AIAA 2002-5236

The Design and Use of Calorimeters For Characterization of High-Enthalpy Flows in Arc-Heated Test Facilities

D. Mark Smith
Jacobs Sverdrup AEDC Group
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389

Henry Moody
Thermal Technologies Inc.
Shelbyville, TN USA

Chris Wanstall
Southern Research Institute
Birmingham, AL, USA

and

Imelda Terrazas-Salinas
NASA Ames Research Center
Moffett Field, CA, USA

11th AIAA/AAAF International Conference Space Plane and Hypersonic Systems and Technologies

September 29 - October 4, 2002
Orleans, France

The Design and Use of Calorimeters For Characterization of High-Enthalpy Flows in Arc-Heated Test Facilities*

D. Mark Smith
Jacobs Sverdrup AEDC Group
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389

Henry Moody
Thermal Technologies, Inc.
Shelbyville, TN

Chris Wanstall
Southern Research Institute
Birmingham, AL

Imelda Terrazas-Salinas
NASA Ames Research Center
Moffett Field, CA

Abstract

High-enthalpy, arc-heated flows used for aerothermal testing present a challenging environment for flow characterization. This paper describes the design and use of cooled dwell probes used for heat-transfer and pressure characterization of the NASA and United States Department of Defense (DoD) arc facilities located at Moffett Field, CA, and Arnold Air Force Base, TN. Dwell calorimeters designed, fabricated, and tested by Thermal Technologies, Inc. (TTI) in the NASA IHF and the USAF H1 and H2 arc test facilities provide heat flux and pressure data with excellent repeatability. These calorimeters use standard Gardon calorimeter gages and pressure ports with unique cooling systems enabling them to withstand the severe arc-heated environments for durations sufficient for acquisition of steady-state data. The TTI probes have proven very robust in the extreme aerothermal environments of these facilities. This paper provides an overview of calorimeter instruments typically used in arc facilities, discusses design features of the TTI dwell probes, presents selected data acquired by the TTI calorimeters, and provides comparisons with data acquired from using measurement techniques.

Nomenclature

A^* Arc heater nozzle throat area, in.^{2}
C^* One-dimensional throat characteristic flow velocity, ft/sec
C_{F-R} Multiparameter factor derived from the basic Fay-Riddell expression, nondimensional
C_{hb} Coefficient of convective heat transfer with surface blowing, Btu/ft^2-sec-R
C_{ho} Coefficient of convective heat transfer, Btu/ft^2-sec-R
c_p Gas specific heat at constant pressure, Btu/lb$_m$-R
D^* Arc heater nozzle throat diameter, in.
Δt Exposure time for Teflon ablation sample, sec
η Blowing correction factor applied to Teflon ablation rate
g_c Gravitational constant, 32.2 ft-lb$_m$/lb$_f$-sec^2
H• Freestream gas enthalpy, Btu/lb$_m$
H_{gw} Gas wall enthalpy, Btu/lb$_m$
Ho_{INF} Inferred (Fay-Riddell) enthalpy, Btu/ lb$_m$
H_r Recovery enthalpy, Btu/lb$_m$
H_T Total enthalpy, Btu/ lb$_m$
H_{Tef} Teflon enthalpy, Btu/ lb$_m$
H_w Probe wall enthalpy, Btu/ lb$_m$
K Thermal conductivity, Btu/ft-sec-R
ℓ Slug calorimeter mass thickness, ft.
Le Lewis number
m_{dot} Teflon mass loss ablation rate, lb$_m$/ft^2-sec
$\dot{m}_g$ Arc heater gas mass flow, lb$_m$/sec
P_e Boundary-layer edge pressure, atm
P_o Arc heater total pressure, atm
P_o' Pitot (stagnation) pressure, atm
Pr Prandtl number
$\dot{q}_{cw}$ Cold wall heat flux, Btu/ft^2-sec
$\dot{q}_{HW}$ Hot wall heat flux, Btu/ft^2-sec
$\dot{q}_{oHW}$ Stagnation hot wall heat flux, Btu/ft^2-sec
$\dot{q}_{rad}$ Radiative heat loss, Btu/ft^2-sec
s Gardon gage foil thickness, in.
S Measured Teflon ablation depth, in.
T Total temperature, °R
U_e, V Edge gas velocity, ft/sec
ρ Material (Teflon) density, lb$_m$/ft^3
r_n Calorimeter nose radius, in.

Introduction

Use of Calorimeters for Arc Heater Flow-Field Characterization

Endoatmospheric aeroheating places extreme demands on aerostructures and materials operating at hypersonic speeds. The extreme aerothermal conditions experienced by thermal protection system (TPS) materials during hypersonic endoatmospheric flight result in complex material thermostructural responses. These effects normally require evaluation in ground test facilities. Arc facilities are unique in their ability to reproduce thermal environments simulating high Mach number flight for the long exposure periods required for aerothermal survivability testing. Consequently, arc heaters have found wide usage in both military and commercial aerospace applications for development of high-temperature mate-

* The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were performed by personnel of NASA Ames Research Center, Moffett Field, CA, personnel of Jacobs Sverdrup AEDC Group, technical services contractor for AEDC. Further reproduction is authorized to satisfy needs of the U. S. Government.

rials and structures for missiles [1]. An important part of ground test evaluations in arc-heated facilities is accurate flow calibration for correlation of ground test performance data with nominal or predicted flight conditions. Perhaps the most fundamental of flow characterizations are measurements of stagnation and surface heat flux and pressure on standard cone and hemisphere probes. Definition of those parameters provides for derivation of the total flow enthalpy, a fundamental arc operating parameter which is calculated from measurements of stagnation heat flux and pressure. Also of interest are surface heat flux and pressure on specific test article geometries such as wedges, cones, flat plates, and various complex geometries. However, obtaining accurate measurements of such parameters in the aero-thermal conditions of an arcjet has many technical challenges. This paper describes the design, fabrication, and use of dwell calorimeter hardware developed by Thermal Technologies, Inc. (TTI) for calibration of high-enthalpy flow fields in the Interactive Heating Facility (IHF) at the NASA-Ames Research Center, Moffett Field, CA and the U.S. Air Force arc facilities H1 and H2 at the Arnold Engineering Development Center (AEDC), Arnold AFB, TN.

Types of Calorimeters Used in Arc Facilities

Calorimeters function primarily in two roles in arc facilities. First, stagnation and wedge calorimeters provide empirical data quantifying the baseline test conditions generated by the arc heater and presented to a test article in an arc-heated flow field. Second, calorimeters of various geometries are used to define incident heat flux and surface pressure conditions for many specific test article configurations. Calorimeter measurements, taken as a whole, define the baseline test condition for a given operating point, and then provide empirical data for validation of aerothermal codes, as well as for correlation of ground test results with flight test predictions and flight data [2].

Many types of heat gages are used in arc facility calorimetry, including slug calorimeters, Gardon gages, coaxial thermocouples, thin-skin thermocouples, and Schmidt-Boelter gages. The first three types of gages, in particular, have been widely used in the NASA and DoD arc facilities. Each gage type has distinct advantages and preferred applications, as discussed further in this paper.

Transient (Heat sink) and Steady-State (Cooled) Calorimeters

Early heat flux measurements in arc facilities were made with uncooled sacrificial probes. These probes, instrumented with a null-point slug or other heat gage, were sometimes shielded with a Teflon" cap to provide temporary protection from the arcjet during facility startup [3]. Once the cap was fully ablated, the heat gage (or gages) provided time-temperature data for a short interval before being destroyed by the high temperatures. Since those techniques were used, improvements in heat flux instrumentation, and in the model injection hardware used in arc facilities, have provided improved alternatives. These improvements include:

1) Rapid-response, durable heat gages, that make it possible to construct diagnostic probes that can accurately measure heat rates while traversing the flow field rapidly enough to prevent damage to the instrument. In addition to the instrumentation and thermal design advances made, model injection hardware has been developed for many facilities which enables the rapid probe sweeps required for the transient sweeps.

2) Cooled probe body and heat gage configurations that are capable of surviving the high-temperature arc environment to provide time-averaged, integrated heat flux measurements within the arcjet. Cooled probes play an important role in the calibration of arc-heated flows because of their ability to make steady-state measurements in the arc flow. Dwell calorimeters provide time-averaged heating measurements which integrate local pressure and enthalpy transients to quantify actual incident heat flux and pressure on a particular test article configuration.

3) The use of “witness ablation” samples with relatively well-characterized ablation behavior. Ablation profiles obtained with such materials can be used to infer the convective heat flux contours over the sample heated planform.

Stagnation Calorimeters

Stagnation heating and pitot pressure measurements are essential parameters used in defining total enthalpy, one of the most basic of arc heater flow-field parameters typically referenced. For equilibrium air, the kinetic and temperature components of total enthalpy may be expressed as

$$H_T = 1/2\, V^2 + \int_0^T c_p dT,\ \mathrm{Btu/lb_m}$$

Several techniques are used to derive the nominal reference enthalpy for a specific arc heater operating point and configuration. The inferred enthalpy technique developed by Fay and Riddell [4] is widely used because it derives directly from measurements made within the flow field. Stagnation heat flux measurements are paired with pitot pressure measurements to infer local total enthalpy within the arcjet by the relation

$$H_{oINF} = \frac{C_{F-R}\, \dot{q}_{oHW}}{[P_o'/r_n]^{0.5}} + H_w,\ \mathrm{Btu/lb_m}$$

where $C_{F\text{-}R}$ is a factor derived from the basic Fay-Riddell expression by combining the nondimensional parameters (Pr and Le) with appropriate values for viscosity, velocity gradient, and probe wall temperature at the particular freestream condition.

Stagnation calorimeters are exposed to the highest heat flux and pressure levels which are normally measured in arc facilities. For example, in the DoD H1 arc facility, stagnation heat fluxes up to 20,000 Btu/ft^2-sec, with an incident surface pressure of 90 atm, have been measured on the centerline of the arcjet on a 0.25-in. nose radius stagnation calorimeter. Consequently, heat gages for such applications must be extremely robust. Null-point and slug calorimeters have served well in this role [5-7]. The calorimeter slug is essentially a thermally insulated calorimetric mass for which the back-surface temperature history can be measured. The assumption is made that all of the incident thermal energy is stored in the slug. Then the expression used to derive heat flux becomes.

$$\dot{q}_{oHW} = \rho \ell c_p dT/dt$$

It can be seen that mass density and specific heat are the only thermophysical properties which must be known, since the calorimeter mass thickness (ℓ) and the measurement time interval can be measured with good accuracy (±0.1 percent).

Care must be taken in fabrication to ensure that the assumptions inherent in this approach are not violated. In particular, strict dimensional tolerances for the mass and slug body, and adequate insulation of the mass from the slug, are essential.

Wedge or Plate Calorimeters

Wedges are used in ground test facilities to test frustra and flat TPS samples. The purpose of wedge calorimeters is to aid in definition of the aerothermal boundary conditions that prevail over the heated surface of TPS samples. This requires that the wedge calorimeter measure the heat flux and pressure distribution over geometries replicating the actual TPS test articles. Since wedge surface heating rates in an arcjet may be as much as 10 to 20 times lower than stagnation heating rates, the use of heat gages such as Gardon gages, coaxial thermocouples, and Schmidt-Boelter gages is in many cases feasible on wedge calorimeters.

Gardon gages consist of a hollow cylinder-shaped heat sink, normally copper, with a constantan foil attached to one end (Fig. 1). A copper wire attaches to the center of the constantan foil, connecting to an insulated copper tube at the center of the gage. With the heat sink (exterior) cylinder cooled to keep it at a constant temperature, a radial temperature distribution is established in the foil proportional to the heating rate on the foil surface. The gage output can then be calibrated at various known heat transfer levels to obtain the appropriate calibration data [8]. Although the output level for Gardons is marginal at low heat fluxes (i.e., below 0.5 Btu/ft^2-sec), this is not an issue within the high-enthalpy flow fields generated by arc heaters. Gardon gages are characterized by excellent calibration stability and an output directly proportional to the incident heat flux [9-10] Consequently, Gardon gages have been used with good results on Thermal Technologies' cooled stationary probes in the NASA and DoD arc heaters.

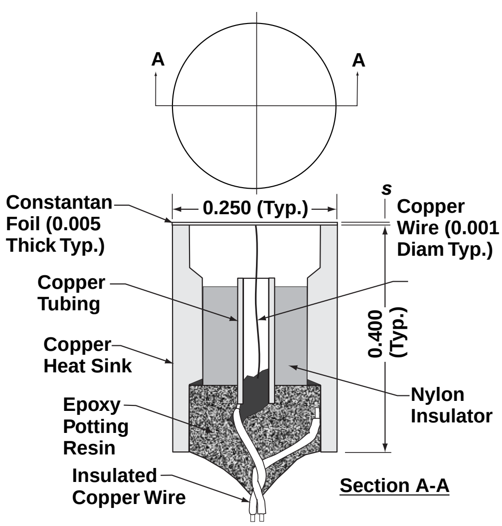


Fig. 1. Gardon Heat Flux Gage

Low-Temperature Ablator Witness Plate Calorimeters

Test articles made of low-temperature ablator materials are very sensitive to convective heat flux variations on a given test article surface and thus can provide a visual "footprint" of the arc test rhombus on a particular model geometry. Such test articles reveal areas of heat flux nonuniformity, enhanced heat transfer zones resulting from shock impingements or interaction, freejet-edge intersection lines on wedges and 3-D bodies, and other heat-transfer discontinuities, regardless of their origin. Because of the high number and/or density of sensors required, such discontinuities are frequently not practical to map using discrete heat gages. Ablator witness plates are simple and inexpensive to fabricate, requiring very short model dwells in arc facilities.

Various correlations are available for use in predicting ablation rates for low-temperature ablators as a function of incident heat flux and surface pressure. Conversely, approximate integrated heat flux levels can be calculated from recession maps of ablated arcjet samples of materials which are well-characterized with respect to ablation rate, such as Teflon (TFE). The ablation behavior of Teflon, TFE-fluorocarbon resin, at the conditions typically encountered in high-enthalpy arc heaters is simple and fairly well characterized [11-12]. As a result of the relatively low ablation temperature and low thermal conductivity of Teflon, thermal transients and lateral conduction prove to be of minor importance. Thus the thermal-ablation response of Teflon for an arc-heated ablation specimen is essentially steady state, with one-dimensional heat conduction. Also, Teflon undergoes simple vaporization with no melt runoff, and the ablation product-air reactions produce very little influence on surface heating (i.e., boundary-layer reactions are unimportant). Consequently, Teflon has been used extensively by TTI to infer convective heating rates in high-enthalpy test facilities. This approach allows for highly spatially resolved mapping of total heat flux on 2-D and 3-D model or wedge surfaces.

The recommended heat balance for Teflon ablation in air, assuming steady state and 1-D heat conduction, is

$$\rho_e U_e C_{hb}(H_r - H_{gw}) = \dot{q}_{rad} + m_{dot}(H_{gw} - H_{Tef})$$

where: ρ_e U_e Ch_b is convective transport with blowing, H_r is the recovery enthalpy, H_{gw} is the gas-wall enthalpy, q_{rad} is the radiation loss, m_{dot} is the Teflon mass loss ablation rate, and H_{Tef} is Teflon enthalpy at initial conditions. The blowing, or ablation, correction to convective transport is given as follows:

$$C_{hb}/C_{ho} = 1 - (\eta * m_{dot})/(\rho_e U_e C_{ho})$$

The TFE properties recommended for use and presented in Table 1 were obtained from Refs. 11 and 12. It should be noted that in high-enthalpy arc heaters, Teflon undergoes fairly high blowing rates, and the laminar and turbulent blowing factors listed in the table have been derived empirically. For purposes of these calculations, 1660°R has been selected as the ablation temperature, since it is evident from the vapor pressure data presented in Ref. 12 that TFE undergoes significant vaporization at that temperature.

The measured TFE ablation depth (S) and exposure time (Δt), together with the density *ρ*, can be used to determine the Teflon mass loss ablation rate as follows:

$$m_{dot} = \rho S/\Delta t,\ lb_m/ft^2\text{-sec}$$

m_{dot}, the estimated recovery enthalpy (H_r), and the properties in Table 1 can be used to compute the convective cold-wall heating rate by the following relation:

$$\dot{q}_{cw} = \rho_e U_e C_{ho} H_r$$

Note that this calculation assumes that the shape change induced by ablation does not significantly influence heating. Consequently, one must exercise care when selecting the exposure time (Δt) to ensure the time is adequate to provide a good ablation measurement, yet short enough so that shape change effects on sample heating rates are secondary. As a

Table 1. Teflon Thermal-Ablation Properties

Property	Temperature, °R	Value
Density, g/cc	540	2.15
Emissivity	-	0.9
Ablation Temp °R	1660	
Gas-Wall Enthalpy, Btu/lb, with Ho = 0.0 at $T_{initial}$	-	940
Blowing Correction, η	0.44 (laminar)	0.15 (turbulent)
Temp, °R	**Cp, Btu/lb-°R**	**K, Btu/ft-sec-°R**
530	0.23	3.8×10^{-5}
1160	0.30	4.8×10^{-5}
1660	0.31	4.8×10^{-5}

general rule, TTI recommends and selects an exposure time that results in about 0.100 in. of maximum ablation for typical arc heater exposures.

Arc Facility Probe Thermal Analysis, Design, Instrumentation, and Fabrication

Thermal Technologies, Inc. has designed calorimeter models to define the aerothermal boundary conditions that exist on thermal protection system (TPS) samples that undergo development and qualification testing in the NASA and DoD arc heater test facilities. For the NASA-Ames IHF facility, a stagnation probe calorimeter was designed and tested to help determine the flow conditions of the facility over the entire facility operating envelope. For the NASA IHF facility and AEDC H1 and H2 facilities, wedge calorimeters were designed and used to help define the heating and pressure distributions over the surface of TPS test samples. Each of the TTI calorimeter models is internally water cooled, in order to assure survivability in the arcjet test flow for times sufficient to result in a steady-state thermal condition, and to provide measurements in the arc-heated flow over relatively long durations. The TTI dwell calorimeter models use Gardon gages with a response time of about 0.020 sec. These gages, when adequately cooled, have demonstrated their capacity to provide good steady-state heat flux measurements in arcjets.

Dwell Stagnation Calorimeter Probe

Design. Design requirements imposed by NASA for probes used to map the IHF arc heater high-enthalpy test rhombus were originally as follows:

1) The probe must measure the convective heat rate, pressure, and probe surface temperature in the stagnation region of a hemispherical probe.

2) The probe must operate continuously at the maximum heating conditions produced by the IHF facility (i.e., the IHF with the probe mounted 3.0 in. aft of the 6.0-in.-diam exit nozzle with the arc operating at 6,000 amps and an arc column pressure of 120 psia).

3) The probe must interface with existing stings and use existing facility water for cooling.

4) The probe must be capable of multiple exposures with minimal refurbishment.

Design conditions incident on the probe surface were estimated based on data acquired by TTI in prior tests [13], as follows:

1) Model stagnation cold-wall heat flux ($\dot{q}_{CW}$) = 1,660 Btu/ft^2-sec (on a 1.50-in.-radius hemisphere)

2) Stagnation pressure = 1.2 atm

3) Total enthalpy = 11,000 Btu/lb_m

4) Cooling water = 600 psia inlet (@ 80°F), 60-psia outlet.

TTI conducted engineering analyses on the probe to design a cooling system allowing the probe and its instruments to operate continuously at the maximum operating condition in the IHF facility. The probe design is presented schematically in Fig. 2. Thermally, the most critical portion of the probe is the Gardon gage. Consequently, the foremost design challenge centered on adequately cooling the stagnation region while providing the ability to measure heat flux, pressure, and surface temperature. The design that was selected used a stem in the probe that is an integral part of the outer shell. In order to provide high thermal conductivity, the outer shell is fabricated from oxygen-free, high-conductivity copper, with no mechanical, braze or weld joints used between shell and stem. The probe stem houses three instruments, a Gardon gage, a pressure port, and a Constantan® lead wire in the pattern illustrated in Fig 3. The stem is convectively cooled by a small annulus formed around the stem by an inner housing. After exiting the stem, cooling water flows into a hemisphere annulus that cools the inner surface of the outer shell. Near-uniform coolant flow over the entire inner surface of the hemisphere is achieved by metering the coolant in the tangent region of the hemisphere-cylinder section. The coolant flow then exits the metering section and enters a slot that collects the water into a single outlet tube.

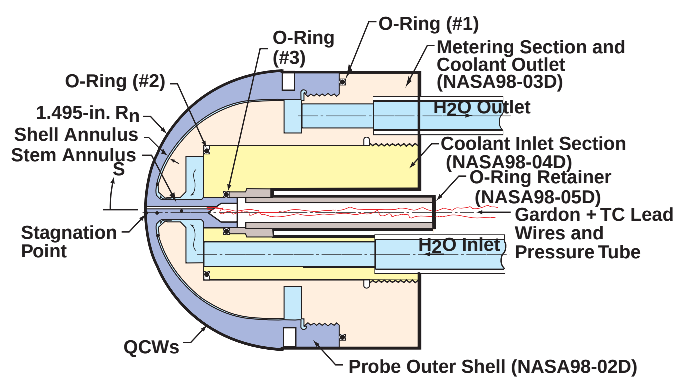
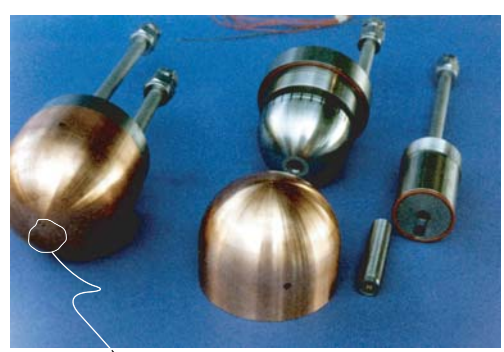
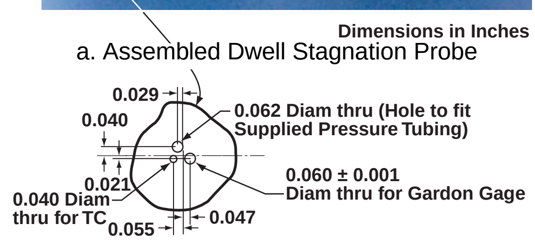


Fig. 2. Schematic of TTI Dwell Stagnation Probe Calorimeter



a. Assembled Dwell Stagnation Probe



b. Stagnation Point Instrumentation

Fig. 3. Detail of Probe Stagnation Point Instrumentation

Proper cooling requires accurately controlled dimensions for the cooling annulus around the stem, the cooling annulus adjacent to the hemisphere's inner surface, and the metering section. This, together with the requirement that the stem needs to be an integral part of the outer shell, makes machining of the outer shell a difficult operation. The task was undertaken successfully by Young's Precision Machining, utilizing precision CNC equipment to produce components conforming to all TTI specifications.

Gardon gages as small as 0.060 in. in diameter are reliably fabricated by Vatell (Ref. 13). Previous TTI experience has indicated that Vatell gages using 0.004-in.-thick foils can reliably measure heat fluxes as high as 2,000 Btu/ft^2-sec, if adequately cooled. Vatell was contracted to fabricate the gages, press the gages into TTI-supplied probes, and conduct calibrations in Vatell's Radiation Calibration Facility.

The probe's surface temperature, adjacent to the Gardon gage, was measured using a Copper-Constantan thermocouple, with the outer copper shell as one leg of the thermocouple, and a 0.015-in.-diam insulated Constantan wire as the other leg. The Constantan® wire had a 0.042-in. diam bead so that it could be pressed into the 0.040-in. hole (see Fig. 3). Figure 4 illustrates a typical thermocouple temperature trace measured during a 1-sec TTI calorimeter dwell in the NASA IHF arc facility operating at the maximum arc-heater conditions. Also shown in the figure is the Gardon gage heat-transfer measurement, made on the same run. Although the thermocouple gave satisfactory results initially, after a few uses the bead became loose and the thermocouple was unreliable.

In the design of the probe, O-rings were used to seal the various coolant passages in the probe. The O-ring sealing method was selected rather than brazing and welding in order to simplify probe maintenance. Use of threaded joints with O-ring seals allowed the probe to be disassembled, and any defective part replaced. The water inlet and outlet tubes were brazed into their respective structures.

Wedge Probe Calorimeters

The wedge calorimeters fabricated for the NASA-Ames IHF and AEDC H1 and H2 heaters were designed to aid in the definition of the aerothermal boundary conditions on the heated surface of TPS samples. This required that the wedge calorimeter assembly replicate the geometry of the TPS test articles mounted on wedge holders. Other requirements placed on the calorimeters included:

1) The dwell times in the arc flow field must be sufficient to obtain steady-state heating and pressure data.

2) The number of convective gages and pressure ports must be adequate to determine the axial distribution of heating rate and pressure over the TPS sample.

3) The calorimeter must interface with existing sting hardware and use existing cooling water.

4) The calorimeter must be capable of multiple exposures without refurbishment.

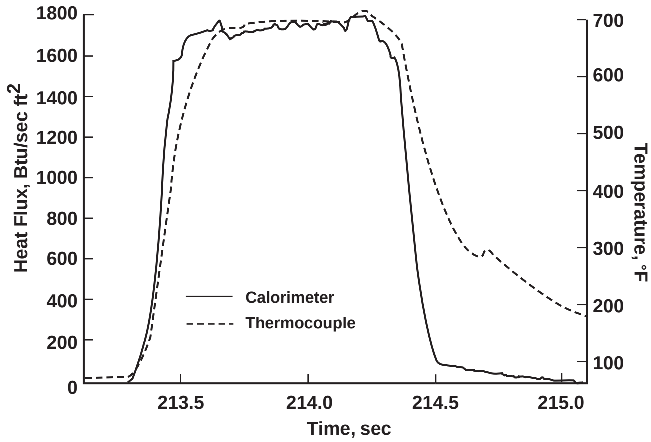


Fig. 4. Typical Dwell Stagnation Probe Responses from IHF Test

Wedge dwell calorimeters were designed and fabricated to replicate the following TPS sample configurations:

1) 20-deg half-angle wedge used in the NASA IHF facility and the AEDC H2 facility (Fig. 5).

2) 15-deg half-angle wedge used in the AEDC H1 facility (Fig. 6).

3) 30-deg half-angle wedge used in AEDC's H1 facility.

The TTI calorimeter incorporates the existing TPS wedge holder and leading edge used in TPS testing. The TPS sample was simply replaced with a water-cooled, instrumented copper plate with Gardon gages and pressure ports located over its heated planform. The gage and pressure locations are given in Figs. 5 and 6 for the 20 and 15-deg calorimeters, respectively. For the 20-deg wedge tested in the NASA IHF and AEDC H2 arc facilities (Fig. 5), the design conditions were a maximum heating rate of 400 Btu/ft^2-sec (continuous) and 600 Btu/ft^2-sec (for about 3.0 sec), respectively. For the AEDC H1 application (Fig. 6), the cooled plate and gages were designed to acquire steady-state heating and pressure data at an expected wedge heating rate of up to 2200 Btu/ft^2-sec for a duration of about 1 sec.

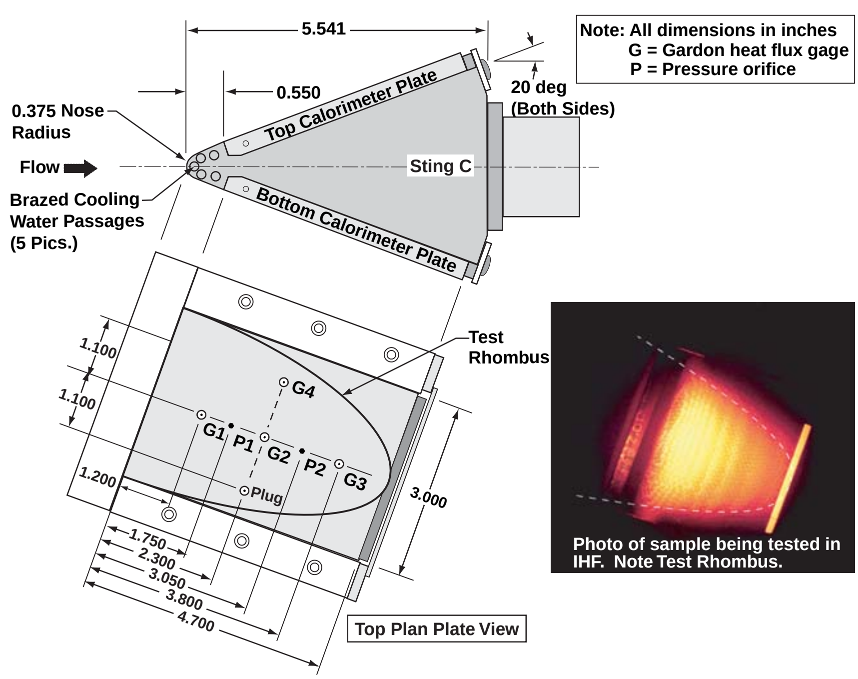


Fig. 5. TTI 20-deg Dwell Calorimeter Used in NASA IHF and AEDC H2 Arc Heater

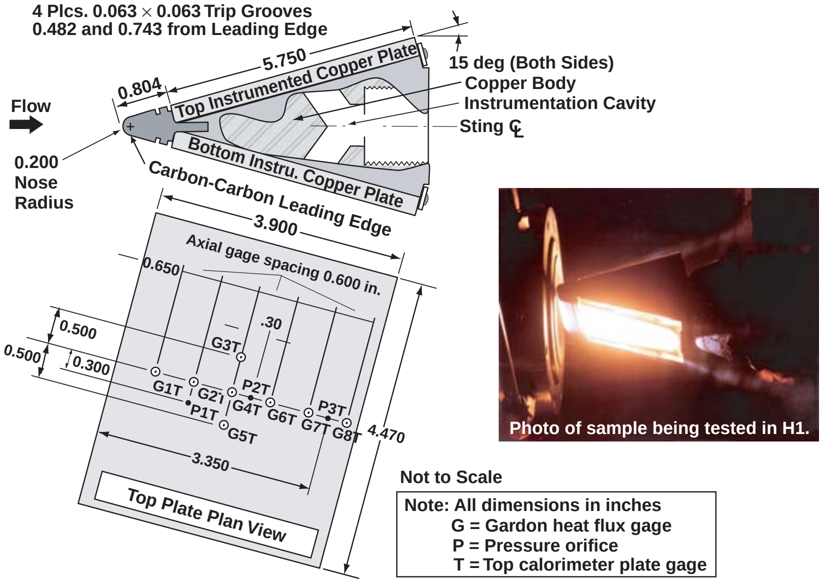


Fig. 6. 15-deg Dwell Wedge Calorimeter Used in AEDC's H1 Arc Heater

The wedge dwell calorimeters also used Gardon gages fabricated by Vatell. The Vatell gages calibrated by the manufacturer during the period from March '97 to March '00 have nominal uncertainties above 15 percent. For those gages calibrated after March '00, the gages appear to be accurate to within less than 10 percent. However, most of the gages used in the AEDC H1 wedge calorimeters presented in this paper are from the earlier calibration set and thus have the higher nominal uncertainty, while the gages used on the NASA and H2 wedge calorimeters were of the later calibration set and thus have the lower uncertainty values.

Dwell Calorimeter Use in Arc Facilities

Use of Dwell Calorimeters in NASA-Ames Arc Facilities

NASA-Ames IHF Facility Description — The Space Technology Division at NASA-Ames Research Center, Moffett Field, CA, operates an Arc Jet Complex for the investigation of atmospheric entry and high-velocity flight phenomena for NASA and DoD vehicles and missions. The facility supports thermal protection system development, certification, and qualification, as well as high-enthalpy propulsion system testing. High-enthalpy gas flows are produced which simulate gas phase chemistry at the surface of vehicles between 15 and 75 Kft/sec equivalent flight velocity. Since 1960 the complex has supported all NASA space flight programs and numerous DoD projects.

The Interaction Heating Facility (IHF) comprises one of four active arc jet facilities at the Ames Arc Jet Complex [14]. The IHF is equipped with a 60-MW segmented arc heater with an 8-cm-diam bore that operates with air at pressures from 1 to 10 atm and enthalpy levels from 3000 to 20,000 Btu/lb_m (air). Cold air can be added in the downstream plenum to obtain centerline enthalpies below 1000 Btu/lb_m. Two nozzle geometries are used in the IHF: conical axisymmetric and semielliptical. The nozzles direct the flow into a walk-in, 8- × 8- × 8-ft test chamber. Flow in the cabin is collected by the 54-in. diam diffuser before being pumped into the steam-ejector vacuum system. Static pressure ranges from 0.1 to 10 torr in the cabin, depending on mass flow and pumping rates. Samples are exposed to the plasma in an open jet formed between the nozzle exit and the entrance to the diffuser. The test chamber houses two hydraulically-actuated model insertion mechanisms, with water manifolds for cooling the test articles, and instrumentation connections made to a data recorder via patch panels within the test cabin. Optical access through ports on both sides and in the ceiling of the test chamber allow imaging of the test article and plasma stream.

Stagnation Calorimeter Probes — TTI has supported NASA in the design and use of Gardon gage calorimeters to define arc-heater freestream conditions and to measure the heating and pressures on TPS wedge configurations. TTI supplied NASA with two sets of Gardon stagnation calorimeter probes described previously. The first set was tested on three NASA IHF runs. During those tests, the 6.0-in.-diam exit nozzle was used to provide maximum heating conditions, with an arc current of 6,000 amps and arc column pressure of 130 psia. The TTI dwell probe was mounted on one sting, and the NASA-designed and fabricated slug calorimeter probe (Fig. 7) was mounted on a second sting, with the two stings sequentially inserted in the flow to acquire comparative probe data.

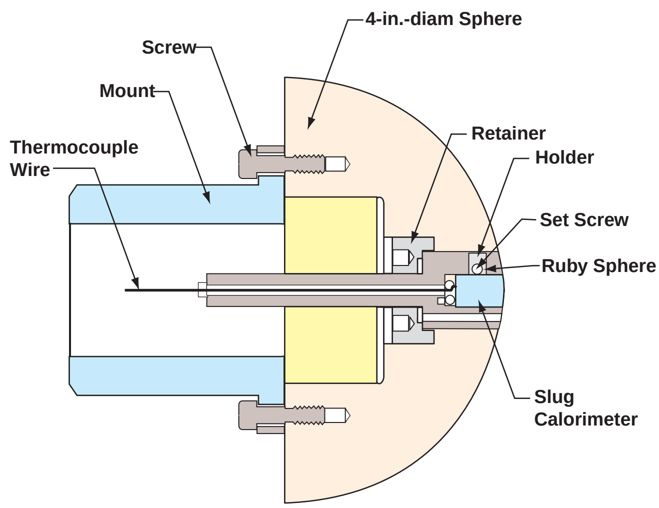
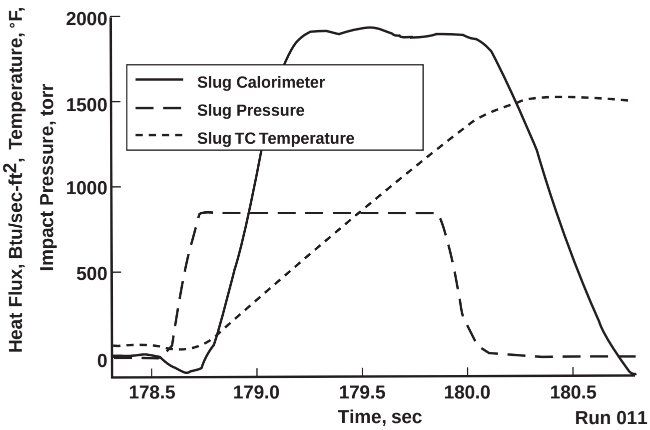


Fig. 7. NASA-Ames Slug Calorimeter

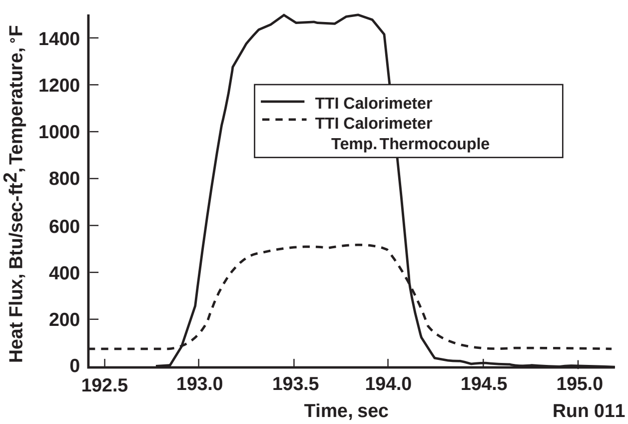
In these first tests, NASA's slug calorimeter performed well, giving stagnation point heating rates that were consistently about 25 percent higher than those measured with TTI's Gardon calorimeter. Figure 8 presents the stagnation pressure and slug backface temperature data as a function of time for the NASA slug calorimeter and the Gardon calorimeter, with the IHF operating at the maximum condition. The inferred slug heating rate from the NASA calorimeter is presented in Fig. 8a. As expected, the NASA slug calorimeter experienced melting at the high-temperature IHF conditions and had to be refurbished after each high power run. Figure 8b presents the surface temperature history and stagnation point heating rate as measured by the TTI Gardon calorimeter. The Gardon gages in the first series of TTI probes were calibrated in 1999 and have the larger calibration errors noted previously. In the second test series, TTI probes were delivered with Gardon gages calibrated using the more accurate Vatell calibrations. Figure 4 is a sample of the test data acquired from the second series TTI probes. The data compared were acquired at nearly the same conditions as the first series of test runs, presented in Fig. 8b. Note that the heating rates measured with the second probe set are over 15 percent higher than measurements made with the first set.

Table 2 provides a comparison of TTI predictions and the corresponding measured values for the stagnation calorimeter at the specified maximum IHF conditions. The measured heating rate is about 10 percent higher than predicted, the surface temperature is about 150°F higher than predicted, and the measured water flow rate is lower than expected. The measured stagnation point temperature is higher than that predicted, probably because of the higher-than-expected heating rate and/or the difficulty in measuring surface temperature (i.e., any surface irregularity in a stagnation region can induce hot spots). With respect to heat flux measurements, the probe performed as designed.

Typical calorimeter measurements at the maximum IHF operating conditions are presented in Fig. 9. The figure compares the IHF conditions inferred from the TTI calorimeter to those conditions measured by NASA in prior investigations. A comparison of Figs. 8b and Fig. 4 indicates that the improved Gardon calorimeter indicates the stagnation heating to be 1760 Btu/ft^2-sec, as compared to 1500 Btu/ft^2-sec from the first test series. Unfortunately, in this second set of probe calibrations runs the NASA slug calorimeter did not reliably measure heating rate, because of thermal shorts in the slug insulator. Repeated refurbishment of the slug calorimeter was unsuccessful in eliminating the problem. Consequently, in the subsequent calibration investigations of the IHF conditions, the TTI Gardon calorimeter was used.



a. NASA Slug Calorimeter



b. TTI Dwell Calorimeter

Fig. 8. Stagnation Probe Responses in IHF with 6.0-in.-Diam Nozzle (Arc Current 6000 amp, Chamber Pressure 130 psia) at 6 in. Aft of Nozzle Exit.

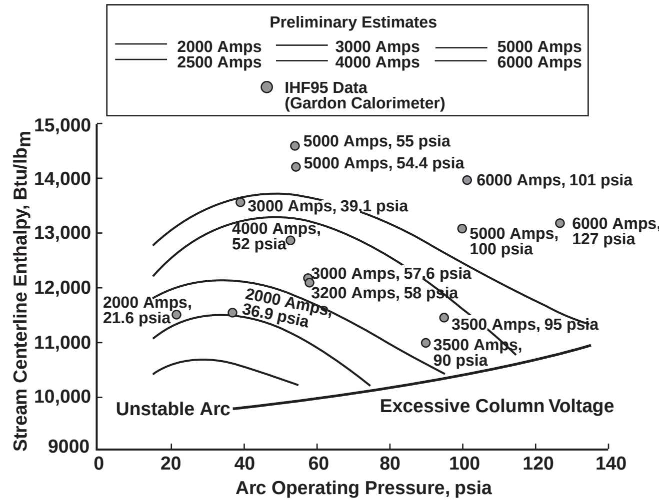


Fig. 9. IHF Operating Envelope and Dwell Stagnation Probe Data Comparison

Wedge Calorimeters — To simulate the relative high-altitude flight regimes on frustrum reentry heatshields, TTI has designed a 20-deg half-angle wedge holder (Fig. 5) for use in the NASA IHF and AEDC H2 arc heaters [13]. The holder designed for this application differs from the more usual "splash-test" sample holder to more closely simulate surface forces produced by gas-wall shear and surface pressure gradients over frustra-mounted TPS. These forces can have a strong influence on TPS ablation and spallation. Thus, relative to "splash" tests, this 20-deg wedge holder configuration requires the added complexity of a leading edge which must be survivable for flight simulations in excess of 500 sec. To prevent leading edge ablation and excessive heat soaking to the wedge substructure, water-cooling for the leading edge was mandated. As a new design, this new 20-deg wedge holder had no prior calibration or supporting data to define the heating and pressures incident on the TPS sample surface. The water-cooled leading-edge holder and copper plates were fabricated and tested to replicate the 20-deg TPS wedge holder, with Gardon gages and pressure ports installed over the plate planform as shown in Fig. 5.

Table 2. Stagnation Dwell Calorimeter Performance

Parameter	Predicted	Measured
Stagnation Point Cold-Wall convective Heat Flux, Btu/ft^2-sec	1660	1750 (Fig. 4)
Stagnation Point Pressure, atm	1.2	1.2 (Measured with slug calorimeter, not dwell cal.
Cooling Water Flow, gpm	7.6 (@ 500 psi delta-P)	7.2 (@ 450 psi delta-P
Stagnation Point Surface Temperature, °F	510	660
Max surface Temperature (F)	810 °F at 60° off Stagnation Point	(Not measured, but copper surface not discolored, indicating temperatures less than 1200 °F.
Gardon Gage Backface Temperature, °F	270	(Not measured, but Teflon Insulation was not damaged.

NASA IHF, 6.0-in.-exit-diam Nozzle Operating at I = 6,000 amps, Pc = 120 psia, and Probe Stagnation Point 3.0 in. aft of Nozzle Exit

Validation of the Gardon wedge calorimeter data and heat flux mapping over the TPS sample planform was accomplished in the IHF using TTI Teflon ablation samples per the technique described previously. A typical IHF data set taken on 12 IHF runs with the TTI 20-deg wedge calorimeter is presented in Fig. 10 for a nominal "pull-out" condition with the IHF operating at the maximum condition allowed for continuous operation of the water-cooled leading edge.

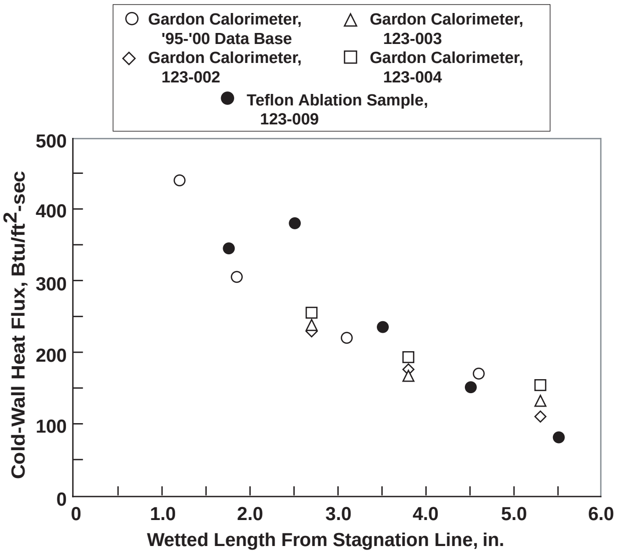


Fig. 10. Comparison of Inferred Teflon and TTI 20-deg Gardon Wedge Calorimeter Heating Rates, IHF Pullout Condition

AEDC Arc Facility Description

The DoD arc-heated test facilities at AEDC [15] include two high-pressure segmented arc heaters (HEAT-H1 and -H3) and one Huels arc heater (H2). Both types utilize a high-voltage, d-c electric arc discharge to heat air to total temperatures up to 13,000°R. High-pressure test flows are achieved by confining the electrical arc discharge to a water-cooled plenum section capable of operation at chamber pressures above 100 atm. The combination of high-enthalpy test gas and high plenum pressure makes it possible to obtain stagnation and wedge surface heat fluxes representative of flight at speeds in excess of Mach 20 at high dynamic pressures simulating flight at low altitude where turbulent boundary layers are the general rule at hypersonic speeds. The DoD arcs at AEDC provide the enthalpy-pressure combinations required for aerothermal testing simulating flight at pressure altitudes below 100 kft and Mach numbers above Mach 8. The DoD arcs can provide model stagnation pressures approaching 100 atm, with maximum stagnation heating rates duplicating those of reentry vehicle bodies.

The AEDC H1 Test Unit [16], a continuous flow, electric arc-heated testing facility, expands arc-heated air to a supersonic freejet in the atmospheric environment of the test building. The H1 arc heater operates at chamber pressures up to 135 atm, with centerline enthalpy levels from 1000 to 8500 Btu/lb$_m$. An optional stilling/mixing chamber can be installed to mix cold air with the arc-heated air, thereby decreasing the total enthalpy and increasing the flow Reynolds number. The H1 test unit has interchangeable contoured nozzles and is equipped with a multiple-strut, programmable rotary model injection system capable of positioning test models sequentially into the test free jet.

The H2 Test Unit is an arc-heated aerothermal tunnel providing high-enthalpy flow at high Mach numbers and dynamic pressures simulating hypersonic flight at pressure altitudes from 70 to 160 kft [17]. H2 utilizes an N-4 Huels-type arc heater to generate high-temperature air for expansion through a hypersonic nozzle into the subatmospheric test cell at Mach numbers from 5 to 9 [18-19]. Direction and distribution of the injected air can be selected to optimize the enthalpy distribution across the flow to match specific test requirements, and run times up to 30 minutes are available in H2 for selected operating conditions.

Dwell Wedge Calorimeters in AEDC H1 — TTI has supported AEDC in the design and use of Gardon gage calorimeters, as well as Teflon ablation samples to aid in the definition of the aerothermal conditions on wedge configurations used to test TPS materials at reentry conditions. TTI calorimeters have been in use in the AEDC H1 arc facility beginning in 1996. Since that time, a number of calorimeter configurations have been run in the H1 and H2 test facilities. The TTI dwell calorimeters have been used to complement the swept calibration probes used at AEDC to define radial heat flux and pressure profiles in the following ways:

1) To provide comparative heat flux and pressure measurements made by the transient AEDC probes;

2) To provide time-integrated heat flux and pressure measurements on specific wedge geometries at a given test condition, and to quantify heating transients traceable to flow unsteadiness or other sources;

3) To provide direct heat flux and pressure measurements of wedge geometries which are not duplicated by the AEDC wedge and stagnation swept probes;

4) To provide calibrations of radiant heat sources used to preheat material samples prior to injection into the H1 and H2 arcjets. The high resolution of the Gardon gages at heat flux levels from 10-100 Btu-ft^2-sec make them very well suited for this task, which is not possible using the standard uncooled, transient wedge probes.

To simulate the relatively low-altitude, high surface pressure reentry flight regimes on frustrum heatshields, TTI designed 15- and 30-deg half-angle wedge holders for use in AEDC's H1 arc heater. Shown in Fig. 6 is the 15-deg, double-sides wedge holder with TPS samples mounted on both sides, allowing the testing of two TPS samples on one sting. A similar wedge holder is used to orient a single sample at 30 deg relative to the flow. As compared to the 15-deg holder, the 30-deg holder increases the sample edge pressure and convective heating rate.

The double-sided, 15-deg wedge calorimeter (shown in Fig. 6) consists of two instrumented calorimeter plates with pressure orifices, one mounted on each side of the copper wedge body, with 0.2-in. radius ablative carbon-carbon leading edge. Each calorimeter plate contains eight Gardon gage heat flux sensors and three pressure measurement orifices, connected to Kulite strain-gage pressure transducers through stainless steel pressure tubing. A typical set of Gardon heat flux data curves acquired in the AEDC H1 facility with the TTI two-sided, 15-deg wedge Gardon calorimeter is presented in Fig. 11. The plot in Fig. 12 was assembled using many such

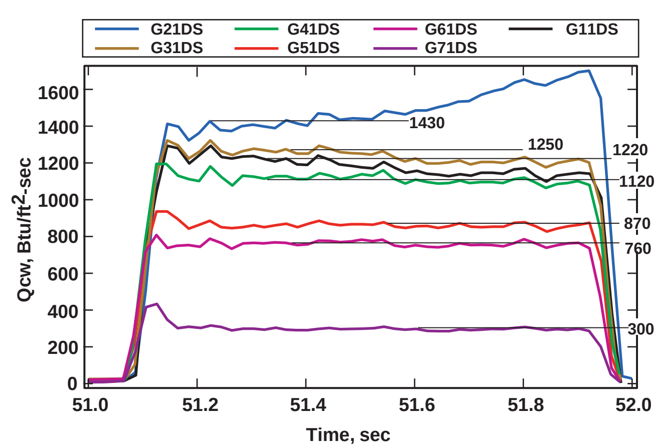


Fig. 11. Typical Gardon Gage Responses for TTI 15-deg Wedge

Gardon data sets, acquired on multiple runs at the same nominal test condition. All of the heat flux data shown in Fig. 12 were recorded with the H1 arc facility operating at the 105-atm chamber pressure test condition configured with the Mach number 3.5 nozzle, with a flow-field nominal inferred enthalpy of 6500 Btu/lb$_m$. The data are plotted as multiple discrete points measured on many runs at various wedge axial stations.

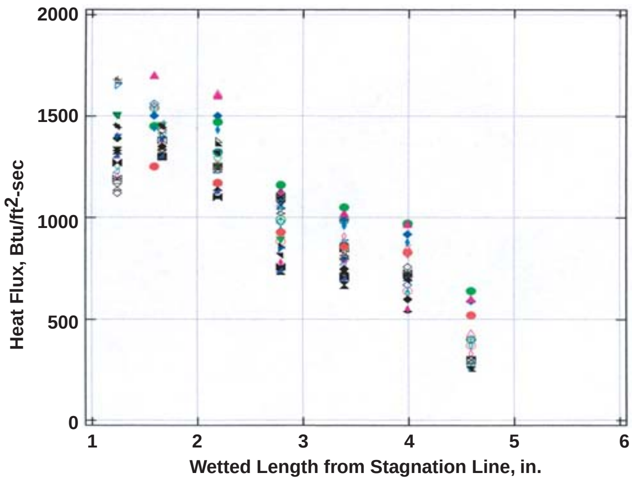


Fig. 12. Gardon Heat Flux Data Measured with TTI's 15-deg Wedge Calorimeter

Low-Temperature Ablator Witness Plate Calorimeters — TTI and Southern Research, Inc. (SRI) have also fabricated Teflon ablation samples for use on the 15- and 30-deg wedge holders to provide an ablation-inferred heating rate over the heated planform of the entire TPS sample. An example of the Teflon ablation sample shape change data used to supplement the Gardon measured heating data, is presented in Fig. 13. The figure presents an ablation contour over the entire heated planform of the Teflon sample. Figure 14 presents the heating data inferred from recession measurements along the centerline of the Teflon sample. The Teflon heating rates were calculated from the ablation data using the Teflon ablation model described in with a derived, matched enthalpy (see previous section) of 5000 Btu/lb$_m$ for H1 [13], and a Teflon exposure time of 0.98 sec. Also presented in Fig. 14 for comparison are the average heating data inferred from the use of the AEDC swept calorimeter in the same test series. The heating rates inferred from the Teflon ablation appear to be higher than the AEDC data in the forward region of the sample, and are within the upper region of the TTI Gardon data scatter.

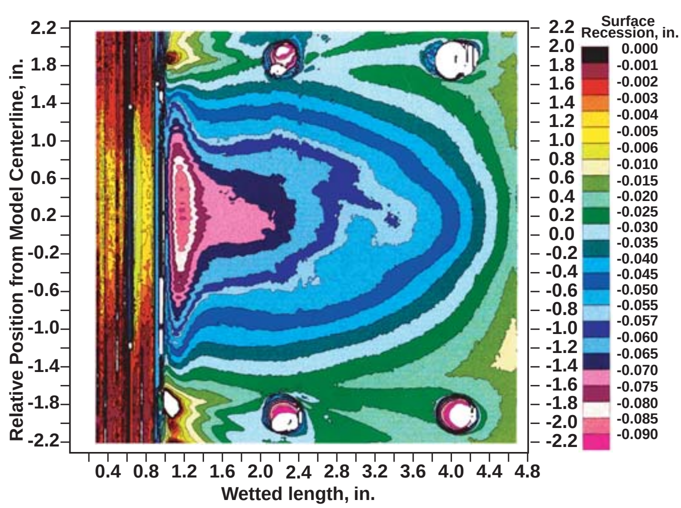


Fig. 13. Sample Shape-Change Data from a Teflon 15-deg Ablation Sample

Typical pressure data acquired for the 15-deg wedge model using the TTI Gardon calorimeter and the 15-deg AEDC swept calorimeter/pressure probe are presented in Fig. 15. Figure 16 presents the TTI Gardon calorimeter data and inferred Teflon heating data acquired in H1 for the 30-deg wedge holder. Although the Gardon and Teflon data were acquired on only a single sample and a single insertion, respectively, the results compare favorably.

Dwell Wedge Calorimeters in AEDC H2 — In addition to its use in the NASA IHF arc facility, the TTI 20-deg wedge

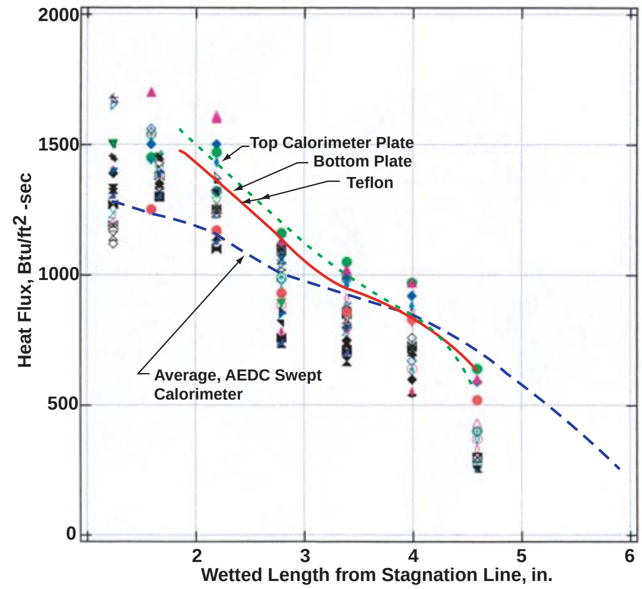


Fig. 14. Comparison of 15-deg Wedge Heating Rates Measured with TTI Gardon Calorimeter, AEDC Swept Calorimeter and Teflon Ablation Sample

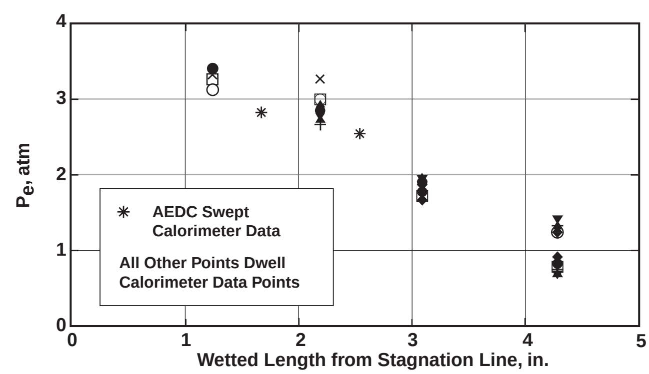


Fig. 15. Comparison of Edge Pressure Data Measured with the TTI Gardon Calorimeter and the AEDC Swept Calorimeter

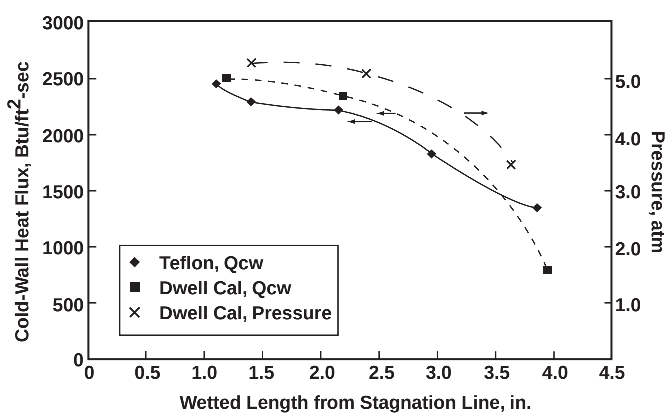
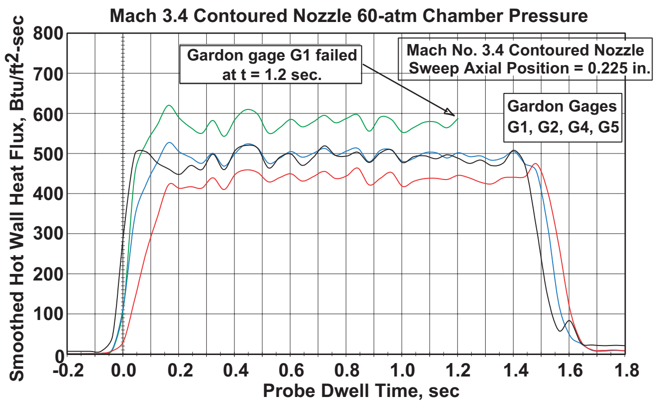
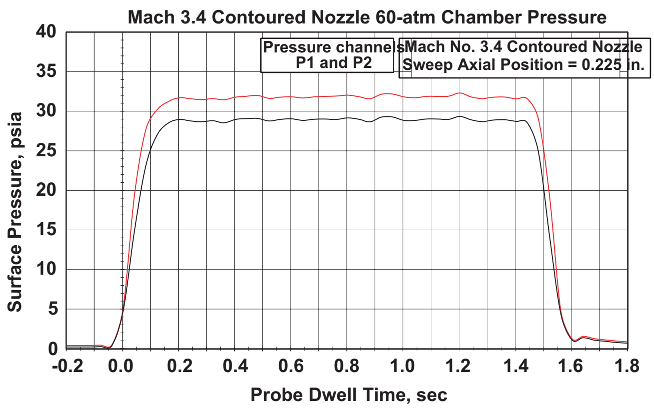


Fig. 16. Comparison of 30-deg Wedge Heating Rates Measured with the TTI Gardon Calorimeter and Teflon Ablation Sample



a. Smoothed Hot Wall Heat FLux



b. Surface Pressure

Fig. 17. TTI 20-deg Dwell Calorimeter Measured in AEDC H2 Arc

configuration discussed previously (see Fig. 5) has been used on several occasions in the AEDC H2 arc-heated wind tunnel. The calorimeter consists of two instrumented calorimeter plates with pressure orifices, one mounted on each side of the cooled copper wedge body, with a 0.375-in.-radius, water-cooled leading edge. Each calorimeter plate contains five Gardon gage heat flux sensors and two pressure measurement orifices, which are connected to Kulite strain-gage pressure transducers through stainless steel pressure tubing. A typical data set of TTI wedge heat flux and pressure measurements made in the H2 arcjet during a 1.4-sec calorimeter exposure is presented in Figs. 17a and b. The heat flux and pressure data were recorded with the H2 arc facility operating at the 60-atm chamber pressure test condition, with a nominal bulk enthalpy of 2200 Btu/lb_m. The probe was inserted and held on centerline of the 5.0-in.-exit-diam nozzle for the specified 1.0-sec dwell, with the data recorded at a rate of 100 Hz. The data sets generated by this probe to date in the H2 facility have been useful in quantifying flow-field properties for the new 5.0-in.-diam nozzle fabricated recently to address terminal dive simulations for specific reentry vehicle trajectories.

Summary

High-enthalpy, arc-heated flows used for aerothermal testing present a challenging thermal environment for flow characterization instrumentation. This paper describes the design and use of cooled dwell calorimeter probes used for heat-transfer and pressure characterization of the NASA and DoD arc facilities located at Moffett Field, CA, and Arnold Air Force Base, TN, respectively. The dwell calorimeters were designed and fabricated by Thermal Technologies, Inc. (TTI) for use in the NASA IHF and the USAF H1 and H2 arc test facilities at AEDC. The calorimeters incorporate active cooling systems which enable them to withstand the severe arc-heated environments for durations sufficient for acquisition of steady-state data. The water-cooled TTI probe designs have proven their survivability in the extreme aerothermal environments of both the NASA and DoD arcjet facilities, providing valuable flow calibration information on a variety of test configurations and test conditions.

Acknowledgments

Hardware development, fabrication, testing and data presented in this paper were sponsored by NASA, the U.S. Navy, and the U.S. Air Force.

References

1. Smith, D. M., and Felderman, E. J., “Aerothermal Testing of Composites and Structures in the DoD AEDC Arc-Heated Ground Test Facilities,” Tri-Service Sponsored Symposium on Advancements in Heat Shield Technology and Applications, Redstone Arsenal, AL, April 2002.

2. Auweter-Kurtz, M., Feigl, M., and Winter, M., “Diagnostic Tools for Plasma Wind Tunnels and Reentry Vehicles at the IRS,” DTIC Report No. ADP010739, April 2000, pp. 2B-7 to 2B-10.

3. Kennedy, W. S., Rindal, R. A., and Powars, C. A., “Heat Flux Measurement Using Swept Null-Point Calorimetry,” AIAA-71-428, Tullahoma, TN, April 1971.

4. Fay, J. A., and Riddell, F. R., “Theory of Stagnation Point Heat-Transfer in Dissociated Air,” *Journal of Aerospace Sciences*, Vol. 25, 1958, pp. 73-85.

5. Carnahan, K. R., Hartman, G. J., and Neuner, G. J., “Development of TPS Flight Test and Operational Instrumentation,” Aerotherm Report FR-75-135, January 1975.

6. Schultz, D. L., and Jones, T. V., “Heat-Transfer Measurements in Short-Duration Hypersonic Facilities,” AGARD-AG-165, February 1973.

7. ASTM Standard Test Method Designation, “Standard Test Method For Measuring Extreme Heat-Transfer Rates from High-Energy Environments Using a Transient, Null-Point Calorimeter,” American Society for Testing and Materials, ASTM E598-96, Oct. 1996.

8. ASTM Standard Test Method Designation, “Standard Test Method For Measuring Heat Flux Using a Copper-Constantan Circular Foil Heat-Flux Gage,” American Society for Testing and Materials, ASTM E511-73, November 1973.

9. Gardon, R., “An Instrument For the Direct Measurement of Intense Thermal Radiation,” *The Review of Scientific Instruments*, Vol. 244, May 1953, pp. 366-370.

10. Trimmer, L. L., Matthews, R. K., and Buchanan, T. D., “ Measurement of Aerodynamic Heat Rates at the AEDC von Karman Facility,” Fifth International Congress on Instrumentation in Aerospace Simulation Facilities, September 1973, pp. 35-44.

11. *Handbook of Aerospace Material Properties*, The Aerospace Corporation, l968

12. Wentink, T.,"High Temperature Behavior of Teflon," AFBMD-TN-59-15, July l959

13. Moody, H. L., "Reentry Vehicle Heatshield and Antenna Window Materials Ground Test Evaluations," AFRL-ML-WP-TR-l99-4l33, April l999.

14. Balter-Peterson, A. Nichols, F., and Mifsud, B. “Arc Jet Testing in NASA Ames Research Center Thermophysics Facilities,” AIAA-92-5041, December 1992.

15. Horn, D. D. and Smith, R. T., “AEDC High-Enthalpy Ablation Test (HEAT) Facility Description, Development and Calibration,” AEDC-TR-81-10 (AD-A101747), July 1981.

16. Carver, D. B., “ Flow Calibrations of the 9-in. and 24-in. Exit Diam. Nozzles in the AEDC HEAT-H2 High-Enthalpy Arc-Heated Wind Tunnel,” AEDC-TR-95-19 (AD-B208590), March 1996.

17. Felderman, E. J., Horn, D. D., Carver, D. B., and Davis, L. M., “AEDC Expanded Flow Arc Facility (HEAT-H2) Description and Calibration,” Proceedings of the 38th International Instrumentation Symposium, Paper No. 92-0191, April 1992.

18. Stewart, J. H., “AEDC H2 Facility – New Test Capabilities for Hypersonic Air Breathing Vehicles,” AIAA-93-2679, Orlando, FL, July 1993.

19. Smith, D. M., and D. B. Carver, "Flow Calibration of Two Hypersonic Nozzles in the AEDC HEAT-H2 High-Enthalpy Arc-Heated Wind Tunnel," AIAA-93-2782, Orlando, FL, July 1993.