

# Challenges with Heat Flux Calorimeters used in Arc Jets

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Occasionally large errors have occurred in some of the calorimeters used in the arc jet facilities. Some slug calorimeters would measure twice the expected heat flux and some Coaxial TC calorimeters would measure half the expected heat flux. While these errors in heat flux measurements are easy to identify and discard / dismiss, the concern is that less spectacular errors are difficult to detect. This inspired a critical look at the calorimetry used to measure stagnation heat flux in the NASA Ames Arc Jet facilities. Numerous sources of error were investigated, and the culprit in the case of slug calorimeters was determined to be leaks in the stagnation calorimeter assembly resulting in flow along the side of the slug. In the case of the coaxial TC calorimeter, it is hypothesized that in some calorimeters there is a partial electrical short circuit in the Coaxial TC sensor element somewhere in the middle of the calorimeter.

## Nomenclature

$C_p$	=	Heat capacity of the material, J/K-kg
$H_r$	=	Recovery enthalpy, MJ/kg
$k$	=	Thermal conductivity of the material, W/m-K
$L$	=	Thickness of spherical shell, m
$M$	=	Mach number
$p$	=	Pressure, Pa
$q$	=	Heat flux, W/cm <sup>2</sup>
$r$	=	Radial distance from the centerline of the jet, m
$R$	=	Radial distance from the center of the sphere, m
$R_o$	=	Radius of curvature of the nose of the model, m
$T$	=	Temperature, K
$t$	=	Time since the start of exposure to the arc heated flow, s

## I. Introduction

Arc jet facilities deliver high enthalpy plasma to a test article producing realistic heating environments characteristic of entry into the atmosphere of planets and moons in the solar system. Thermal Protection System (TPS) developers rely on the arc jets to validate their designs. Knowing the heating environment in the arc jet is of paramount importance to the development effort.

Copper slug calorimeters [1] have been the main-stay of stagnation heat flux measurements in arc jet testing for the last several decades (see Fig. 1). They do not require calibration but rather rely on first principles. From an accuracy point of view, the only real concerns were conduction losses through the ruby balls used to hold the slug in place [2], and the unknown convection effects through the gap between the slug and its holder. Operationally, the main limitation of the slug calorimeter is the need to dwell in the flow for a sufficient period of time to get a steady state measurement, and not dwell so long as to overheat or melt the slug. Temperature is measured by a thermocouple attached to the back side of the slug. The rate of temperature change with time is used to deduce the heat flux incident on the front face of the slug. There is a short time delay between when the temperature rise begins and when the heat

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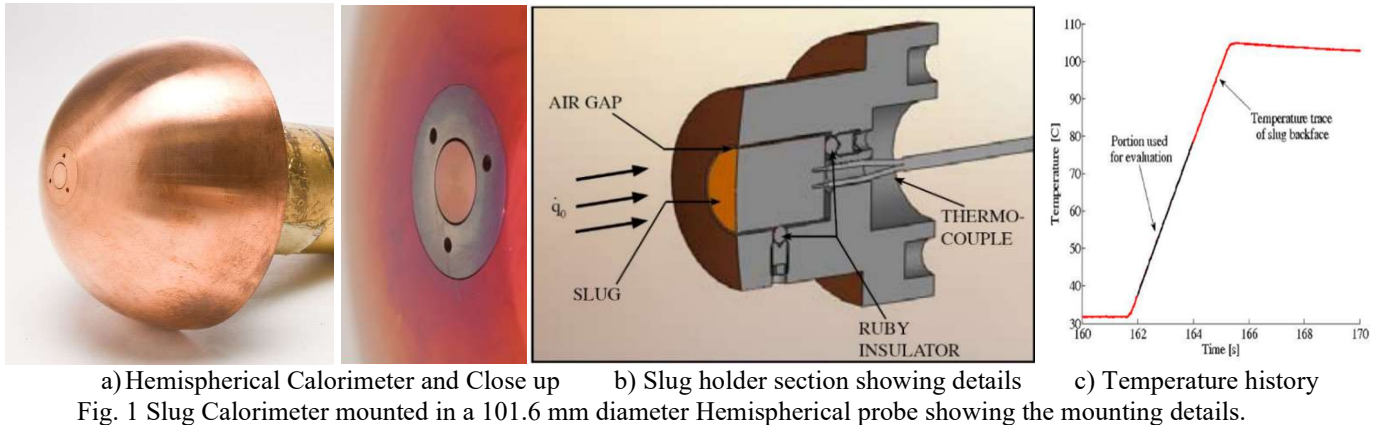
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is first applied to the front face of the slug. This device is well suited for measuring heat fluxes that are steady, but not so useful for measuring rapidly changing heat flux levels, such as those encountered during flow field surveys.



Unfortunately, there have been occasions when the slug calorimeters have measured unrealistically high levels of heat flux, significantly higher than that predicted by theory of Fay-Riddell [3] using the Zoby correlations for gas constants [4] ( $q_{FayRiddell} = H_{centerline} K \sqrt{P_{stagnation}/R_{nose}}$ ). Enthalpy used in the Fay-Riddell is estimated from either sonic flow analysis [5] or from an energy balance on the arc heater. Note that the enthalpy is typically very uniform across the jet.

The reason for the slug calorimeters measuring unrealistically high was not known at the time. Repeat measurements with different calorimeters were used to rule out and dismiss the unrealistically high measurements. When 3 repeat measurements give the same answer to within 15% then materials testing would commence.

Coaxial thermocouple calorimeter (Coaxial TC) [6] are another tool for measuring heat flux. A thermocouple sensor, in the shape of a cylinder, is constructed by swaging a copper tube around a slender constantan pin (coaxial centered inside the tube) – the two elements (pin and tube) are separated (electrically) by a thin layer of insulation (MgO) sandwiched between them. One end of the cylinder (windward tip) is coated with copper (via vapor deposition) creating an electrical junction between the constantan pin and the outer copper tube. Constantan and copper lead wires are attached to the corresponding elements on the other end (backside) of the cylindrical tube. These sensors are commercially available from Medtherm [7] and Arnold Engineering Development Center (AEDC) [6] mounted them into copper bodies of various shapes and sizes. An example of this is the 9mm diameter sphere cone coaxial TC calorimeter shown in Fig. 2.

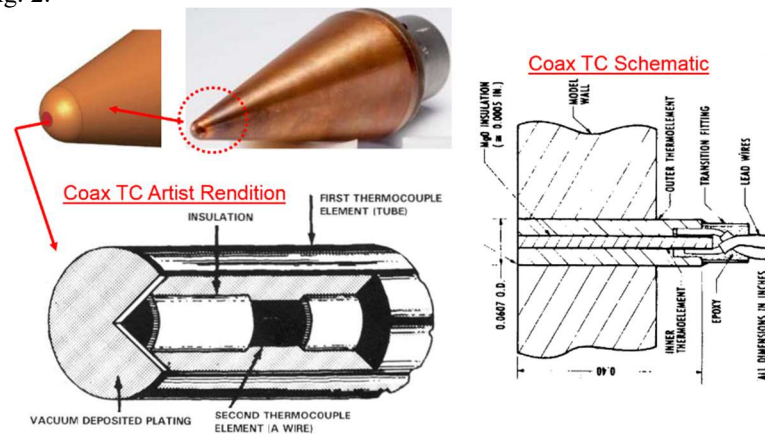


Fig 2. Coaxial TC Calorimeter built into a 9mm diameter sphere cone probe.

Similar to the slug calorimeter, the temperature of the Coaxial TC rises with time of exposure to heating, but unlike the slug calorimeter, the useful part of the thermocouple's time history is in the early stages of the transient before the heat wave reaches the backside of the Coaxial TC sensor (after which the 1D analysis becomes more complicated). The analysis follows that of a Null point calorimeter. [8].

Since the thermocouple junction is on the windward surface of the sensor, these sensors respond instantaneously to changes in heat flux, making them ideal for use in rapid sweeps through the arc heated flow, thus providing a distribution of heating with distance along the sweep. The analysis involves performing a 1D inverse numerical conduction analysis (implicit in time). The analysis is easily performed in today's computers, where it is possible to perform the analysis in real time as the arc jet is running.

While coaxial TC calorimeters are theoretically ideal for measuring heat flux, in practice it can be challenging to eliminate or correct the 2D effects associated with spherical nose and non-uniform heating distribution around the body (a violation of the 1D semi-infinite slab assumption used in the analysis) [9]. But a bigger issue is that some of the coaxial TC calorimeters appear to be dead or are slow to respond and measure heat fluxes that are low relative to Fay-Riddell predictions. Testing revealed that some of the coaxial TC calorimeters measured unrealistically low levels of stagnation heat flux (brown circles in Fig. 3). Here we recast the centerline heat flux in the form of centerline enthalpy using Fay-Riddell ( $H_{centerline} = q_{measured} K \sqrt{R_{nose}/P_{stagnation}}$ ). [10] This is done in the interest of comparing different size and shape calorimeters along with different stagnation pressures.

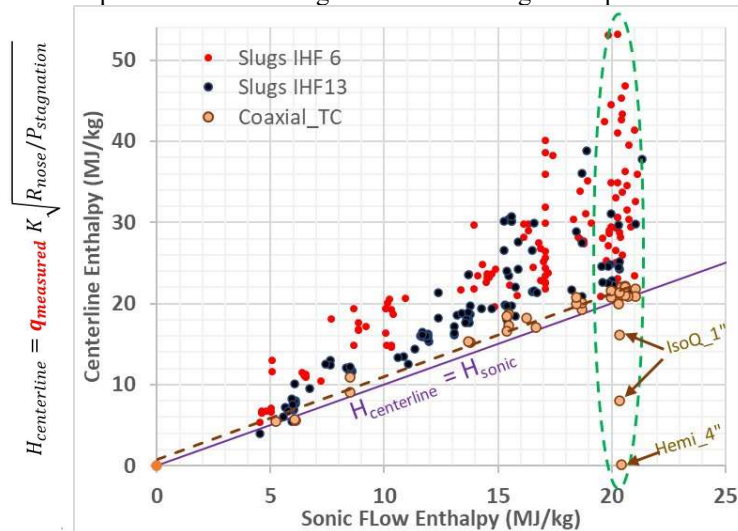


Fig. 3 Slug and Coaxial TC Calorimeter measurements in the IHF facility.

Tests were performed in the IHF 6" and IHF 13" nozzle at a large range of conditions. It appears that the problem of slugs measuring high occurs mainly in the 6" nozzle and to some extent in the 13" nozzle where the stagnation pressure is high. Repeatability is most egregious in the IHF 6" nozzle at the highest condition. It is interesting to note that the majority of measurements from the coaxial TC calorimeters agree well with the Fay-Riddell correlation, except for a few calorimeters. Also note that Coaxial TC calorimeters almost never measure higher than expected levels of heat flux. And slug calorimeters, almost never measure lower heat flux than predicted by Fay-Riddell. When the two instruments agree, then there is a high confidence in the measurement accuracy. To help understand the discrepancies between these instruments, a series of arc jet tests were conducted in the IHF 6" nozzle at the maximum condition (green oval in Fig 3.) Two objectives were pursued:

1. discover why some slug calorimeters measure unrealistically high levels of heat flux, and
2. discover which of the Coaxial TC calorimeters are flawed (measuring unrealistically low levels of heat flux) so that those calorimeters can be retired.

The majority of the paper focusses on the anomalous slug measurements.

## II. Slug Calorimeters Measuring Unrealistically High Levels of Heat Flux

It appears that the heating on some slug calorimeters is augmented by something other than convective heating to the face of the slug. Where does the additional heating come from? Conceivably, some of the augmentation in heating could be coming from any one of a number of different phenomena:

- 1) Electrical arc attaching to the slug?
- 2) Gentle flow of superheated gas coming in contact with TC wires on the backside of the slug?
- 3) Inductive Coupling between TC wires and the magnetic field in the arc heater or plasma?
- 4) Catalysis in the gap drawing in hot gas ( $O + O \rightarrow O_2$ , volume decrease – steady flow into gap)?
- 5) Free stream turbulence impinging on calorimeter?
- 6) Air flow in the gap heating the side of the slug?

This section describes the investigation into each of these possible sources of heating augmentation. Spoiler alert, it appears to be the last item on the list.

#### A. Electrical arc attaching to the slug

Electric arc attachment (joule heating) was considered and studied by measuring the voltage difference between the slug and the body of the calorimeter (which are electrically isolated from one another by non-conducting ruby balls). If charge particles from the plasma are electrically conducting back to the arc in the arc heater, one would expect to see a voltage difference between the slug and the calorimeter body (calorimeter body electrically grounded). Only small differences in voltage between the slug and the calorimeter body were seen (see Fig. 4).

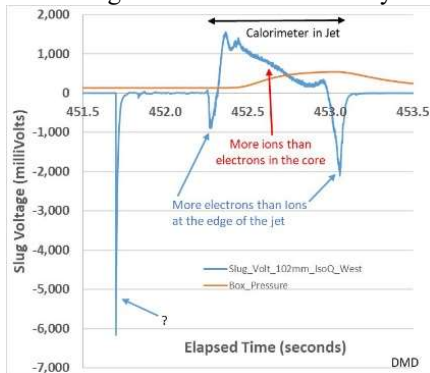


Fig 4. Voltage difference between the slug and calorimeter body during insertion into the flow

The difference in voltage between the slug and the calorimeter body was less than 2 volts, which was miniscule relative to the voltage drop across the arc heater (6000 volts). In the absence of a short circuit between the slug and calorimeter body, this seems to indicate that the plasma was not significantly conducting between the arc in the heater and the slug.

#### B. Gentle flow of superheated gas coming in contact with TC wires on the backside of the slug

Heating of the TC wires on the back of the slug, would likely be accompanied by a jump in temperature when the calorimeter exits the jet and passes into vacuum of the test chamber. There was no such jump in temperature.

#### C. Inductive Coupling between TC wires and the magnetic field in the arc heater or plasma

It is well known that magnetic fields can cause errors in thermocouple measurements. The arc jet plasma heated in the arc heater by electrical current is one potential source of a magnetic field, along with coils in the electrodes (carrying current) that are designed to stabilize the arc [11]. To test this theory, consider the following thought experiment. If magnetic fields are present in near proximity to the calorimeters, strong enough to induce a current in the thermocouples, then one would expect to see a jump in the thermocouple reading when the calorimeter is removed from the flow or when the arc is shut off. No such jump existed.

#### D. Catalysis in the gap drawing in hot gas ( $O + O \rightarrow O_2$ , volume decrease – steady flow into gap)

The gap between the slug and the slug holder is relatively narrow (0.010”), but not zero. The aerodynamic front face of the calorimeter (exposed to the flow) is acting as a 3<sup>rd</sup> partner in collisions between atoms that come together and form molecules such that the surface absorbs the energy released by the reaction. Perhaps recombination is happening in the gap as well. CFD studies have been performed on gaps (cavities) that are exposed to flow, and it has been shown that heat transfer (convective and catalytic) is relatively low relative to aerodynamic surfaces in direct contact with the flow.

#### E. Free stream turbulence impinging on calorimeter

In the literature [12] there are examples of stagnation heating being augmented to levels beyond that expected for laminar flow, with heating rate correlating with turbulence intensity of the free stream. Arc jets are typically turbulent in the plenum chamber, and there can be large variations in enthalpy due to poor mixing. For the purpose of comparing to data in the literature it is conservative to assume that the free stream turbulent intensity is on the order of 10%, from which a turbulent Reynolds number can be estimated. Data from the IHF 9” nozzle tests performed at maximum conditions are compared to the heating measurements seen in the literature. Here the heating rates measured by some

of the slug calorimeters far exceed the heating rates seen in the literature for comparable levels of turbulent Reynolds number. The figure implies that it unlikely that turbulence is the source of high heating seen by some of the slugs. Furthermore, why would turbulence effect only some calorimeters and not all calorimeters of the same size and shape.

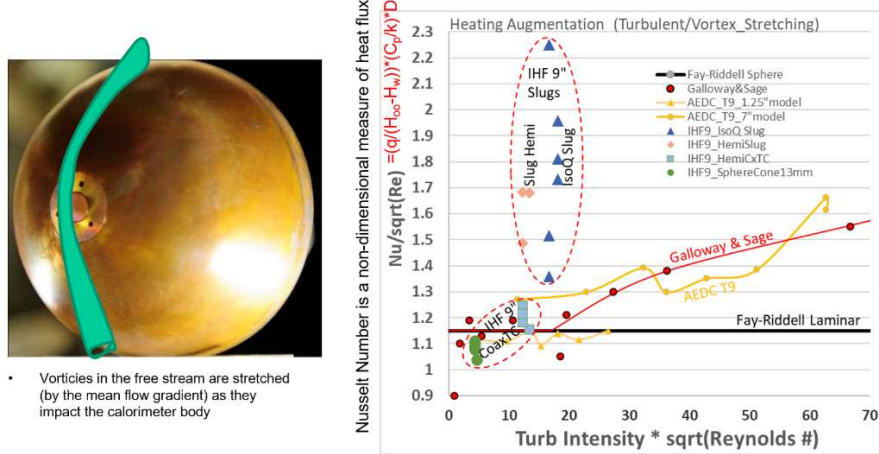


Fig. 5 Free stream turbulence effects on stagnation heating of blunt bodies

The augmentation in heating rate (over laminar flow) associated with turbulent free stream is far greater in the present arc jet studies than has been seen in past studies published in the literature.

**F. Air flow in the gap – heating the side of the slug**

CFD studies [13] have been performed on gaps (cavities) that are narrow relative to their depth, and it has been shown that heat transfer (convective and catalytic) on the cavity walls is quite low relative to the aerodynamic surfaces that the gaps are built into. If the flow were hitting the calorimeter at an angle perhaps the stagnation point would sit on top of the gap (rather than being centered on the middle of the slug). To test this scenario, the calorimeter was deliberately misaligned, by pitching the slug calorimeter 4.4° (relative to the axis of the jet) causing the flow to stagnate directly onto one portion of the gap (see Fig. 6). Note that all other portions of the gap are away from the stagnation point (where the surface pressure is lower).

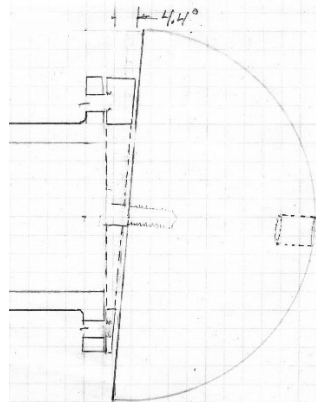


Fig. 6 Calorimeter deliberately pitched at angle of attack

This provides incentive for the flow to go into the gap at the stagnation point and out of the gap away from the stagnation point. Measurements were obtained for the case where the calorimeter was pitched relative to the centerline of the jet, followed by another run where the calorimeter axis of symmetry was aligned with the centerline of the jet. The resulting heat fluxes measured in these two cases was nearly identical. This result seemed to point to the gap not being the source of heating augmentation.

**G. Air flow in the gap – heating the side of the slug – Part 2**

If the augmentation in heating is not the issue, then plugging the gap (or partially plugging the gap) should make no difference to the heat flux measurement. The plan was to run calorimeters in the arc jet as usual, and when a calorimeter measured an unrealistically high level of heat flux, then plug the gap in that same calorimeter and see if

that makes a difference. The gap was plugged by sliding a hoop of brass shim stock into the gap so that it would occupy most of the gap, thus taking away some of the volume available to interact with the slug (see Fig. 7a). The modification was done without taking the calorimeter off the model traverse system, in the interest of not disturbing the existing setup and introducing any more variables into the problem. The figure shows an example of shim stock partially inserted into the gap.



Fig 7. a) Slug Calorimeter with brass shim stock partially inserted into the gap. b) post-test discoloration

After running in the arc jet, a streak of discoloration on the side of the slug where the two ends of the brass shim stock had not completely come together (see Fig. 7b). The streak appears to be evidence of local high heating (or oxidation) on the side of the slug where the shim stock was missing. Also, the resulting heat flux measurement was greatly reduced when the shim stock was installed (see Fig. 8). The measurements were repeated with other slug calorimeters that measured unreasonably high levels of heat flux and the result was the same. It was not obvious how or why the shim stock was producing lower heating. It was not due to enhanced conduction between the slug and the slug holder (by virtue of the shim) – losses measured after the calorimeter exposure to the flow were the usual 1 or 2%. All that could be said was that plugging the gap helped.

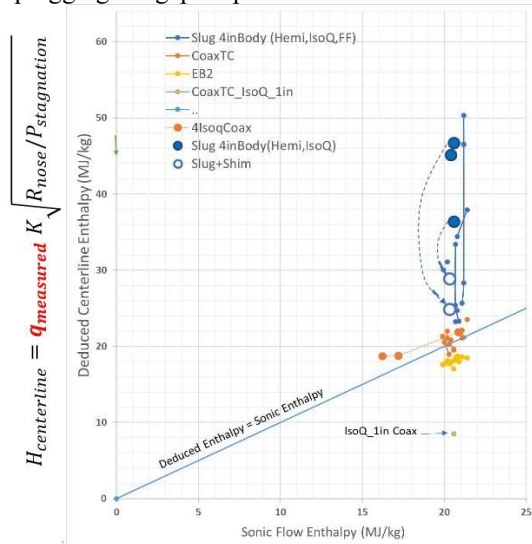


Fig. 8 Heat transfer of slug calorimeters with and without brass shim stock installed in the gap.

To be clear, we are not advocating that a shim stock be used to ameliorate the heating augmentation, this exercise (of plugging the gap) was merely a learning tool.

An inadvertent flow visualization helped provide clues as to why plugging the gap may be helping. On one occasion a slug measuring unreasonably high levels of heat transfer got so overheated that it melted (see Fig. 9). Upon disassembling the slug from the holder it was possible to see that some of the melting copper was flowing along the side of the slug. This accident of good fortune allowed us to visualize the flow pattern on the side of the slug.

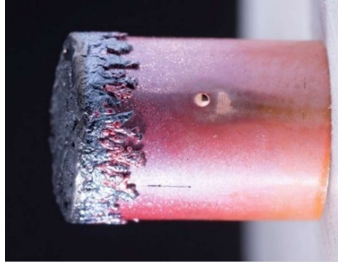


Fig. 9 Flow visualization associated with a slug that was overheated and melted

In the photo (see Fig. 9) it appears that there is flow of copper (and hot plasma) along the side of the slug running from front to back of the slug (left to right in the picture). Perhaps there was a leak on the backside of the slug holder allowing the hot plasma to flow alongside the slug.

Checking calorimeters for leaks was accomplished by putting a vacuum on the face of the slug calorimeter body and see if the vacuum would hold (after valving off the slug cavity from the vacuum source). This involved capping off the front face of the slug holder (see Fig. 10a) and applying a vacuum (see Fig. 10b).

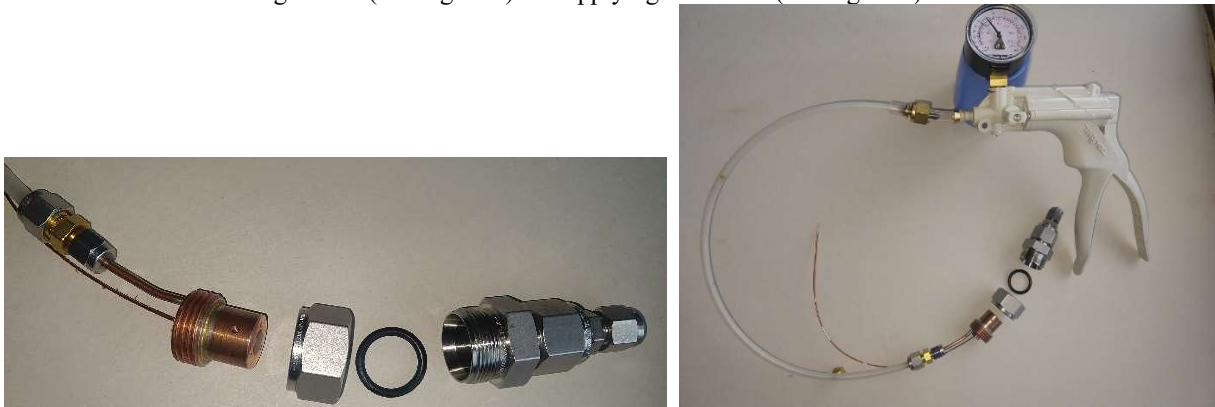


Fig. 10 Apparatus for capping off the slug holder so that it could be checked for leaks.

Leak checking revealed that several slug holders were leaking to various degrees. When examining the slug holders that leaked, it was apparent that the adhesive had debonded from the slug holder (see Fig. 11). The adhesive sealant was designed to seal the cavity in the slug holder (where the slug resides) from leaking hot plasma out the backside. In the absence of sealant, hot plasma (stagnating on the slug and cavity) would exhaust out the back through a hole designed to pass the thermocouple wires out of the cavity.



Fig. 11 Slug holder backside with Ceramabond sealant that has debonded

It was apparent that those slug calorimeters measuring high heat rates also showed cracks and debonds of the adhesive. Relative leak rates were quantified by measuring the rate at which the pressure would rise after valving off the vacuum source from the slug holder. Typically a vacuum of  $-20$  mm Hg was imposed on the slug followed by measuring the time for the pressure to rise to  $-19$  mm Hg. It was found that the measured heating rate correlated reasonable well with the leak rate (see Fig. 12).

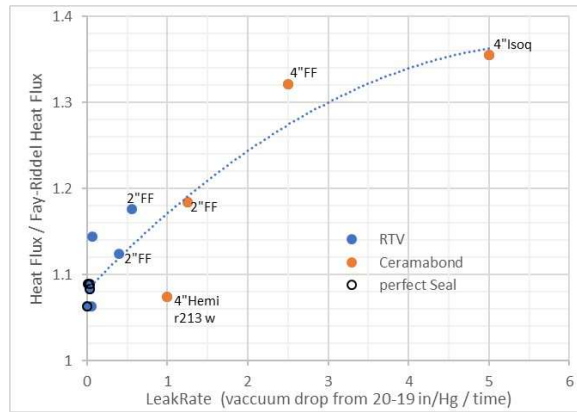


Fig. 12 Correlation between leak rate and heat flux

To help appreciate the effects of a backside leak, the adhesive/sealant on the back side of one of the slug holders was omitted, creating an unimpeded path for the hot plasma to exit through the TC wire hole. In this case the heating was about double that of a well-sealed slug holder, and on par with some of the worst-case leaks (where significant debonding was present).

Keep in mind that no leaks are acceptable, and the goal is to eliminate all leaks. This involved adopting a different adhesive/sealant (RTV as opposed to ceramic adhesive) and developing a mechanical means of holding the RTV down so it would not inadvertently be pushed away from the slug holder causing a debond. Improvements to the design involved threading screws into the backside of the slug holder so that the heads of the screws could act to restrain the solidified pool of RTV (surrounding the TC wire), see Fig. 13a.

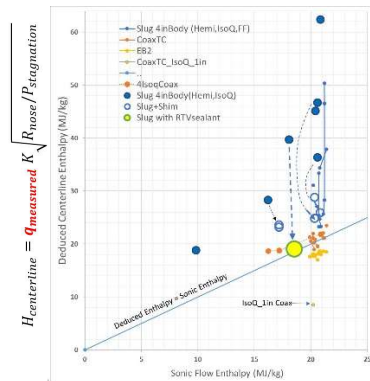
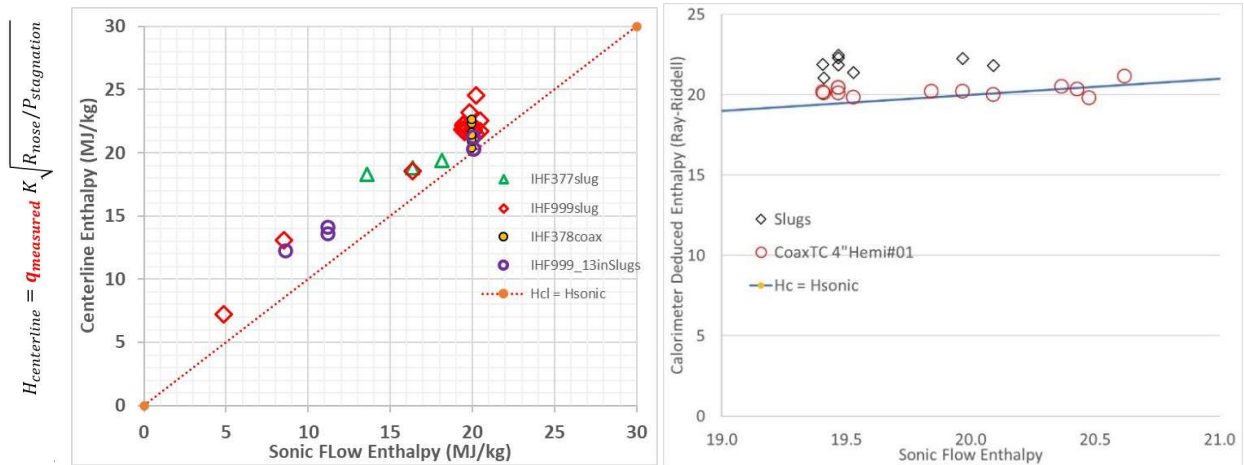


Fig. 13 a) Slug holder with RTV sealant b) Heat flux measurement with and without RTV

Stagnation pressure on the front of the slug cavity is greater than the near vacuum on the backside of the calorimeter producing a pressure differential across the sealant that acts to push the sealant off the back side of the slug holder. The RTV design worked well (see Fig. 13 b) and has been added to the slug assembly procedure. The revised slug assembly procedure also requires that a vacuum and pressure test be performed on the slug holder before (and after) testing in the arc jet to verify no leaks are present. As a result, the slug calorimeters have been producing much more repeatable and reliable measurements of heat transfer (see Fig 14).



a) Variety of conditions in both IHF6'' and 13'' nozzles      b) close up of high condition in the IHF 6''nozzle  
 Fig. 14 Slug measurements after employing RTV to seal the backside of the slug holder

All data shown in Fig. 14 were obtained in the Interaction Heating Facility (IHF) [11]. Fig 14 a shows good repeatability over a variety of conditions and calorimeter shape and sizes. Fig 14b shows the repeatability for the maximum facility condition in the IHF 6'' nozzle. In Fig 14b, the small variation in heat flux measurements (enthalpy) are due to small changes in facility conditions from run to run.

A secondary source of leaks, discovered by the technicians, was due to air flowing through the outer jacket surrounding the pair of thermocouple wires (leak traveling along the length of the lead wire). While the jacket is surrounded by RTV, the stripped off end of the jacket was not, and it was necessary to make sure the RTV flowed over the end of the jacket and on to the individual thermocouple wires (Copper and Constantan in this case). Admittedly these leaks are small but any leak is intolerable.

### III. Coaxial TC Calorimeter Challenges

Coaxial TC calorimeters provide very valuable data about the flow uniformity across the jet (or lack thereof). For example three coaxial calorimeters mounted on a 3 prong probe holder (known as a trident) were simultaneously swung through the flow downstream of the nozzle exit (see Fig. 15a). Each probe measures heat flux as a function of distance from the centerline of the jet. These identical probes provided very good agreement with each other (see Fig. 15b).

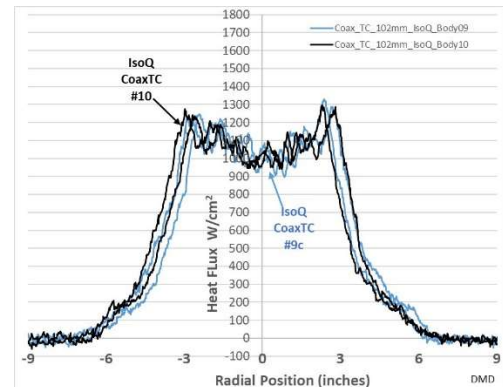


Fig 15 a) Coaxial TC probes mounted on a trident      b) Radial distribution of heating measured by probes 9 & 10

However, some identical coaxial TC calorimeters gave very different results from one another. One extreme example shown in Fig 16 shows the 4'' Hemispherical Calorimeters #01 and #21 agreeing with each other to about 6% while the 4'' Hemispherical calorimeter #22 appears to be dead. When comparing the thermocouple histories for each of the calorimeters, calorimeter #22 appears to show a more gradual rise in temperature than the others, and the rise in temperature occurs after the calorimeter has exited the flow.

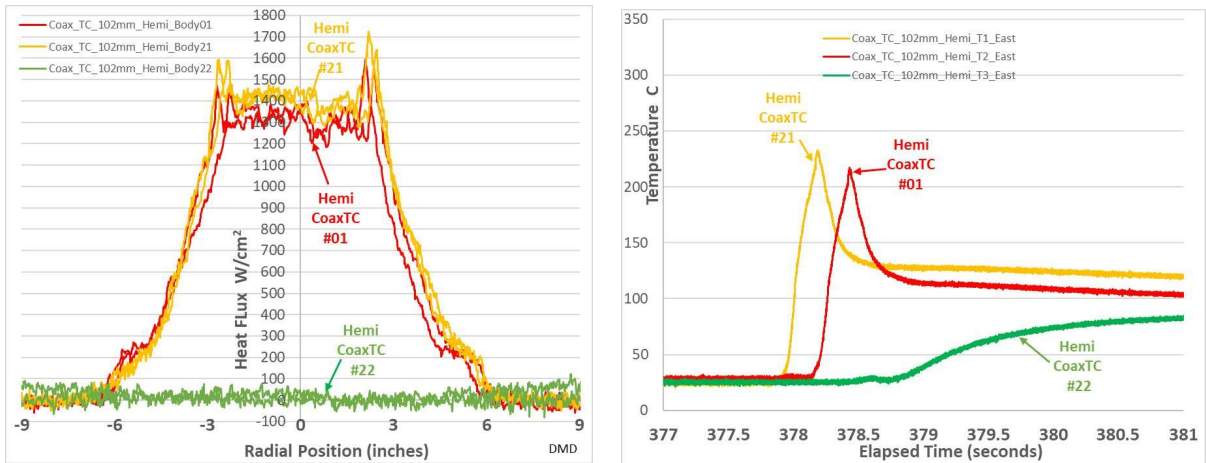
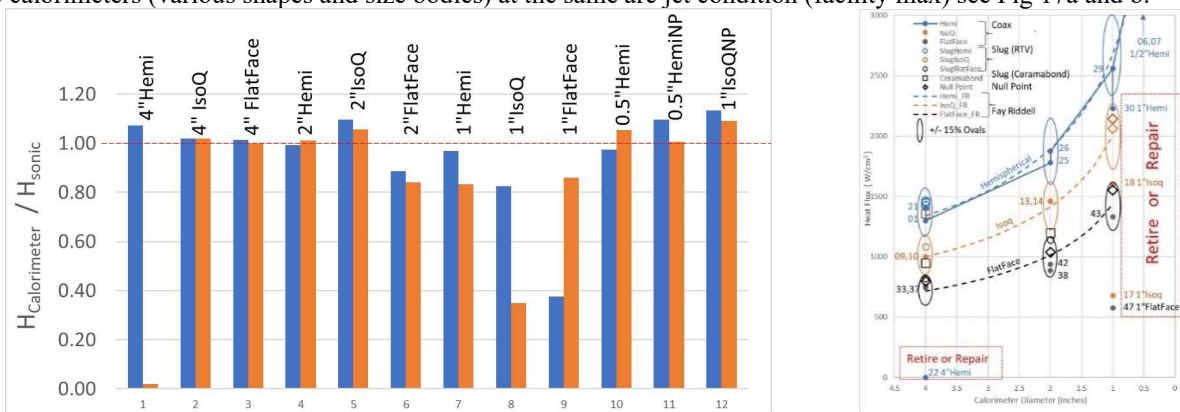


Fig. 16 a) Heat Flux measured by Coaxial TC Calorimeters b) Temperature history of Coaxial TC calorimeters.

One thought is that the thermocouple was partially shorted at a location other than the tip of the sensor. There was not much that could be done to fix the problematic calorimeter (Coaxial TC #22), nor could the analysis be easily “adjusted” to correct the measured heat flux. Consequently, it was decided to conduct a test campaign in which problematic coaxial TC calorimeters could be identified and removed from service. This involved testing all coaxial TC calorimeters (various shapes and size bodies) at the same arc jet condition (facility max) see Fig 17a and b.



a) Bar graph showing comparison between identical pairs of calorimeters b) Same measurements as a function of  $R_{nose}$  Fig 17. Coaxial TC calorimeter measurements compared to each other and Fay Riddell

The pairs of bars (Blue and Brown) shown in Fig 17a. shows the agreement (or not) between the primary calorimeter (Blue) and its corresponding identical twin (Brown). Testing pairs of identical calorimeters helps to identify problem calorimeters.

Most coaxial TC calorimeters compared well with each other and the Fay Riddell estimate of heating. However several did not (4”Hemi#22, 1”IsoQ#17, 1”Isoq#22, 1”Hemi#30, 1”FlatFace#47). Those that did not were deemed to be unreliable and were taken out of service. Our current best theory is that these problematic coaxial TC calorimeters likely have a short internal to the sensor body, and that there is a secondary electrical junction somewhere other than at the tip of the sensor where the junction is designed to be.

#### IV. Conclusions

Anomalous high heating on some slug calorimeters has been creating the need for large error bars on the advertised heating rates quoted to customers. Reducing the uncertainty in heat flux measurements will reduce the size of margins inflicted on the design of future heat shields. This study revealed that some slug calorimeters have been leaking flow out the back of the slug holder body, allowing hot plasma to flow past the side of the slug. This appears to be the source of unwanted augmentation to the heating rate which is over and beyond that of the front face of the calorimeter (desired measurement). It is important to eliminate all leaks from the cavity in the calorimeter body that holds the slug in place. This has turned out to be more difficult than one might think. It is important to be vigilant when testing

by checking and verifying that the calorimeter cavity is free of leaks before and after testing so as not to introduce unwanted bias errors in the measurement.

In the course of improving the measurement techniques, it is apparent that one can not take for granted that Coaxial TC calorimeters work as advertised without some kind of a process for check out. In this study there were 5 out of 20 calorimeters that were suffering problems that caused an under measurement of heat flux. One hypothesis is that there may be an internal short circuit in each of the 5 problematic coaxial TC calorimeters – this theory is supported by the late rise in temperature relative that that seen in healthy calorimeters.

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