Calorimetry at the NASA Ames Arc Jet Complex

Joe Hartman

Sierra Lobo, NASA Ames Research Center, Moffett Field, CA

and

Megan E. MacDonald

NASA Ames Research Center, Moffett Field, CA

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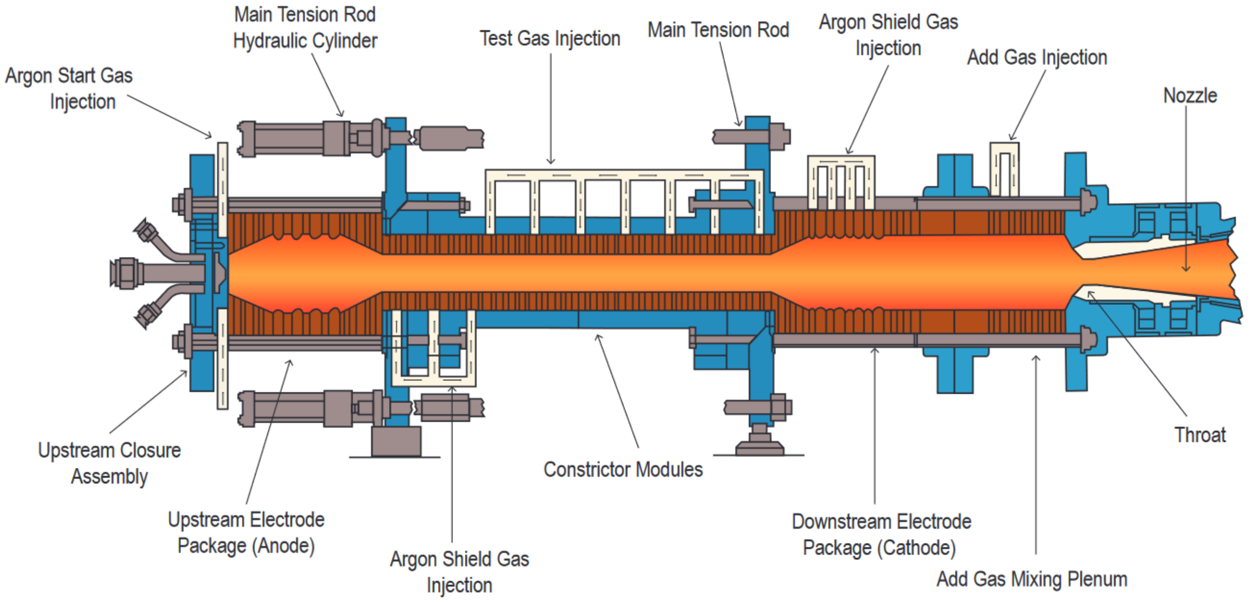
NASA Arc Jet Complex

- 60 MW Interaction Heating Facility (IHF)
- 20 MW Aerodynamic Heating Facility (AHF)
- 10 MW TP3
- 20 MW Panel Test Facility (PTF)
- 20 MW 2x9 Turbulent Flow Duct (TFD)

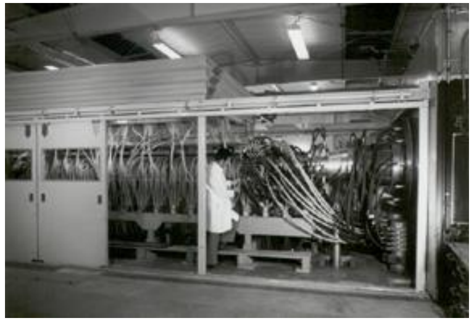
- Gases
  - Air
  - Nitrogen
  - Oxygen
  - Carbon Dioxide

Supersonic Test Stream from Arc Heater

- Segmented-constricted arc heaters which operate at pressures from 0.1 to 1 MPa and enthalpies from 5 to 28 MJ/kg
- Various nozzles available, from 7.6 cm (3 in) which can produce heat flux as high as 4.5 kW/cm^2 to as large as 76 cm (30 in)
- Can operate in stagnation, free jet wedge, or flat panel test configurations for simulated hypersonic boundary layer flow environments

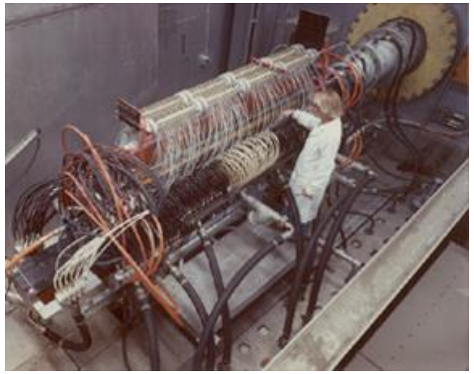


NASA Arc Jet Complex Test Legs

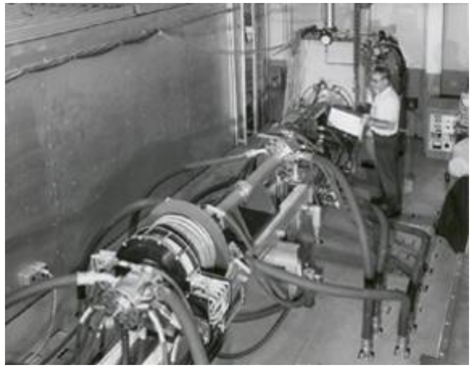


Interaction Heating Facility
60 MW - TPS Free Jet Testing

Panel Test Facility
20 MW - TPS Panel Testing



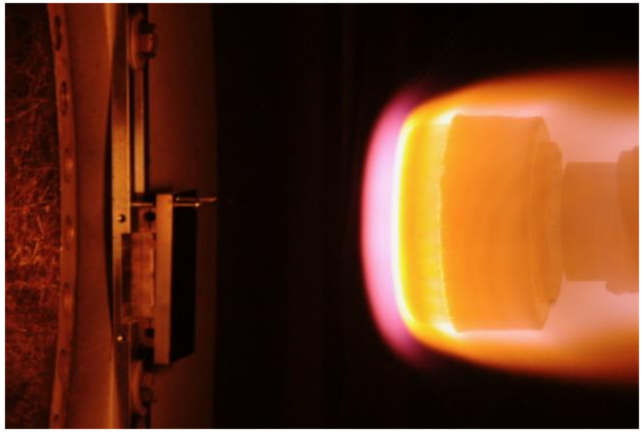
Aerodynamic Heating Facility
20 MW - TPS Free Jet Testing



2”x9” Turbulent Flow Duct
20 MW - TPS Panel Testing

Calorimetry

- A selection of heat-flux sensing devices for characterizing the flow environment for both stagnation and flat-plate tests
  - Variety of sizes and ranges
  - Water cooled for continuous operation
  - Transient, uncooled sensors



Thermal Capacitance (Slug) Calorimeter - 1

- The primary sensors for characterizing centerline stream conditions have been slug-type calorimeter probes
  - Hemispherical probes: 2.4, 3.0, and 4 in (6.1, 7.6, and 10 cm) diameter
  - Flat-faced cylinders: 4.0, 5.0, 6.0, and 8.0 in (10, 13, 15, and 20 cm) diameter
  - Iso-q (base diameter = nose radius) geometry

Representative slug calorimeters:
3 in hemisphere, 4 in iso-q, and 6 in flat

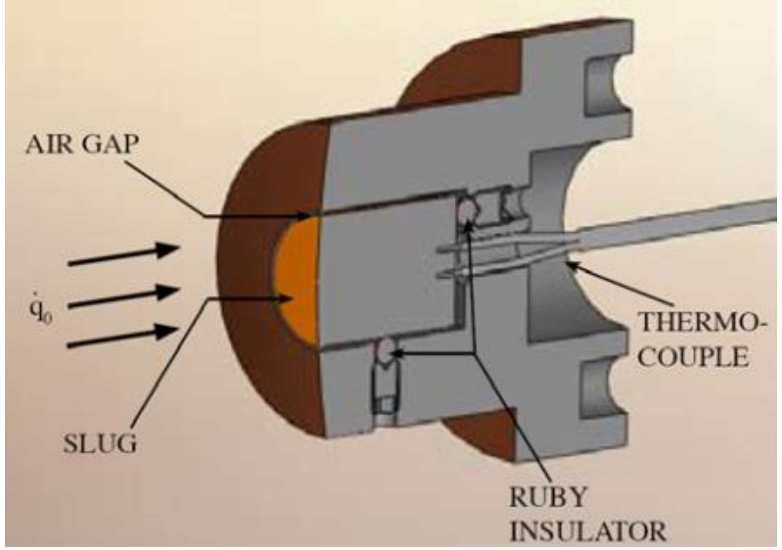
Thermal Capacitance (Slug) Calorimeter - 2

- NASA Ames design by Lewis A. Anderson in ~1964
  - cylindrical slug made of oxygen free high conductivity (OFHC) copper
  - slug is insulated with an Air Gap against the rest of the calorimeter body and held in position through ruby balls

- Calibration is not required – use first principles and known material properties

- This design was used for the SRI calorimeter used in the Round Robin I[1] (1966) and Round Robin II[2] (1968) Test Series

- 100 to 2000 W/cm^2 (88 to 1750 Btu/s/ft^2)



Principle setup of a slug calorimeter [3]

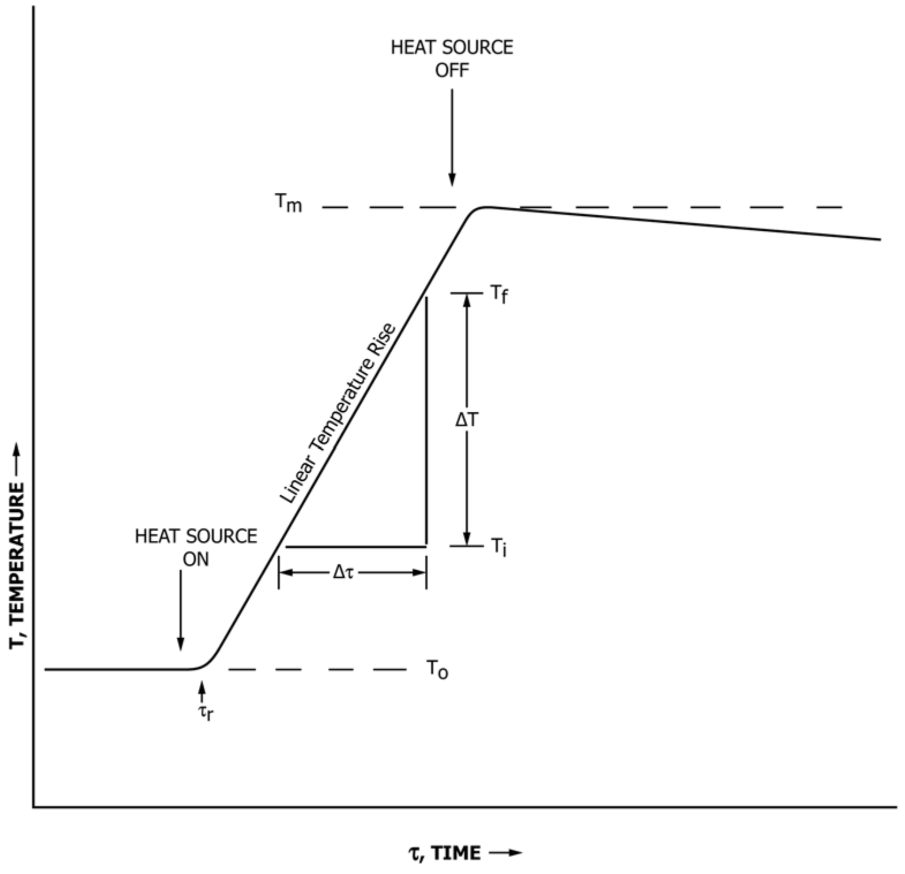
1 Hiester, N.K. and Clark, C.F., "Feasibility of Standard Evaluation Procedures for Ablating Materials," NASA CR-379, Feb. 1966
2 Hiester, N.K. and Clark, C.F., "Comparative Evaluation of Ablating Materials in Arc Plasma Jets," NASA CR-95378, Feb. 1968

3 Terrazas-Salinas, I., Carballo, J. E., Driver, D. M., and Balboni, J. A., "Comparison of Heat Transfer Measurement Devices in Arc Jet Flows with Shear," 10th Thermophysics Conference, AIAA, 2010

Thermal Capacitance (Slug) Calorimeter - 3

- ASTM E457, *Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter*
  - provides information/guidance for use of the slug calorimeter, including
    - Summary of Test Method
    - Significance and Use
    - Description of the Instrument
    - Characteristics and Limitations
    - Procedure for Selection and Use
    - Precision and Bias
- Measured Heat Flux:

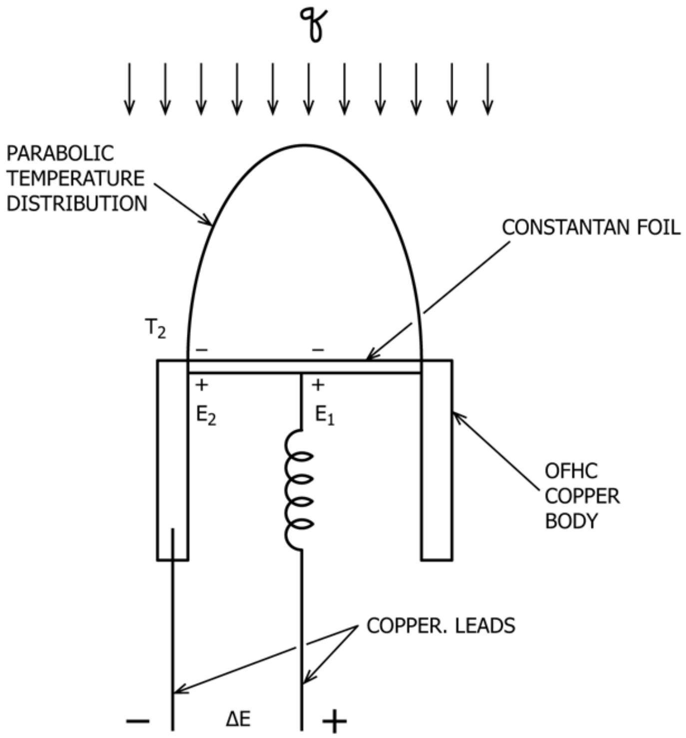
$$q_c = \rho C_p l\ (\Delta T/\Delta\tau) = (MC_p/A)\ (\Delta T/\Delta\tau)$$



Typical Temperature–Time Output Curve for Slug Calorimeter

Copper-Constantan Circular Foil Heat Flux Transducer (Gardon Gage) - 1

- The center – perimeter temperature difference produces a thermoelectric potential, E, that will vary in proportion to the absorbed heat flux[1]
- Calibration by radiant source at manufacturer
- Nearly linear output over a gauge temperature range from –45 to 232 °C (–50 to 450 °F)
- Requires either water cooling of the body with a surrounding water jacket or conducting the heat away with sufficient thermal mass
- Fast response, sweeps possible
- 1 to 2000 W/cm^2 (0.88 to 1750 Btu/s/ft^2)



Sectional view of a Gardon Gage

1 Gardon, R., "An Instrument for the Direct Measurement of Intense Thermal Radiation," The Review of Scientific Instruments, Vol 24, No. 5, May 1953.

Copper-Constantan Circular Foil Heat Flux Transducer (Gardon Gage) - 2

- ASTM E511 *Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil Heat Flux Transducer*
  - provides information/guidance for use of the Gardon Gage calorimeter

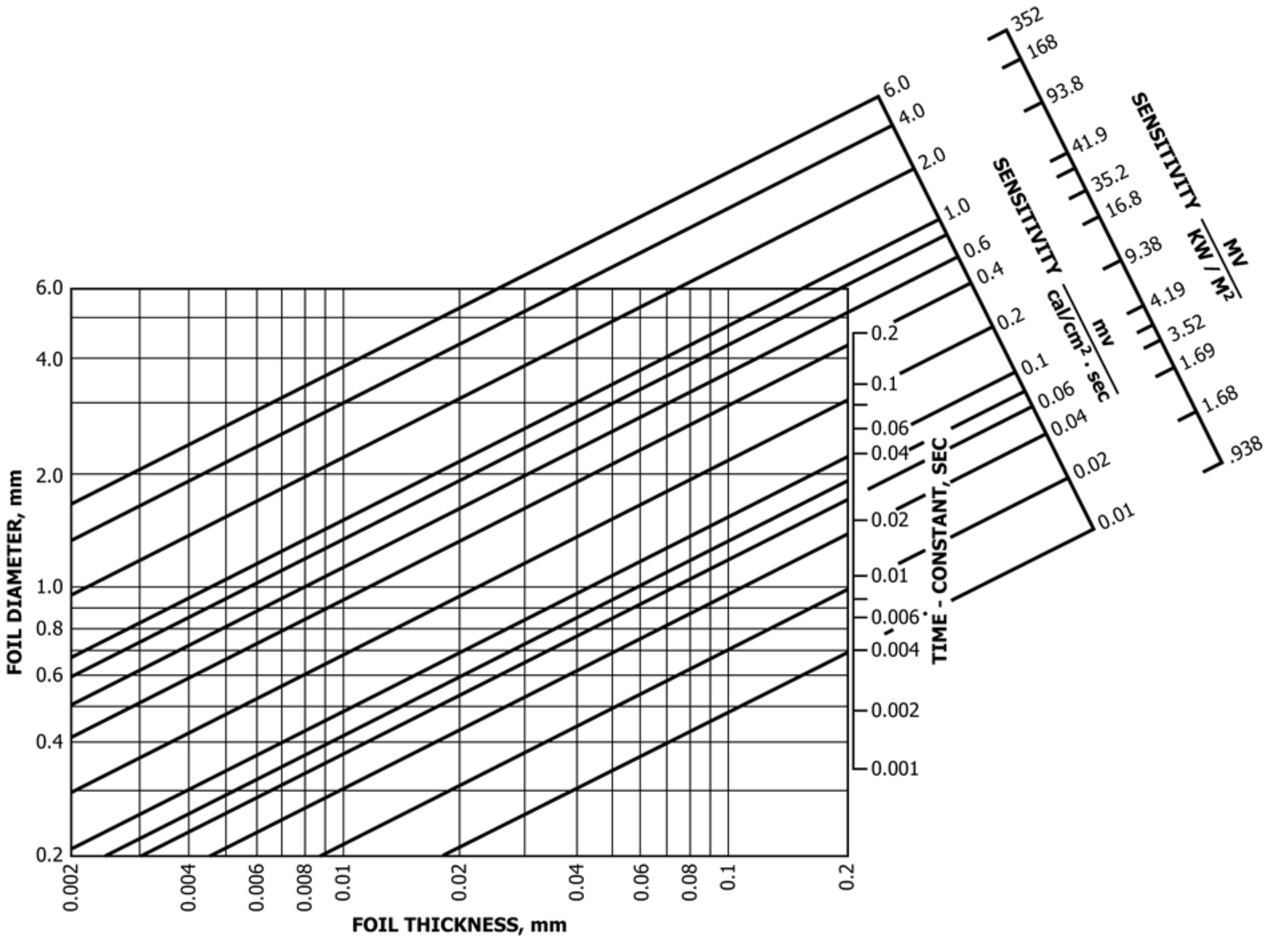


Chart for Design of Copper-Constantan Circular Foil Calorimeters (SI Units) (from E511)

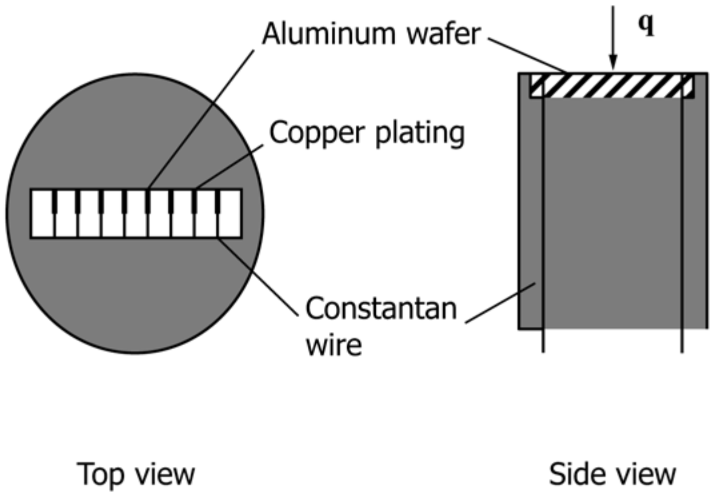
Flush-Mounted Insert Temperature-Gradient Gages

- Measurement of the temperature gradient normal to the surface to determine the heat that is exchanged to or from the surface

- The Wire-Wound Gage, generally known as the Schmidt-Boelter Gage, is being used as a replacement for the Gardon Gage in certain applications

- is quite broad in its field of application, size and construction

- Refer to ASTM E2683, *Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages* for a thorough discussion of the various designs and configurations of this type of gage



Schematic of a Wire-Wound Heat-Flux Gage

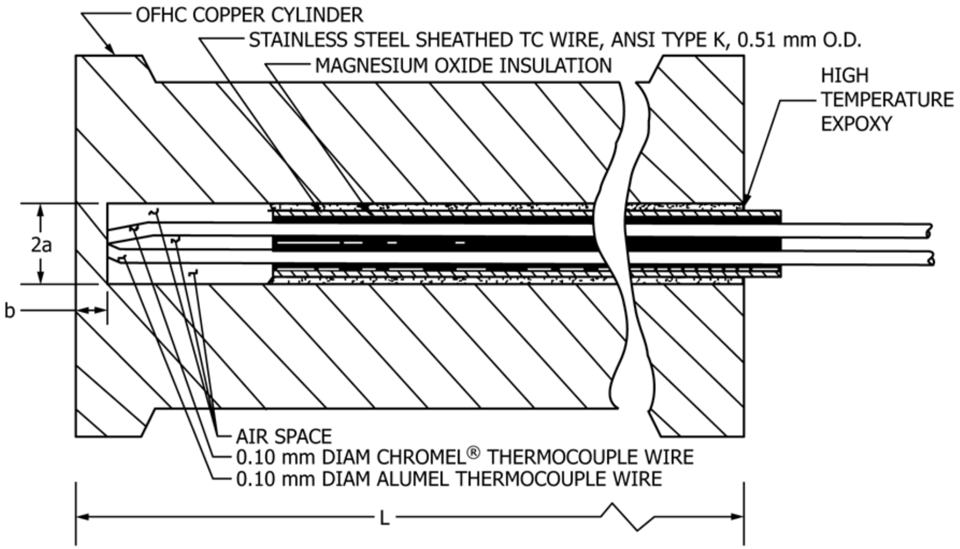
Calorimetry - Transient

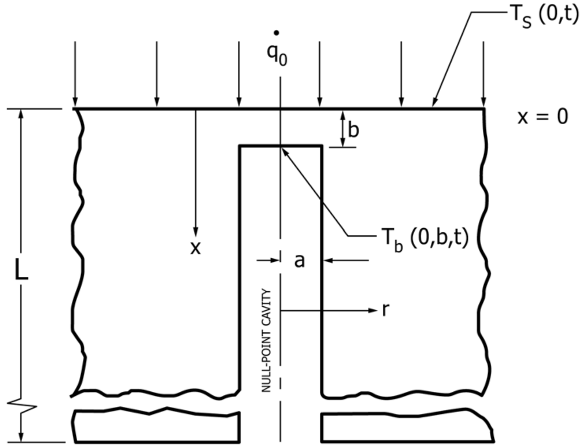
- Null point calorimeters and coaxial thermocouple gages are used to map the distribution of stagnation point heat flux across the test stream
  - 15°-taper cones: 0.18 in (4.6 mm) and 0.25 in (6.4 mm) nose radius
  - Hemispherical, iso-q-shaped and flat-faced bodies of 1 in (25 mm), 2 in (50 mm), and 4 in (100 mm) nose radii

representative null-point calorimeters:
4-in iso-q , 4-in hemisphere, and a
small-diameter sphere/cone

Transient Null Point Calorimeter - 1

- Measures the heat flux to the surface of a solid using the measured transient temperature rise of a thermocouple located at the "null point" of a semi-infinite solid
  - the null point condition is achieved at the end of a hole drilled in the semi-infinite body such that the end of the hole is one hole radius from the heated surface
  - at the "null point" the measured transient temperature rise is the same as the surface temperature history of a semi-infinite solid subjected to the same incident heat flux[1]





- The null point calorimeter has fast response, high sensitivity, but is difficult to manufacture

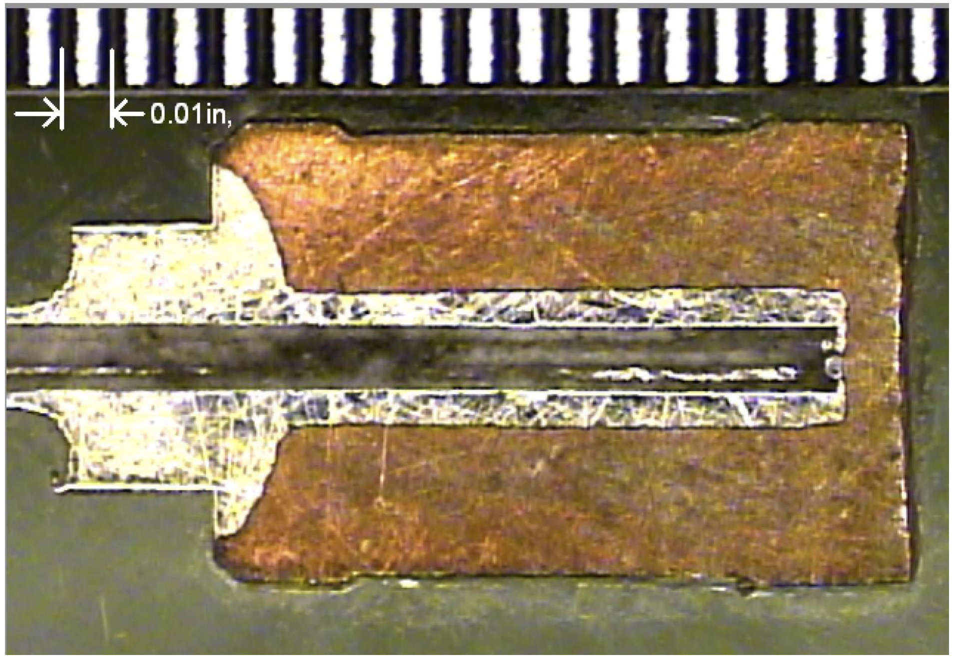
1 Kennedy, W. S., Rindal, R. A., Powars, C. A., "Heat Flux Measurement Using Swept Null Point Calorimetry," AIAA Paper No. 71-428

Transient Null Point Calorimeter - 2

- The swept null point technique has been utilized to successfully perform flow field surveys in all NASA/Ames arc jets

- “Multiple calorimeter exposures in the AFFDL 50 MW arc jet facility in conjunction with numerical error analyses considering design constraints and manufacturing variations reveal that a swept null point calorimeter may be repeatedly used to measure heat flux levels up to 20,000 Btu/ft^2-sec with +/- 10% accuracy”[1]

- ASTM E598, *Measuring Extreme Heat-Transfer Rates from High Energy Environments Using a Transient Null Point Calorimeter*
  - provides information/guidance for use of the Null Point Calorimeter



Section View of 1/8-inch Diameter Null Point Calorimeter

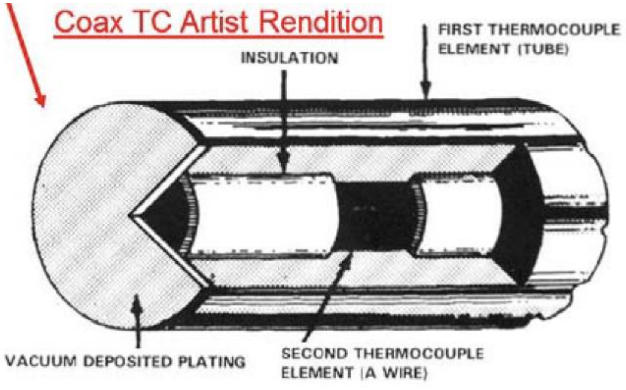
1 Kennedy, W. S., Rindal, R. A., Powars, C. A., “Heat Flux Measurement Using Swept Null Point Calorimetry," AIAA Paper No. 71-428

Coaxial Thermocouple (COAX) Calorimeter- 1

- Manufacture of a COAX TC[1]:

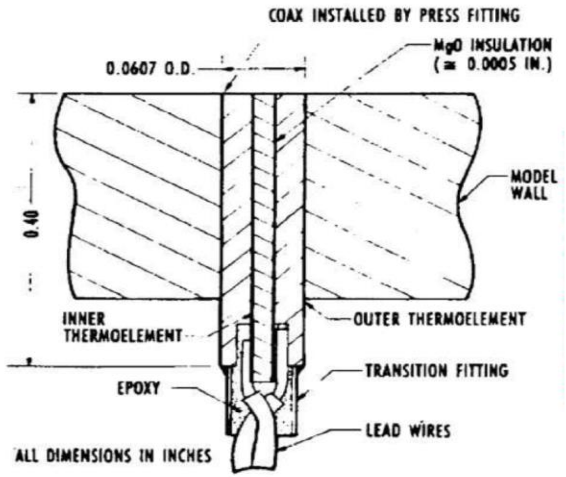
Medtherm CoaxTC Bulletin 500 *COAXIAL SURFACE THERMOCOUPLE PROBES*

One thermocouple element (a tube) is swaged over the second element (a wire) with 0.0005" thick insulation between the elements. The Thermocouple junction is formed by a vacuum deposited metallic plating across the sensing end of the assembly. (Artist's rendering shows thickness of insulation and metallic plating exaggerated in size.)



AEDC CoaxTC NASA1992CP_3161Kidd

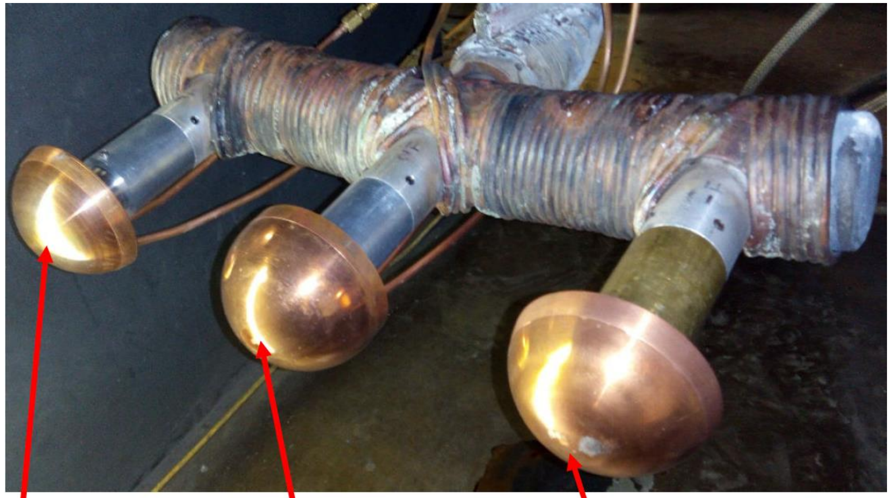
The three component unit (Wire, InsulationMgO, tube) is drawn down from 0.125" to 0.067" with the possibility of going as small as 0.015". The hot junction is completed by abrading the center conductor and outer tube together with #180 grit emery paper.



1 Driver, D., Philippidis, D., Terrazas-Salinas, I., "Uncertainty Analysis of Coaxial Thermocouple Calorimeters used in Arc Jets," AIAA, 2018

Coaxial Thermocouple (COAX) Calorimeter- 2

- This new type of sensor has become so attractive that we are considering relying more heavily on it for the primary measurement of stagnation heat flux in the NASA Ames arc jets[1]
  - Coaxial TC truly measures the surface temperature
  - The 1D finite slab inverse analysis algorithm for calculating heat flux from the coaxial TC data follows that of a Null Point calorimeter
- ASTM Standard is being prepared by Subcommittee E21.08

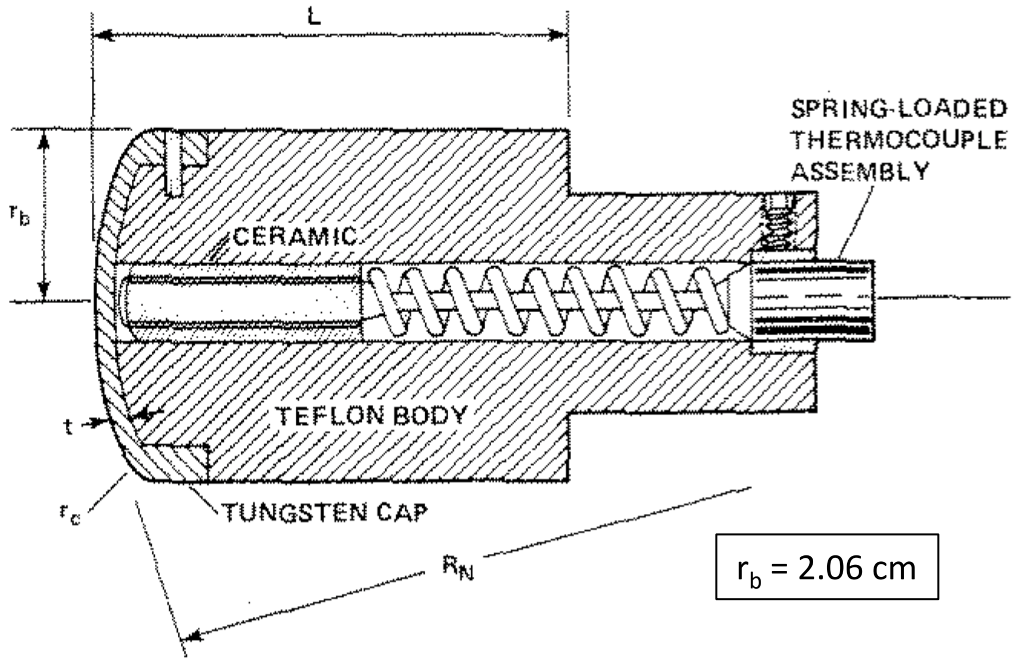


102mm Hemi Heat Flux Measurements with Various Sensors

1 Driver, D., Philippidis, D., Terrazas-Salinas, I., "Uncertainty Analysis of Coaxial Thermocouple Calorimeters used in Arc Jets," AIAA, 2018

Unique Thin-Skin Calorimeter

- A unique calorimeter used in the Giant Planet Facility (GPF)[1]
    - GPF was rated at 100 MW and operated with a hydrogen-helium gas mixture to produce a stagnation-flow region with simultaneous high radiative and convective heating
- A light plastic sabot was used to protect the calorimeter during the time required to insert the calorimeter into the stream centerline
    - aerodynamic forces removed the sabot in about 8 msec, which ensures a step-function heating pulse
- Measured 15 kW/cm^2 convective and 6 kW/cm^2 radiative
- ASTM E459, *Measuring Heat Transfer Rate Using a Thin-Skin Calorimeter*



Thin-Skin, Transient, Expendable Calorimeter Design

1 Winovich, W. and Carlson, W. C. A.,"THE GIANT PLANET FACILITY", 25th ISA Symposium, 1979

Acknowledgements

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Send questions to…

joe.hartman@nasa.gov
megan.e.macdonald@nasa.gov

Questions?

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division