flux
- Radiation
- Pressure
- Future Technology

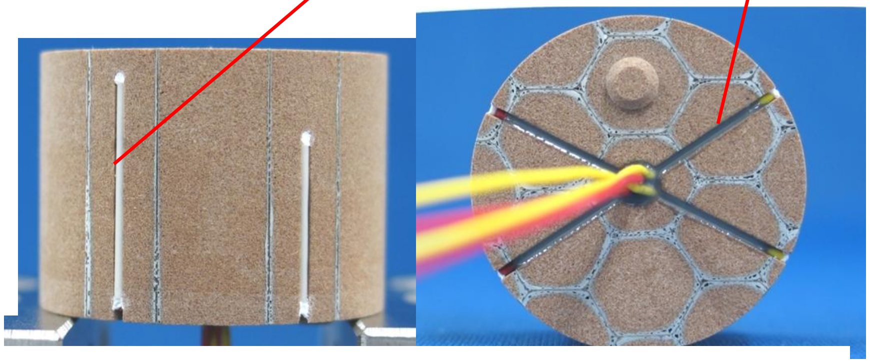
TPS Thermal Plugs: Standard Practice





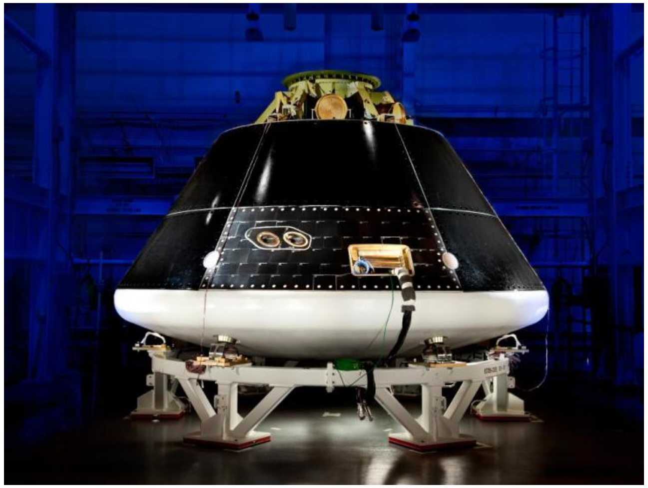
- 3 in-depth TCs
- Alignment feature
- Consolidated harness





TPS plug: two TCs at 0.1 and 0.3-in from OML

Mars Science Laboratory

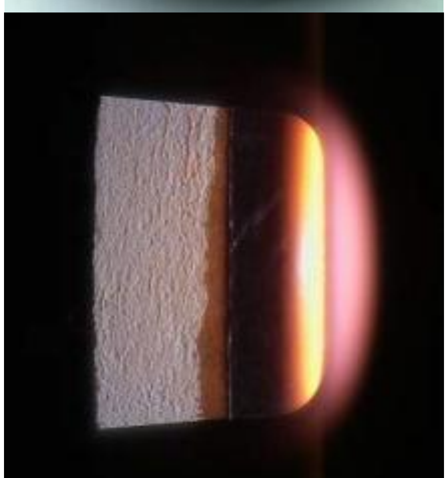


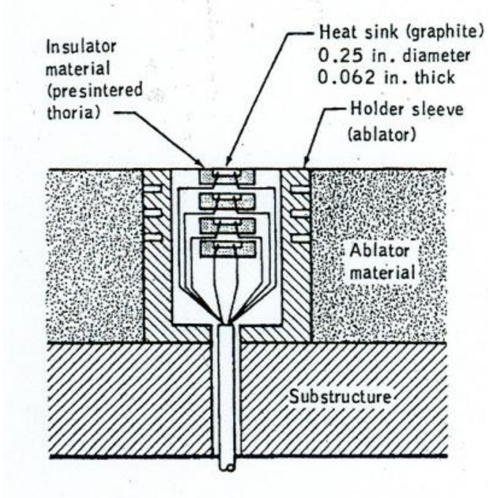
Multi Purpose Crew Vehicle

Outline

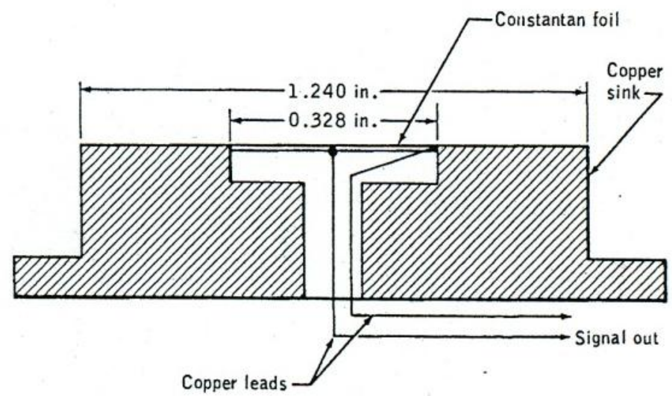
- Introduction
- Recession
- Temperature
- Plug Design
- **Heat Flux**
- Radiation
- Pressure
- Future Technology

Heat Flux Instrumentation



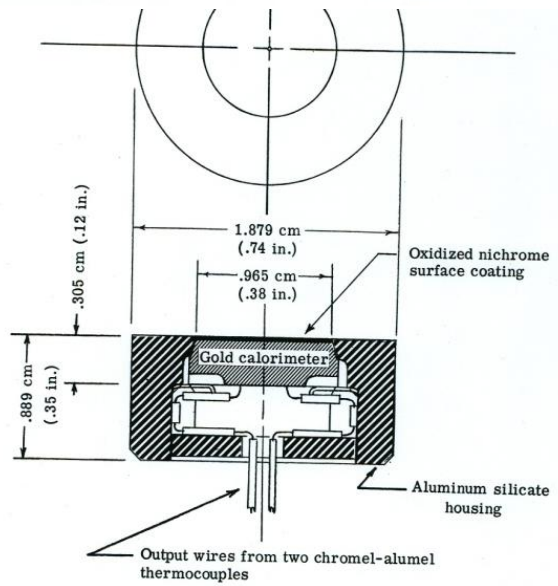


(c) Wafer calorimeter. (See ref. 4.)



(d) Asymptotic calorimeter.

Apollo 4, 6
NASA TN D-679



FIRE II
NASA TM X-1319

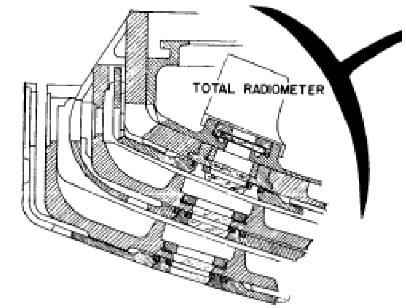
Outline

- Introduction
- Recession
- Temperature
- Plug Design
- Heat Flux
- **Radiation**
- Pressure
- Future Technology

Fire/Apollo Radiometers

- Fire I and II: Three beryllium layers, which also functioned as calorimeter, jettisoning outer layers as time progresses.
  - Sensitivities of the thermopiles were on the order of 15 to 20 mV/(W/cm 2)
  - the low mass of the receiver provided a time constant of about 10 msec.
- Apollo 4 and 6: Hole and radiometer in ablating TPS.
  - Produced mixed result with a clogged port
  - Needed to perform post-flight model test to evaluate errors by TPS.
  - Port size speculated from illustration is Φ0.27 in. at OML
  - The Apollo pressure port design had Φ0.25 in. size

Fire I and II



Apollo

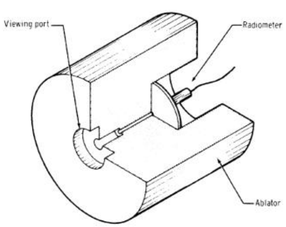


Figure B-5. - Sketch of radiometer model.

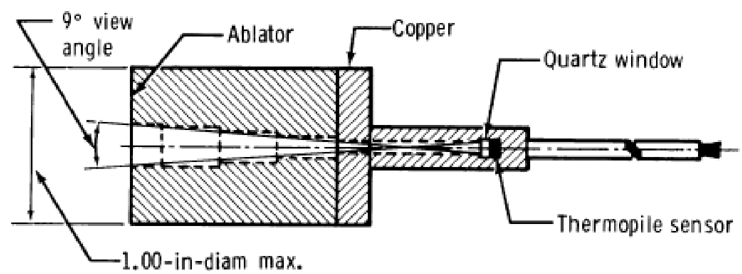
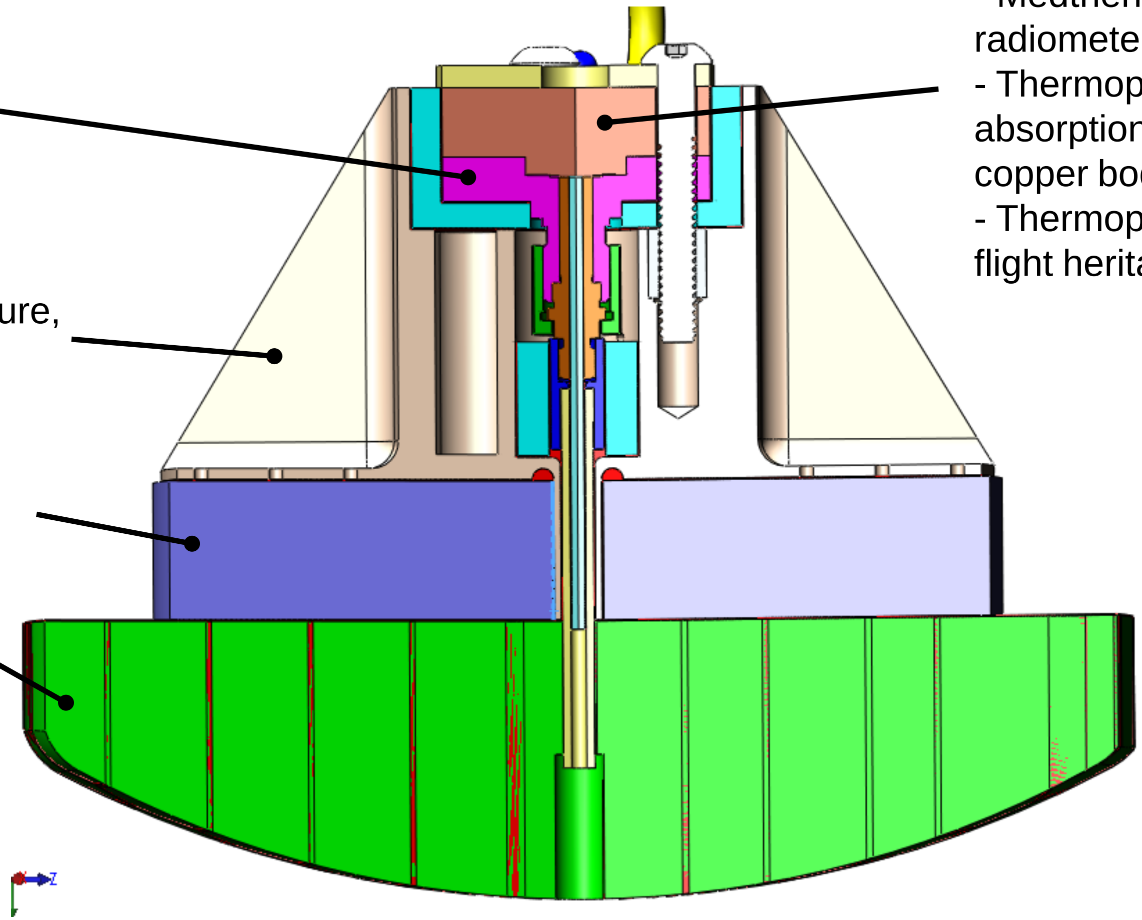


Figure 19. - Sketch of radiometer.

Source:
"RADIATIVE HEATING RESULTS FROM THE FIRE 11 FLIGHT EXPERIMENT AT A REENTRY VELOCITY OF 11.4 KILOMETERS PER SECOND, NASA-Tk X-1402
"RADIATIVE HEATING TO THE APOLLO COMMAND MODULE ENGINEERING PREDICTION AND FLIGHT MEASUREMENT NASA TM X-58091

Radiometer Arc-jet Model

- The radiometer sensor measures radiative heat flux from the shock layer during atmospheric reentry



- Medtherm, 22025-XX, radiometer sensor
- Thermopile based with absorption coating on copper body
- Thermopile design has flight heritage

Radiometer Sensor and Fiber Mount

- Medtherm Corp. 22023 - series
  - thermopile on copper body
  - Sensing surface is coated with absorbing paint
  - Different configuration provides different sensitivity and time constant
    - 9 to 15 mV per 10 W/cm2 of hemispherical incident WITHOUT fiber
    - 50 to 150 msec to 63% step change.
  - -04-4 is chosen for high sensitivity

Medtherm, SMA
Fiber mount adaptor

Medtherm Thermopile

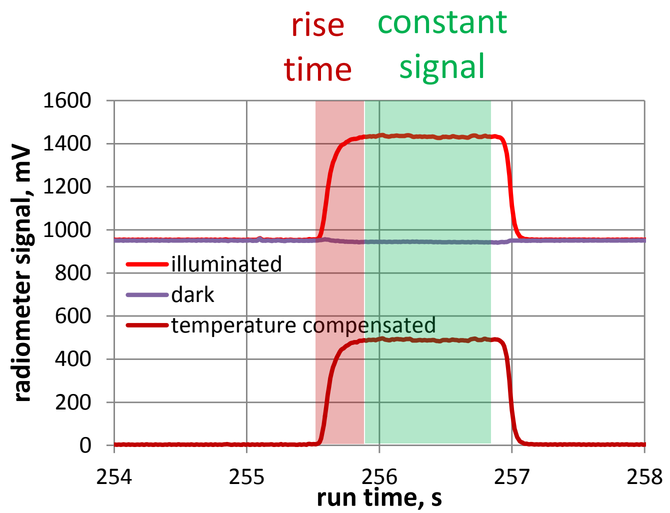
-XX	Output (mV) at 10 W/cm2 Hemispherical Incident (without optical train)	Time constant 63 %	Time constant 99%
-01	11.76	0.056 sec	0.7 sec
-02	16.97	0.099 sec	2.4 sec
-03	11.68	0.087 sec	0.25 sec
-04-3	8.79	0.151 sec	1.20 sec
[-04-4]	20.77	0.153 sec	1.19 sec
[-04-5]	11.50	0.136 sec	1.03 sec

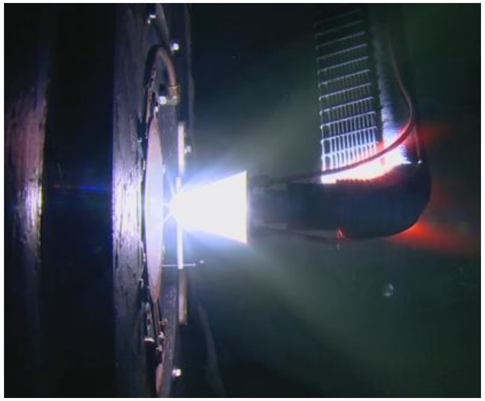
[] indicates unit not at ARC as of 04/23/2012

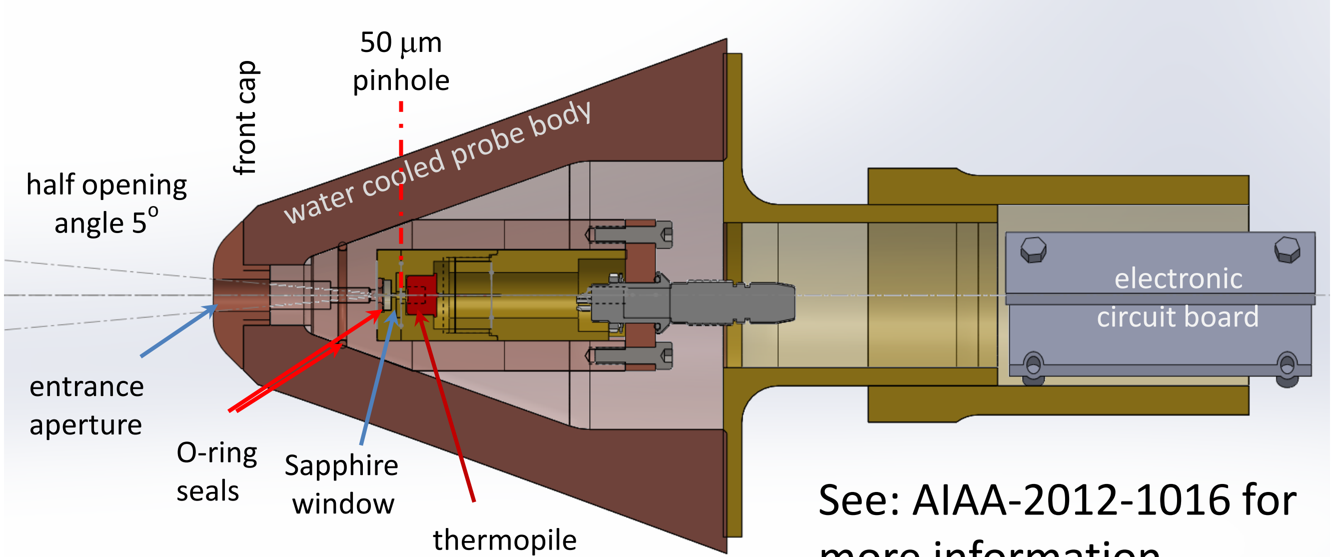
Optical probe: Set-up and Design

Radiometer/Spectrometer Probe

- Sensor and electronics inside the probe body
- Detection through a Dexter Research thermopile sensor ST120 comp (two thermopiles, one shielded from radiation for temperature compensation)
- Customized electronic board (signal amplification x 60)
- Designed with respect to possible application in flight
- Second probe with optical fiber for spectrometer
- Major contributions from arc-discharge







See: AIAA-2012-1016 for more information

Outline

- Introduction
- Recession
- Temperature
- Plug Design
- Heat Flux
- Radiation
- **Pressure**
- Future Technology

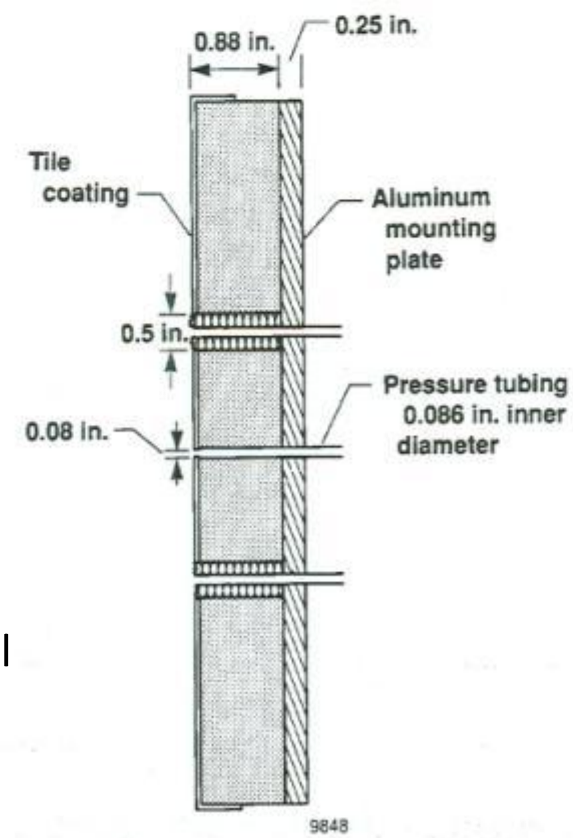
Pressure Sensors

Manufacturer	TAVIS	Taber Industries	Kulite	Columbia Research Laboratories, Inc.	Honeywell
Sensor Type	Variable reluctance	Bonded Strain Gage	Piezoresistive	Piezoelectric	micromachined silicon chip with piezoresistive strain gauges
Measurement Range	0-1/0-2400 kPa	0-14 kPa	0–35 kPa to 0–7000 kPa	0.10 x 10^{-4} to 70 kPa	10 kPa to 3500 kPa depending on model
System Mass	450 g	287 g	227 g	225 g	150 g
Vibration Limit	20 g	30 g	100 g max.	100 g max.	1500 g max
Operating Temperature	-53 to +93 C	-54 to +121 C	Si diaphragm (-55 to +482 C)	-23 to +260 C	-40 to +85 C

Pressure Sensors for Aeroshell Forebody

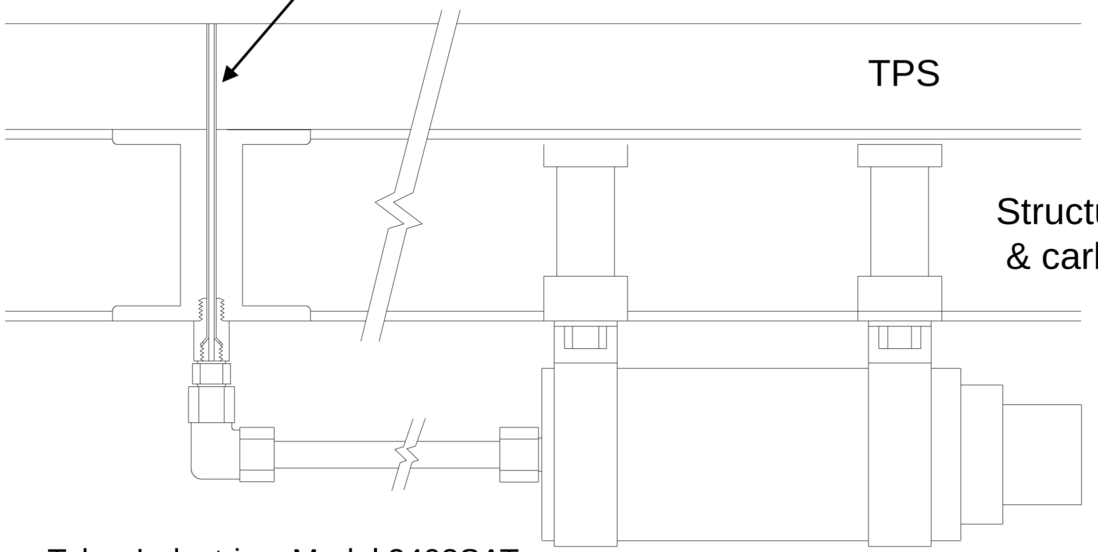
Design Issues / Considerations

- TPS Penetration
  - Small penetration not a problem if flow does not penetrate structure
    many tests with missing cells in honeycomb of TPS,
    missing tiles in Shuttle TPS, etc (B. Laub)
  - TPS melt could flow into hole – use tube/sleeve through TPS
  - TPS recession - tube/sleeve to recede faster than TPS
  - Tube/sleeve material burning, melting must not block hole
- Thermal Analysis
  - Conduction through penetration and tubing to sensor
- Material Selection
  - Sleeve for TPS penetration – non-porous and
  - ablates faster than surrounding TPS
- Mass and space constraints between payload and aeroshell structure
- Testing requirements
  - Arc Jet Tests – no. of tests depends on range of heat fluxes and pressures, configuration alternatives



Shuttle Pressure Orifice
NASA TM 4219

Pressure Sensors for Aeroshell Forebody

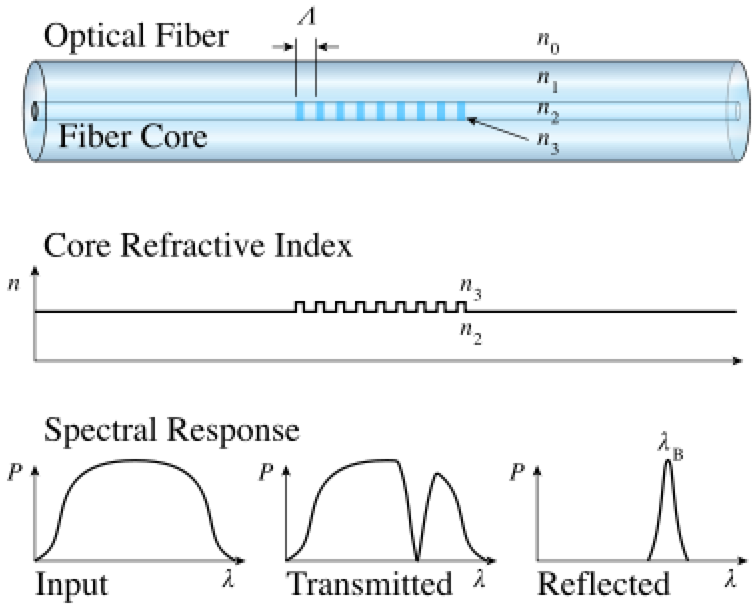


- Taber Industries, Model 2403SAT
  - MER carrier s/c, Hubble, ISS, commercial satellites
  - Dimensions: 3-1/2” x 1-1/4” dia (89 mm x 32 mm dia)
  - Pressure accuracy & range: ±0.25% FS static, ±1.5% FS with temperature error band),
  - available for 0-2 thru 0-20k psi
- Tavis Corporation, Model P1
  - Shuttle, ISS, Delta, Atlas, Viking backshell
  - Dimensions: 2.9” x 1.0” dia (74 mm x 25 mm dia)
  - Pressure accuracy & range: ±0.5% FS static, ±2.0% FS with temperature error band), available for 0-1 thru 0-350 psi

Outline

- Introduction
- Recession
- Temperature
- Plug Design
- Heat Flux
- Radiation
- Pressure
- **Future Technology**

Fiber Bragg Gratings



- Distributed Bragg reflector
  - Constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others
  - Achieved by creating a periodic variation in the refractive index of the fiber core
- Can be used to measure strain or temperature (or both)
- By adjusting frequencies many sensors multiplexed on one fiber path

Optical Fiber Properties

- Silica fiber survives to 1100°C; Sapphire to 2000°C
- Standard UV-written gratings in silica fiber survives to 500°C
- Special gratings can survive to 800 - 1000°C
- Work in progress at NASA Dryden and Intelligent Fiber Optic Systems (IFOS)

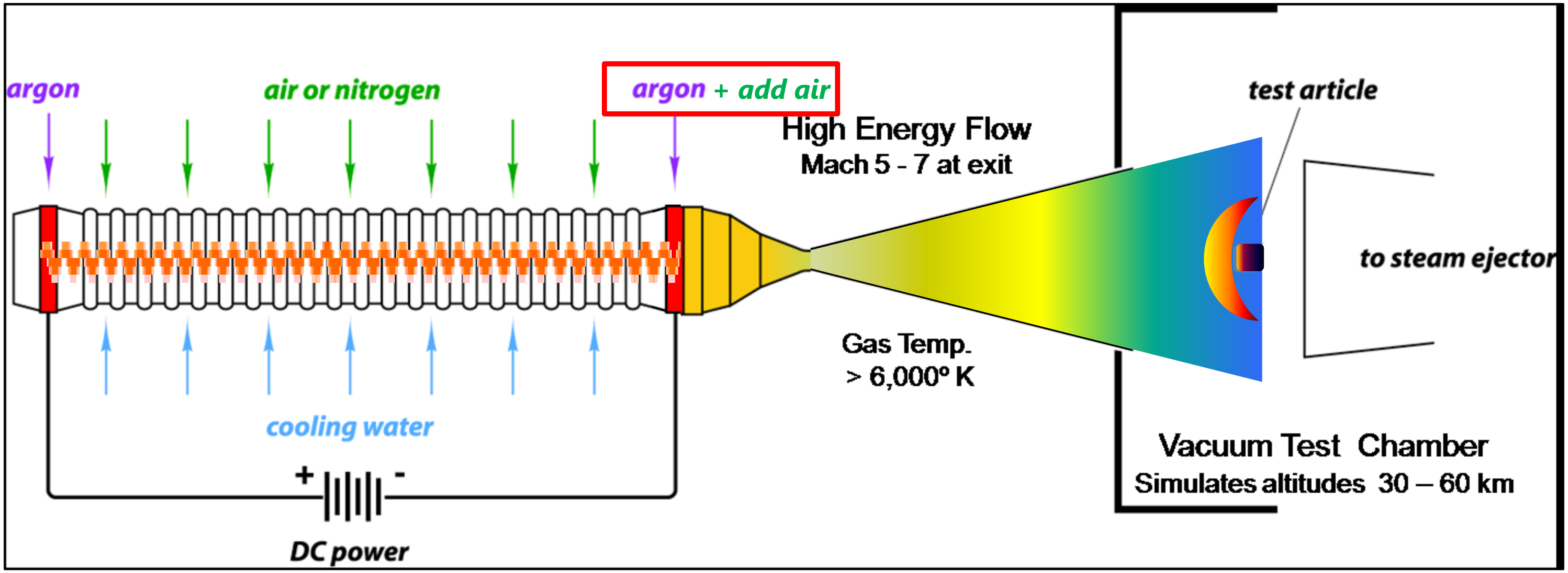
For Further Reading

- Measurement Systems: Application and Design, E.O. Doebelin, McGraw-Hill, 1983
- Guelhan, A., Burkard, E., et al, "Comparative Heat Flux Measurements on Standard Models in Plasma Facilities", AIAA Paper No. 2005-3324, June 2005
- Cauchon, Dona L., "Radiative Heating Results From the FIRE II Flight Experiment at a Reentry Velocity of 11.4 KM per Second", NASA TM X-1402, 1967
- Slocumb Jr., T.H., "Project Fire Flight II Afterbody Temperatures and Pressures at 11.35 KM per Second", NASA TM X-1319, 1966
- Lee, D.B., Goodrich, W.D., "The Aerothermodynamic Environment of the Apollo Command Module During Superorbital Entry", NASA TN D-6792, April 1972
- Milos, *Journal of Spacecraft and Rockets* 34, 705-713 (1997)
- Planetary Mission Entry Vehicles Quick Reference Guide, v1, NASA Ames, 2003
- Gardon, R., ''An Instrument for the Direct Measurement of Intense Thermal Radiation'', *Rev. Sci. Instrum*., 24, No. 5, pp. 366–370, 1953
- Fields, R.A., "Flight Vehicle Thermal Testing with Infrared Lamps", NASA TM 4336, 1992
- Marschall, J., Squire, T., Huynh, L., Chen, Y.K., Bull, J., "Analysis Approaches for Temperature Measurements from the SHARP-B2 Flight Experiment", SHARP Documentation A9FP-9901-XD03 NASA Ames Research Center, 1999
- Manual On The Use Of Thermocouples in Temperature Measurements, 4th Edition, ASTM Manual Series: MNL 12, American Society for Testing and Materials, Philadelphia, PA, 1993.
- Hartman, G.J., Neuner, G.J., "Thermal and Heat Flow Instrumentation for the Space Shuttle Thermal Protection System", ISA
- Wakefield, R.M., Pitts, W.C., "Analysis of the Heat-Shield Experiment on the Pioneer-Venus Entry Probes", AIAA Paper No. 80-1494, July 1980

Backup

IHF Arc-jet Facility

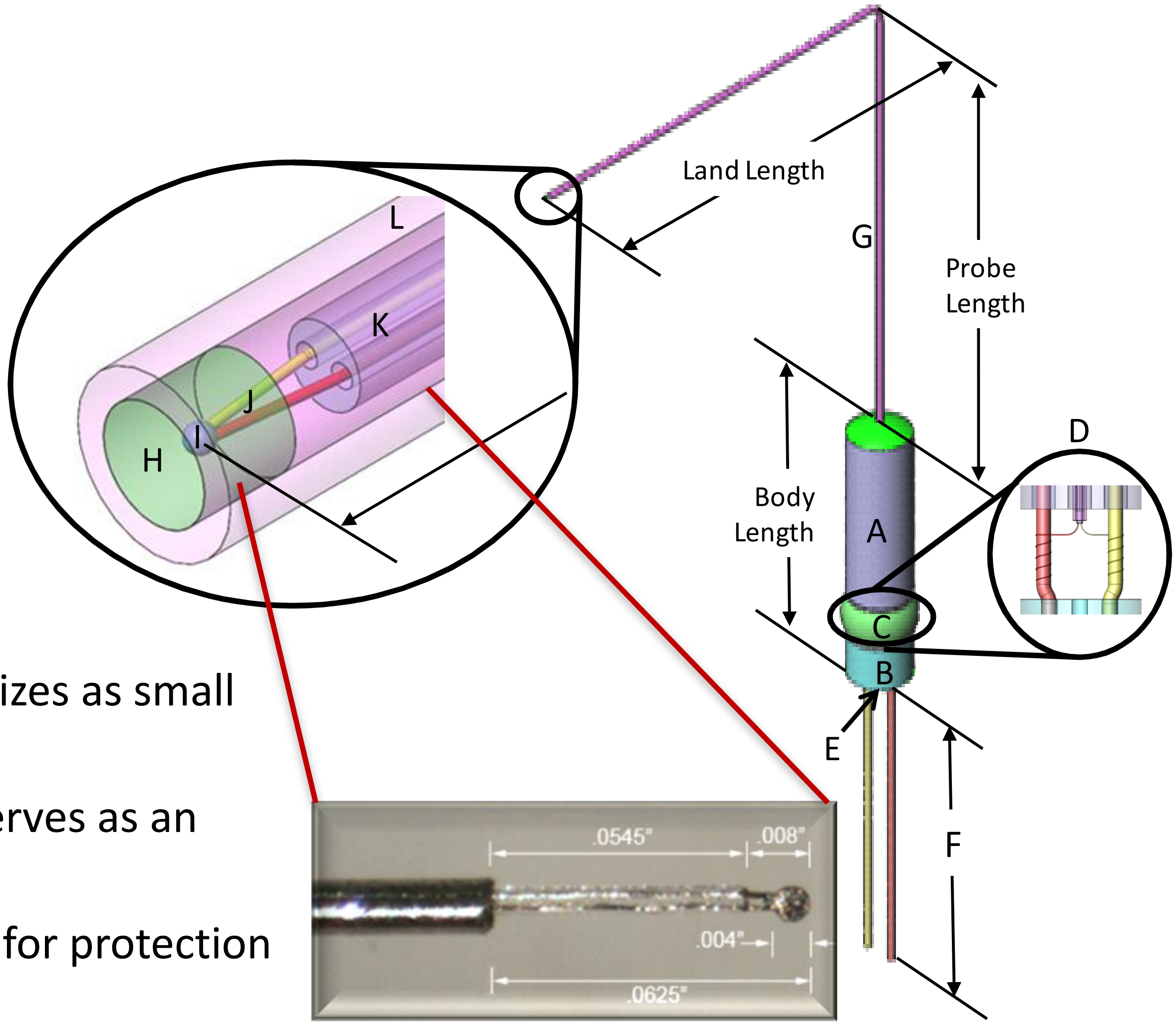
- 60MW constricted arc-heated plasma wind tunnel for heat shield material test and qualification
- Pressures from 1 to 9 atm, stagnation pressures from 0.01 to over 1 atm
- Enthalpy levels from 7 to 47 MJ/kg, heat fluxes from 5 to >6000 kW/m^2
- Interchangeable conical nozzles with exit diameters ranging from 152 mm (6”) to 1 m (41”),
- Stagnation, free jet wedge, swept cylinder, or flat panel with semi-elliptic nozzle



SMART* Sensor Design

(*Sheathed Miniature Aerothermal Reentry Thermocouple)

KEY	
A	Front Ferrule
B	Back Collar
C	3M 1838 Epoxy over Ceramabond 569 Cement covering welded area
D	Transition area of fine wire wrapped and welded to lead wire
E	3M 1838 Epoxy over teflon tube and back face of back collar
F	Teflon covered lead wire
G & L	Sheath
H	Boron Nitride V
I	Junction
J	Fine wire
K	Double bore quartz tube

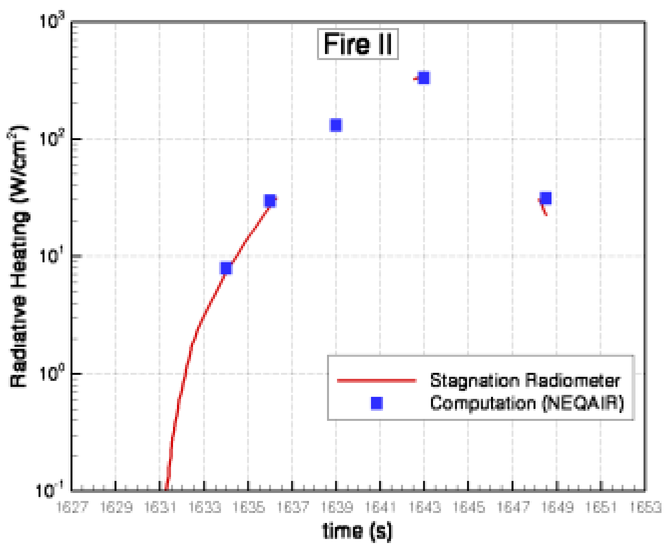


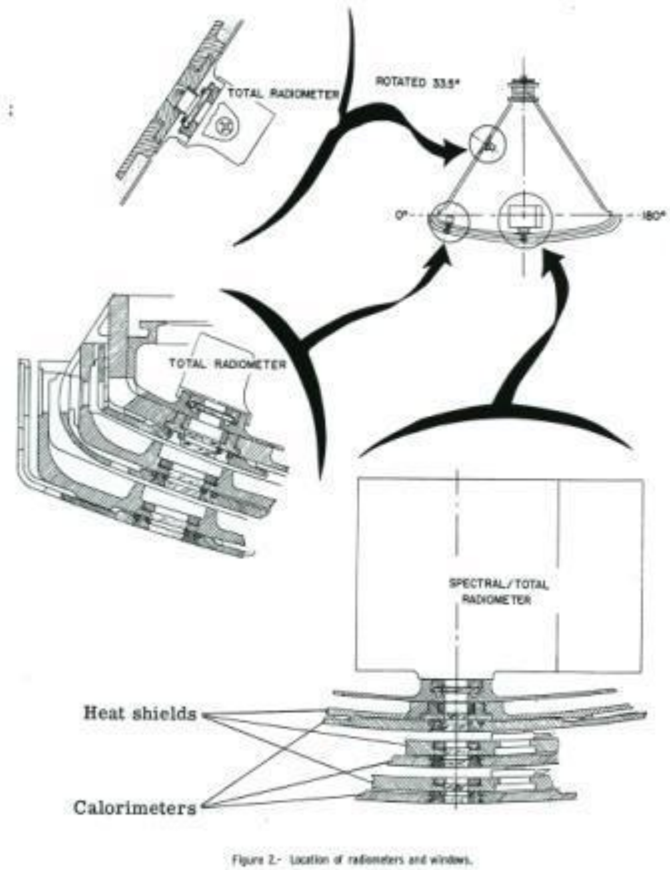
- Fine thermoelement wire sizes as small as 0.0005-in dia.
- 0.004-in dia. quartz tube serves as an electrical insulator
- 0.008-in O.D. metal sheath for protection from corrosion

Radiation Instruments

Radiation Flight Data Sources:

- Fire I&II (Radiometers, Spectrometers)
- Apollo AS-201,AS-202, 4, 6 (Radiometers)
- PAET (Spectrometers)
- Shuttle (Radiometer)
- BSUV 1 & 2 (Spectrometers)
- DEBI (Spectrometers)
- Other DoD Payloads (primarily Spectrometers)

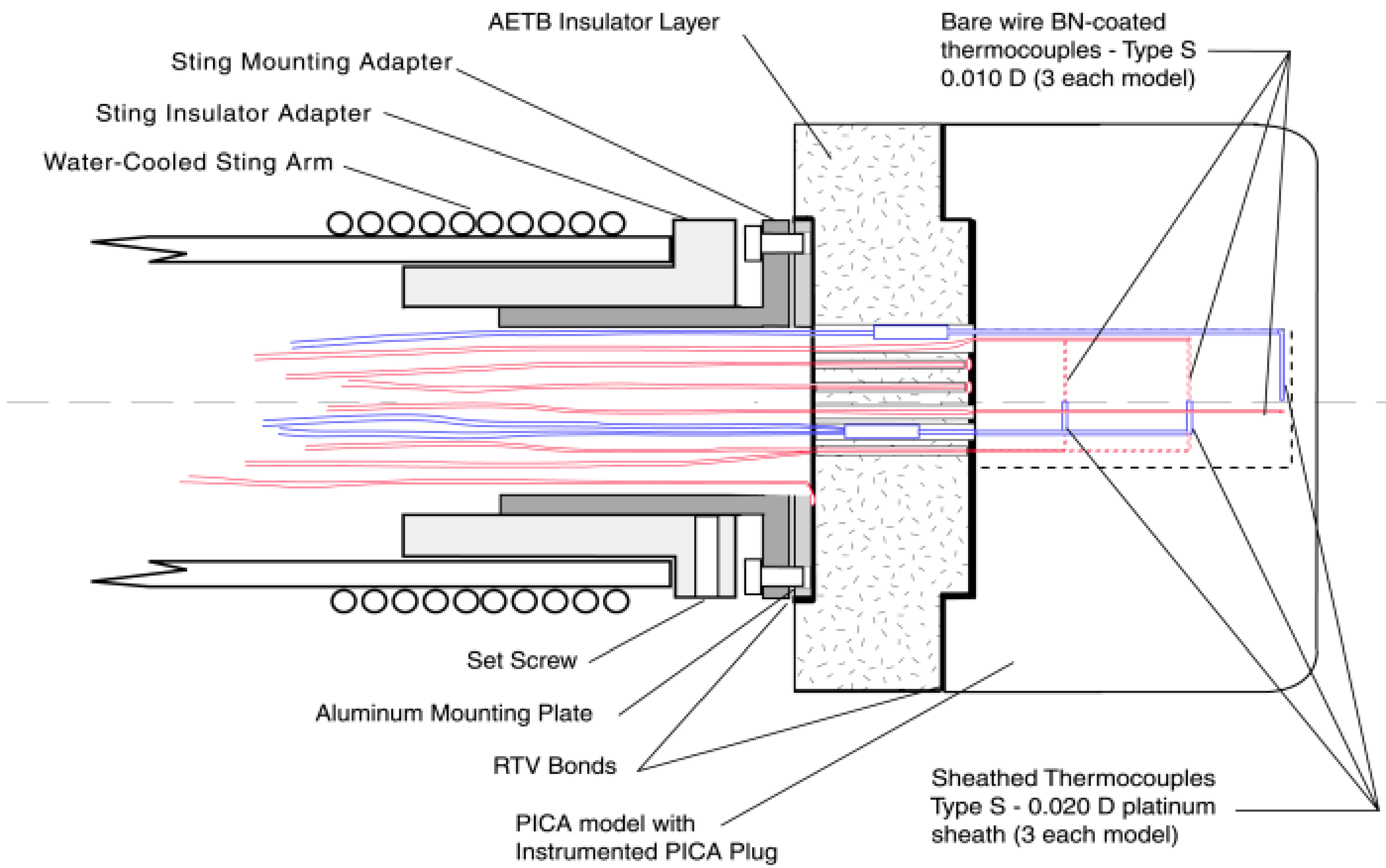




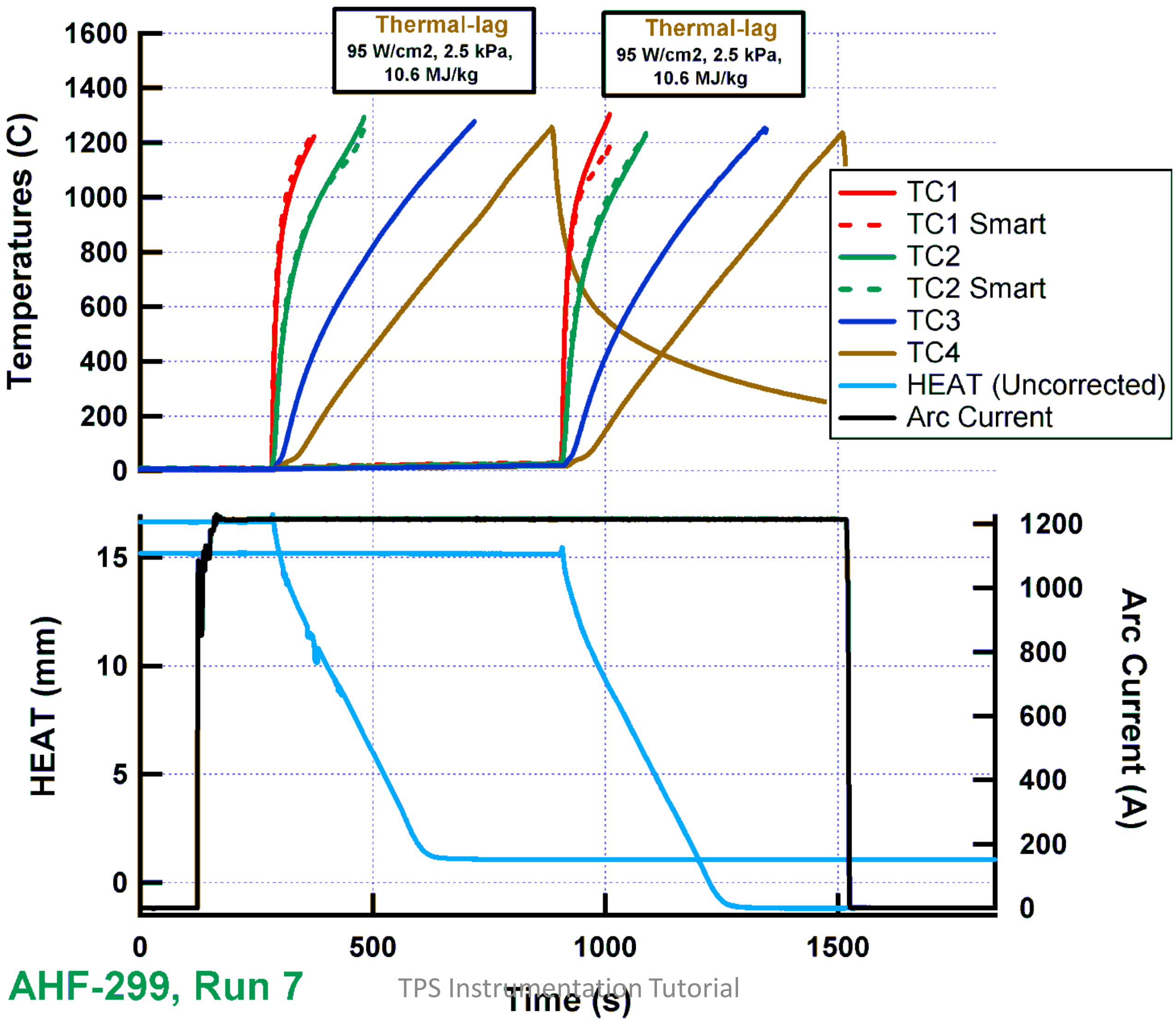
FIRE II
NASA TM X-1402

Application to TPS ArcJet Models
PICA Model

4-inch PICA Model Assembly (Revision A)



Run 7: TCs and Heat sensors produced useful data



AHF-299, Run 7

TC-2 Near surface Type K compared with “Smart” Type-K

Entry Systems and Technology Division