

Heat Flux Measurements in the Ohio State University Rate of Heat Release Apparatus

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16. Abstract A copper slug calorimeter was used to measure the cold-wall heat flux and the convective heat transfer coefficient in the Ohio State University (OSU) Rate of Heat Release Apparatus specified in Federal Aviation Regulation (FAR) 25.853(a-1). The copper slug calorimeter is an American Society of Testing (ASTM) primary standard used for measuring the heat flux of radiant energy sources (ASTM E 662) and oxyacetylene torches (ASTM E 457). In contrast to the Gardon Heat Flux Sensor, the slug calorimeter provides an absolute measurement of heat flux and does not require calibration. The average convective heat transfer coefficient is obtained from the transient response of the slug calorimeter and is potentially useful as a system diagnostic since it is sensitive to air flow rate, temperature, and turbulence within the OSU chamber. Slug calorimeter construction, measurement of the heat transfer coefficient, and both global and local (e.g., at the impinging pilot flame) heat fluxes incident on the sample are discussed. The accuracy and reproducibility of sample heat fluxes are compared to those obtained with a Gardon Heat Flux Sensor. On average, the heat flux measured with an optimal copper slug calorimeter, when taking into account the absorptivity of the black surface coating, is within experimental error of the value measured with a National Institute of Standards and Technology (NIST) calibrated Gardon Heat Flux Sensor.					
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INTRODUCTION

The Ohio State University (OSU) fire calorimeter is the mandated test apparatus for aircraft interior materials as described in Federal Aviation Regulation (FAR) 25.853(a-1). Initial round-robin testing by the Federal Aviation Administration (FAA) and three members of the Aerospace Industries Association (AIA) of five types of composite panels and three thermoplastic materials showed a 25.2% Relative Standard Deviation (RSD) for the 2-minute integrated heat release when tests were conducted in accordance with the American Society of Testing (ASTM) E 906, "Heat and Visible Smoke Release Rates for Materials and Products"[1]. Although other equipment modifications were made to the OSU [2], standardization of the various test apparatus with a single heat flux transducer was thought to be the most important factor in reducing the interlaboratory disparity to the more manageable 14.1% RSD that was seen for the second round robin. A third round robin involving 15 laboratories in the United States, Europe, and Canada and 13 aircraft materials demonstrated 7.7% RSD for the 2-minute integrated heat release and 7.8% RSD for the peak heat release value [3].

Variation in the specified 35 kW/m^2 incident heat flux at the sample surface remains a potential source of error and significant effort has been expended in addressing this problem. This paper addresses the measurement of incident heat flux in the OSU apparatus at both the overall sample surface and at the spot of pilot flame impingement. The slug calorimeter represents a potential corroborating method for Gardon Heat Flux Sensor measurements of cold-wall heat flux in applications where measurement of constant, uniform heat flux is required [4].

Unlike the Gardon Heat Flux Sensor, the slug calorimeter is a primary standard. This means calibration is not required, since the temperature change, weight, and surface area of the slug are measured and used to calculate the heat flux for a mass of known heat capacity. The weight of the copper slug is measured on a calibrated balance, accurate to the milligram. The heat capacity of copper at 18°C (65°F) is 384.9 J/(Kg-K) [5]. The surface area of the slug is measured using a ruler. The slug temperature is recorded using a data acquisition system and a thermocouple. The rate of temperature change of the copper slug is then defined as the change of energy applied to the slug. The only variable remaining for the system is the absorptivity (α) of the blackened coating that is applied. If all incident radiation is assumed to be completely absorbed, then $\alpha = 1.00$. The actual absorptivity (α) of 3M ECP-2200 Solar Absorber Coating has been determined by reflectance Fourier transform infrared spectroscopy (FTIR) to be $\alpha = 0.96$ [6]. Since energy can only be lost through conduction, convection, or reradiation, the resulting energy balance is compared to the Gardon gauge test standard, which was used to calibrate the radiant source immediately prior to insertion of the slug.

ANALYSIS

Figure 1 shows the geometry of the 10- by 10- by 0.63-cm slug calorimeter in the OSU heat release rate calorimeter sample chamber. A cold-wall radiant energy flux of 35 kW/m^2 generated by the glow bars is incident on the 100-cm^2 sample/slug surface in a forced convective environment.

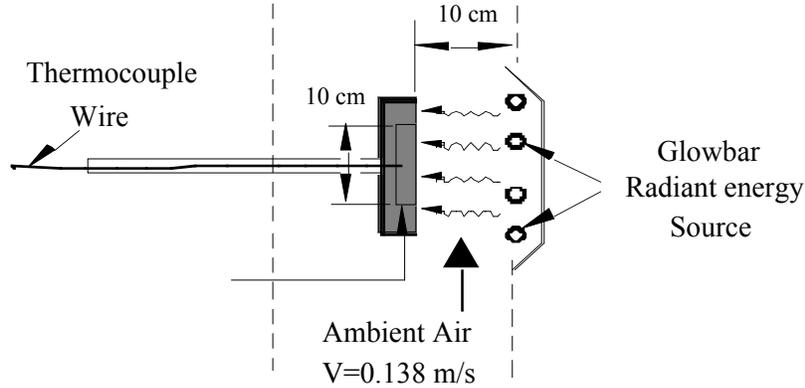


FIGURE 1. OSU CHAMBER AND ENVIRONMENT

Calculating the Reynolds number (Re) for the OSU chamber length $L = 0.79$ m for 300°C air at linear velocity $V = 0.138$ m/s (including sample holder obstruction)

$$Re = \frac{VL}{\nu} = \frac{(0.121 \text{ m/s})(0.79)}{1.6 \times 10^{-5} \text{ m}^2/\text{s}} = 6100 \quad (1)$$

shows that the flow is laminar throughout since $Re < 5 \times 10^5$. The average convective heat transfer coefficient at the sample surface \bar{h} is calculated from the average Nusselt number (Nu) in laminar flow: $Nu = \bar{h}l/k = 0.664 Re^{1/2} Pr^{1/3}$ for sample (slug) length $l = 0.1$ m, air thermal conductivity $k_a = 0.045$ W/m-K (300°C), and Prandtl number $Pr = 0.7$. Thus

$$\bar{h} = \frac{(0.664)(0.045 \text{ Wm}^{-1}\text{k}^{-1})(6100)^{1/2}(0.7)^{1/3}}{(0.1 \text{ m})} = 21 \text{ Wm}^{-2}\text{k}^{-1} \quad (2)$$

The transient response of the calorimeter to an instantaneously imposed heat flux α , is modeled using a lumped analysis which treats the material as having a uniform temperature which changes with time. The error of a lumped analysis is of the order of the dimensionless Biot number $Bi = \bar{h}b/k_c$, which is the ratio of the internal/external resistance to heat flow for a copper plate thickness b and thermal conductivity k_c . If the error in the lumped analysis is to be less than 10^{-3} (0.1%) the upper bound on the plate thickness is

$$b < \frac{(10^{-3})(377 \text{ Wm}^{-1}\text{K}^{-1})}{(21 \text{ Wm}^{-2}\text{K}^{-1})} = 0.018 \text{ m} \quad (3)$$

A copper plate less than 1.8 cm thick is therefore suitable for a slug calorimeter in the convective, laminar flow OSU environment.

The lumped energy balance for the slug is

$$\left[\text{Rate of change of slug energy} \right] = \left[\text{Rate of heat addition from radiant source} \right] - \left[\text{Rate of heat loss to surroundings} \right]$$

For a slug of absorptivity α at uniform temperature T exposed to a radiant heat flux \mathcal{Q} in a convective environment, the mathematical form of the energy balance is

$$\rho V c \frac{dT}{dt} = \alpha A \mathcal{Q} - \bar{h} A (T - T_o) \quad (4)$$

Defining $\theta = (T - T_o)$ and $\tau = \rho V c / \bar{h} A = \rho b c / \bar{h}$, equation 4 takes the familiar form for the transient response of a dynamic system with response time τ subject to a forcing function $\mathcal{Q}(t)$

$$\frac{d\theta}{dt} + \frac{\theta}{\tau} = \frac{\alpha}{\rho b c} \mathcal{Q}(t) \quad (5)$$

COLD-WALL HEAT FLUX.

The solution of equation 5 for the transient temperature change of the slug in the OSU for an incident heat flux, \mathcal{Q}_o imposed at $t = 0$, $T = T_o$ is

$$\theta(t) = \frac{\alpha \mathcal{Q}_o}{\bar{h}} (1 - e^{-t/\tau}) \quad (6)$$

From which the slope of the transient temperature rise is

$$\frac{dT}{dt} = \frac{d\theta}{dt} = \frac{\alpha \mathcal{Q}_o}{\rho b c} \exp[-t/\tau] \quad (7)$$

For $t \ll \tau$, or, as $t \rightarrow 0$ the term $\exp[-t/\tau] \rightarrow 1$ in equation 7 and the slope of the temperature-time curve is related to the cold-wall heat flux as

$$\frac{mc}{\alpha A} \left[\frac{dT}{dt} \right]_{t \rightarrow 0} = \mathcal{Q}_o \quad (8)$$

Equation 8 is the defining equation for cold-wall heat flux measured by slug calorimetry according to ASTM E 662 (F 814) “Standard Method for Specific Optical Density of Smoke Generated by Solid Materials (for Aerospace Applications),” and was proposed by the National Institute of Standards and Technology (NIST) as the method to calibrate the radiometer used during routine operation of the instrument [7].

CONVECTIVE HEAT TRANSFER COEFFICIENT.

The heat transfer coefficient was estimated to be $\bar{h} = 21 \text{ W/m}^2\text{-K}$ from equation 2 for use in calculating the Biot modulus to determine the suitability of the lumped analysis. A more accurate method for determining \bar{h} is to take the natural logarithm of equation 7

$$\ln \left[\frac{dT}{dt} \right] = \ln \left[\frac{\alpha A \mathcal{Q}_o}{mc} \right] - \frac{t}{\tau} \quad (9)$$

and obtain τ from the reciprocal slope of a plot of $\ln[dT/dt]$ versus time at the initiation of heating when the incident heat flux is equal to the net heat flux entering the calorimeter. The average cold-wall surface convective heat transfer coefficient is then calculated from the slug mass, area, and heat capacity m , A , and c , respectively as

$$\bar{h} = \frac{mc}{\tau A} \quad (10)$$

or,

$$\bar{h} = -\frac{mc}{A} \frac{d \ln\left(\frac{dT}{dt}\right)}{dt} \quad (11)$$

Less accurate is the determination of \bar{h} by the transient temperature rise and steady-state methods because the incident heat flux has decreased relative to the cold-wall value ($\alpha < \alpha_0$) because of reradiation by the slug and conductive losses from the back and sides of the slug at the high equilibrium temperature ($\geq 500^\circ\text{C}$). In the transient temperature rise method, $\theta(t) = \theta(\tau)$ is determined at $t = \tau$ and from equation 6

$$\bar{h} \approx \frac{\alpha \alpha_0}{\theta(\tau)} (0.632) \quad (12)$$

At steady-state when the slug temperature is constant over an extended period of time, $\theta(t) = \theta(\infty)$, $d\theta/dt = 0$, and the convective heat transfer coefficient is obtained from equation 6 as

$$\bar{h} = \frac{\alpha \alpha_0}{\theta(\infty)} \quad (13)$$

Values for \bar{h} determined using equations 12 or 13 using the nominal α_0 will be larger than the cold-wall value (equation 9) because reradiation and conduction heat losses to the surroundings become significant at $T \gg T_0$.

EXPERIMENTAL

SLUG CALORIMETER CONSTRUCTION.

RADIANT HEAT FLUX. Three thicknesses of 100% pure copper (0.675, 1.27, and 6.35 mm) are used to make the slug calorimeters described below. Each foil was cut on a precision metal shear to be 100 by 100 mm (3.93 inches) square. Four holes are drilled using a No. 59 (0.042 in.) bit located 2 mm from each corner. The slugs are then weighed to five significant figures, 58.796 g, 113.31 g, and 556.79 g, respectively. High-temperature calcium silicate mill board, 12.8 mm (1/2 in.) thick (40 lbs./cu. ft. density, thermal conductivity 0.8 Btu @ 800° F), is cut 152 mm (6 in.) square. Strips are cut to 21 mm (7/8 in.) wide by 101 mm (4 in.) and 152 mm (6 in. long). The strips are attached using Saueriesen Insa-lute cement on the surface of

and along the edge of the square piece. When assembled, the frame for the slug looks like a 1- by 6- by 6-in. board with a 4- by 4- by 1/2-in.-deep recess in the center. Four 3.175-mm (1/8-in.) holes are drilled midway along the diagonal bisector from the corners of the frame and the corners of the recess. One-eighth-inch copper (3.175-mm) refrigeration tubing is cut into 25.4 mm (1 in.) lengths that are cemented into the holes. A Nichrome wire (0.025 inch) passes through the holes in the corners of the slug and the copper reinforcing tubing to suspend the slug above the recess, without touching the mill board frame. Details are shown in figure 2.

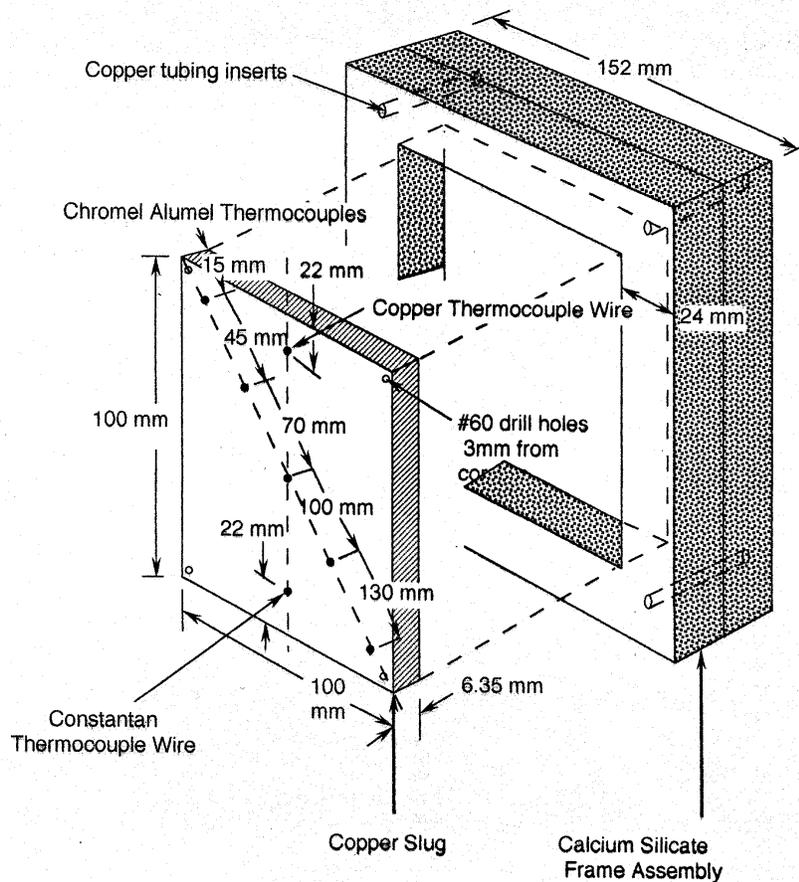


FIGURE 2. SLUG CALORIMETER

The copper is cleaned using 15% hydrochloric acid solution, rinsed with water, and dried with acetone. The face of the copper slug is blackened with 3M ECP-2200 Solar Absorber Coating, which is applied with a polyurethane foam brush. After the coating is allowed to dry, Kaowool batting is pressed loosely between the side of the copper slug and the frame to minimize convective heat losses.

The slug calorimeter assembly is placed in a standard OSU Rate of Heat Release Apparatus sample holder that has a hole in the retainer spring to allow the thermocouple lead wires to pass through the back. A special sample injector is fabricated from 24-gauge stainless steel, 1-in. conduit tubing, and aluminum sheet which replaces the outer chamber door. It is held in place

using vise-grip sheet metal pliers. In this way, the thermocouples pass out of the OSU apparatus to the data acquisition system, yet allow the slug to be placed in the holding chamber and injected into the OSU apparatus in the same manner as a test specimen.

Five 30-gauge chromel/alumel (Type K) thermocouples are evenly spaced along the diagonal of the 6.35-mm slug, 15 mm from the corners, at the geometric center and at the bisector between those points (shown roughly on figure 2, ± 3 mm). One copper-constantan (Type T) thermocouple is placed along the vertical center line 22 mm (7/8 in.) from the top and bottom of the slug. Type T was chosen because, although the maximum equilibrium temperature exceeds the operating range of that type of thermocouple, the slug itself creates the bimetal junction. Each conductor of the Type T thermocouple was 0.508 mm (0.020 in.) and was individually sheathed. The 6.35-mm slug was thick enough that thermocouple attachments were made by drilling half way through the slug, inserting the thermocouple or individual wire, and peening the copper slug to hold the wire in place.

The two thin slugs (1.27 and 0.675 mm) are constructed by silver soldering three 30-gauge chromel-alumel thermocouples along the center line at the midpoint and 38 mm (1.5 in.) to either side. Tests were conducted in both the horizontal and vertical orientation.

PILOT FLAME HEAT FLUX. The 6.35-mm slug calorimeter is modified to measure the heat flux of the OSU apparatus ignition pilot. The OSU apparatus pilot impinges the test specimen 5 mm above the lower edge on the vertical center line. The pilot burner consists of 6.3-mm steel tubing having 0.8-mm wall situated 10 mm from the specimen face, through which passes 120 cm³/min methane and 850 cm³/min air. The slug calorimeter modification added a second copper slug to the slug assembly. A 10.7-mm (27/64- inch) hole was drilled 13 mm deep into the mill board at the spot of pilot impingement. A 9.5-mm (reagent grade) copper rod is precisely cut to 10 mm long and weighed. The mass of the copper slug is 6.0694 grams. Single conductors of copper and constantan are peened into the back of the slug and the slug placed into the hole drilled to accommodate it. Kaowool ceramic insulation is pressed between the slug and the wall of the hole to hold the slug in place and insulate it from the wall. The slug is painted with the same solar absorber coating noted previously and connected to the data acquisition system. When the slug assembly is in position the pilot flame covers approximately 2/3 of the surface area of the 9.5-mm slug.

TEST PROCEDURES

A Strawberry Tree QuickLog PC V2.4.0 Data Acquisition System with T21 thermocouple board is used to gather the slug calorimeter thermocouple data. Analog input is configured to log in units of centigrade degrees in low-noise mode with a data acquisition rate of 17 μ s per channel, with one second between each sample set. It was found early on that only one of the thermocouples could be grounded or the data was excessively noisy due to ground loops. Therefore, all but one negative to ground jumper was disconnected during wiring of the slug calorimeter. It was also found that the jaws of the vise-grip pliers should be insulated using fiberglass tape or dissimilar metal junctions could feed erroneous voltages through the ground lead. Each thermocouple is recorded once each second, with the timing such that there is exactly one second between each data point for each channel.

Tests of the pilot flame heat flux are conducted by first checking the radiant heat flux with the Gardon gauge. The slug calorimeter is then run with the pilot flame off and two measurements are made, one for each slug. The assembly is allowed to cool back to room temperature. The Gardon gauge again checks the heat flux, the pilot is then lit, and the heat flux determined with both slugs.

OSU APPARATUS HEAT FLUX CALIBRATIONS

A Thermogauge Model 1000-1 Gardon Heat Flux Sensor was calibrated by the NIST. This particular gauge was used as the FAA standard during round-robin testing of the OSU apparatus as an appropriate regulatory device and was used as the basis for comparison to the slug calorimeters described in this report. Repeated testing of the Gardon Heat Flux Sensor at the William J. Hughes Technical Center over a period of 9 years and multiple calibration checks at NIST have shown the calibration factor to be repeatable to 0.65%. The most recent calibration performed at NIST was 0.6556 Watts/cm²/millivolt output.

The OSU Rate of Heat Release Apparatus is operated in accordance with the regulatory requirement of 14 FAR 25.853 Appendix F. The Gardon Heat Flux Sensor is inserted into the OSU apparatus after a minimum of two hours to equilibrate to operating temperature. The millivolt output of the Gardon sensor is recorded with the Strawberry Tree Acquisition System. A minimum of 10 data points are averaged to determine the reading. The Gardon Heat Flux Sensor is then removed. The thermocouple acquisition system is started, the outer door of the OSU apparatus is opened, and the slug calorimeter assembly is clamped in place. The radiation doors of the OSU apparatus are opened and the slug is inserted into position at the preset distance of 100 mm from the radiation doors. Typically, the slug is allowed to reach 200°C before removal. A few tests were run where the slug was allowed to reach equilibrium temperature (approximately 510°C). The high temperature, however, causes the black absorber coating to peel and crack, and this requires refinishing of the slug. The time/temperature data is manipulated after the test with Microsoft Excel software.

Typical runs of the three slug calorimeters at a nominal heat flux of 35-kW/m² (3.5 Watts/square centimeter) are shown in figure 3. Differences in the final equilibrated temperature are consistent with differences in actual heat flux.

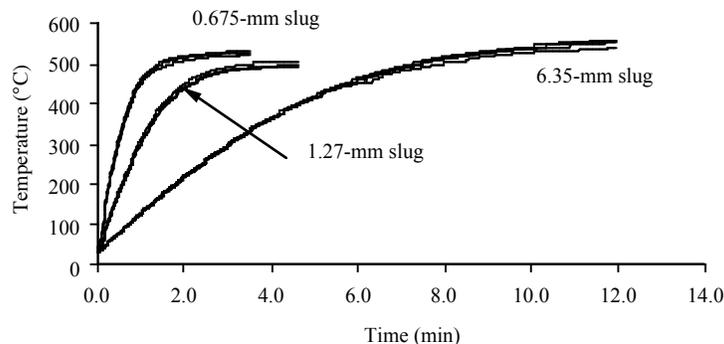


FIGURE 3. TEMPERATURE HISTORIES OF 0.675-, 1.27-, AND 6.35-mm-THICK SLUG CALORIMETERS IN OSU AT 35 kW/m² INCIDENT HEAT FLUX (Triplicate experiments shown for each calorimeter.)

All energy put into the system is accomplished by radiation. Losses of energy are either reflection of the incident radiation or convective heat transfer from the back of the slug to the sample holder. Conduction can only be accomplished through the suspending wires or the thermocouples themselves, and this quantity is assumed to be negligible. Convective heat transfer is zero if there is no temperature differential between the slug and its surroundings. If this number was zero, the rate of temperature change of the slug would be constant until the equilibrium temperature is reached at which point the rate of change becomes zero. Clearly, the convective losses will increase with increasing rate of temperature change of the slug, since the heat flow is proportional to the temperature differential. The rate of temperature change of the three slugs is shown in figure 4.

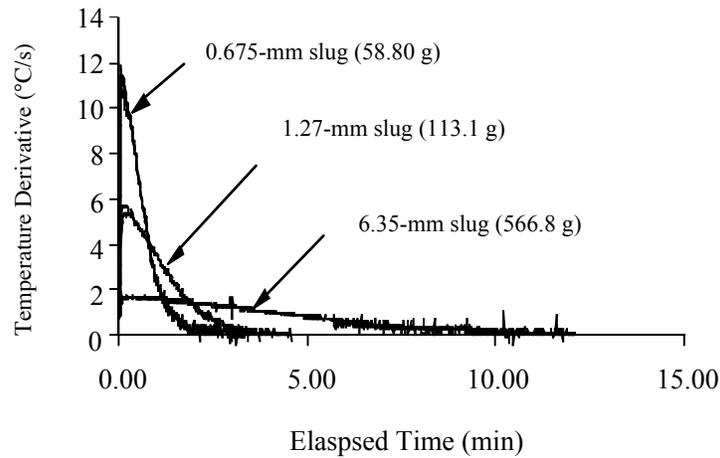


FIGURE 4. RATE OF TEMPERATURE CHANGE FOR 0.675-mm (58.8-g), 1.27-mm (113.1-g), AND 6.35-mm (558.8-g) SLUG CALORIMETERS (Triplicate experiments shown for each calorimeter.)

RESULTS

RADIANT HEAT FLUX.

Results of the radiant heat flux measurements using three thicknesses of copper slug are shown in tables 1 through 3. The cold-wall heat flux is calculated (equation 8, $\alpha=0.96$) from the rate of temperature change when the slug is initially inserted into the test chamber. The rate of temperature change is calculated by subtracting consecutive data points, with the result being in units of degrees centigrade per second.

The heat flux measurement using the 6.35-mm copper slug with the Type T (copper/constantan) thermocouple was within the experimental error ($\pm 1\%$) of the heat flux measured with the Gardon gauge. As expected the thick slug has a nearly constant initial rate of temperature change. The thin slug had the greatest temperature rise over the measurement interval and therefore had the largest convective heat loss. The rate of temperature change for the 6.35-mm slug is calculated using the first 10 consecutive data points after the rate of change stabilized. The 1.27- and 0.675-mm slugs use the first five data points to determine the rate of temperature change because the rate of temperature change itself begins to get smaller.

TABLE 1. HEAT FLUX MEASUREMENTS WITH THE GARDON GAUGE AND 6.35-mm/556.8-gram COPPER SLUG FOR TYPE K AND T THERMOCOUPLES

Experiment Number	Gardon Gauge W/cm ²	Slug Calorimeter (Type K) W/cm ²	Slug/Gardon Ratio (Type K)	Slug Calorimeter (Type T) W/cm ²	Slug/Gardon Ratio (Type T)
1	3.382	3.322	0.982	3.435	1.016
2	3.519	3.413	0.970	3.427	0.974
3	3.579	3.514	0.982	3.613	1.010
4	3.586	3.480	0.970	3.545	0.989
5	3.650	3.500	0.959	3.590	0.984
6	3.676	3.513	0.958	3.621	0.995
7	3.800	3.705	0.975	3.808	1.002
Average			0.971		0.996
RSD			1.06 %		1.48 %

TABLE 2. HEAT FLUX MEASUREMENTS WITH THE GARDON GAUGE AND 1.27-mm/113.1-gram COPPER SLUG WITH TYPE K THERMOCOUPLES

Experiment	Gardon Gauge	Slug Calorimeter	Ratio Slug/Gardon
	W/cm ²	W/cm ²	
1	3.546	3.012	0.849
2	3.521	3.053	0.867
3	3.470	2.975	0.857
4	3.454	3.096	0.896
5	3.425	2.760	0.806 (vert)
6	3.194	2.797	0.876
7	3.111	2.740	0.881
Average			0.862
RSD			3.37 %

TABLE 3. HEAT FLUX MEASUREMENTS WITH THE GARDON GAUGE AND 0.675-mm/58.81-gram COPPER SLUG WITH TYPE K THERMOCOUPLES

Experiment	Gardon Gauge W/cm ²	Slug Calorimeter	Slug/Gardon Ratio	Slug(corrected) W/cm ²	Slug/Gardon Ratio (corr)
1	3.482	2.630	0.755	2.932	0.842
2	3.433	2.648	0.771	2.907	0.847
3	3.360	2.646	0.788	2.934	0.873
Average			0.771		0.854
RSD			2.14 %		1.95 %

As mentioned, the initial rate of temperature change for the thin (0.675-mm) slug was very high, complicating measurement of the temperature derivative. At the inception of heating when $t \ll \tau$, the exponential term in equation 7 can be approximated as $\exp[-t/\tau] = (1 - t/\tau)$ showing that the temperature derivative in equation 14 is a linearly decreasing function of time at short times.

$$\frac{dT(t)}{dt} = \left[\frac{dT}{dt} \right]_{t=0} - \left[\frac{\alpha \phi_0 \bar{h}}{(\rho b c)^2} \right] \cdot t \quad (14)$$

The intercept at zero time $[dT/dt]_{t=0}$ is the initial rate of temperature rise which should be used in the calculation of the cold-wall heat flux. Consequently, a linear extrapolation of the best fit line to the temperature derivative versus time data at short times is performed to determine the initial slope $[dT/dt]_{t=0}$ as shown in figure 5.

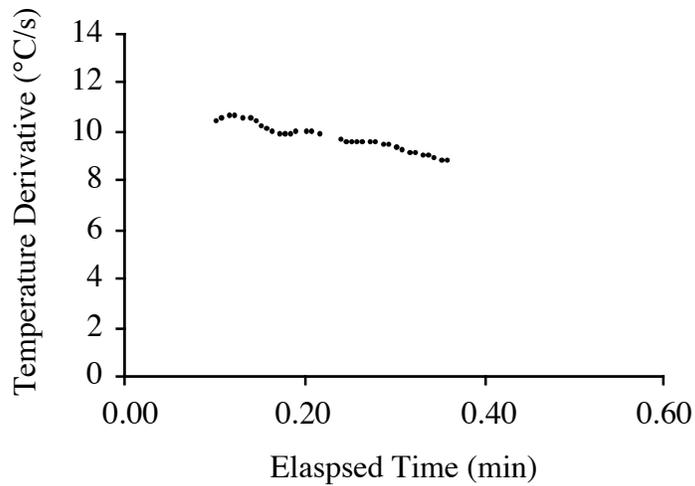


FIGURE 5. PROCEDURE FOR OBTAINING COLD-WALL HEAT FLUX BY EXTRAPOLATING TEMPERATURE DERIVATIVE DATA TO TIME OF SLUG INSERTION (zero elapsed time)

Heat losses to the sample holder increased as the thickness of the slug decreased. For slugs equipped with chromel/alumel thermocouples as the temperature sensor, the loss amounted to 3% for the 6.35-mm slug, 14% for the 1.27-mm slug, and 23% for the 0.675-mm slug. It is not clear why Type T performed better except that since the slug material itself forms the junction there can be no dissimilar metals voltage artifact. When the 0.675-mm slug is corrected for initial time and temperature heat losses are approximately the same as the 1.27-mm slug. Figure 6 shows the graphical interpretation of actual data for the 0.675-mm slug.

PILOT FLAME HEAT FLUX.

The pilot heat flux is found to be 27.16 W/cm^2 with a 3.56% RSD for triplicate runs. The pilot slug measured radiant heat fluxes, which were 12.6% higher than the large area radiation slug when the pilot was not on. This uncertainty is likely to be caused by radiation impinging on the side of the cylindrical slug, which increases the effective surface area for energy absorption.

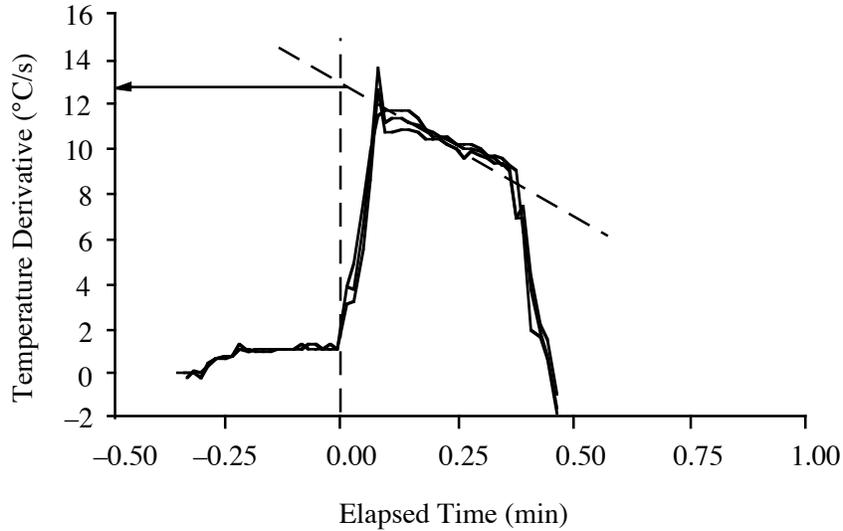


FIGURE 6. HEAT FLUX CORRECTION SHOWING EXTRAPOLATION OF TEMPERATURE-TIME DERIVATIVE TO INITIAL TIME OF RADIANT HEAT EXPOSURE (zero elapsed time)

CONVECTIVE HEAT TRANSFER COEFFICIENT IN THE OSU APPARATUS.

The convective heat transfer coefficient is obtained by taking the natural log of the rate of temperature change of the slug calorimeter. Figure 7 shows the natural log of actual data for the 6.35-mm slug and the best fit line.

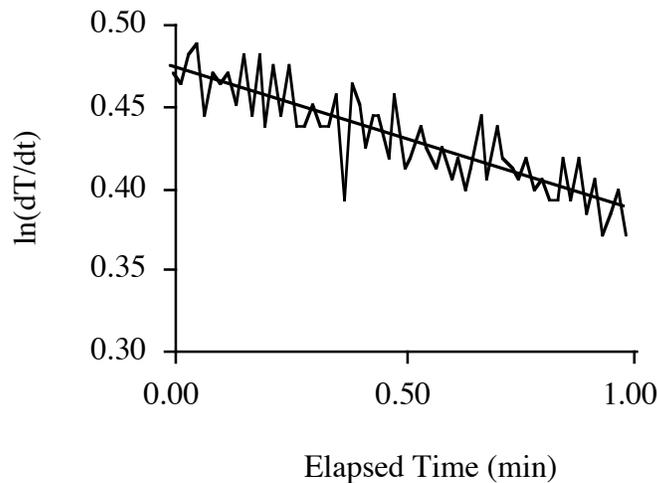


FIGURE 7. NATURAL LOG OF TEMPERATURE-TIME DERIVATIVE (Data showing best fit line extrapolated to zero elapsed time.)

The natural logarithm of the temperature derivative tends to be noisy. The chromel/alumel thermocouple (Type K) signal has more noise than the copper/constantan thermocouple (Type T). Results for each slug are presented in table 4, as calculated using equation 11.

TABLE 4. CONVECTIVE HEAT TRANSFER COEFFICIENTS

Thickness (mm)	Slug Mass (g)	Slope of $\ln(dT/dt)$	% RSD	\bar{h} (Conv. Heat Trans. Coef.)
6.35	556.8	-0.0893	12.12	30.6 (Type T)
1.27	113.3	-0.5600	13.40	39.1 (Type K)
0.675	56.76	-1.0751	31.27	38.9 (Type K)

CONCLUSIONS

1. The slug calorimeter is a primary standard that requires no calibration. Results are repeatable to 1.48% RSD and accurate to within 0.4% of a NIST traceable Gardon gauge when using a Type T thermocouple and 6.35- mm-thick copper slug. The device has practical use as a corroborating method of the calibration of Gardon gauges.
2. The heat flux of the impinging pilot flame in the OSU Rate of heat release apparatus specified in FAR 25.853 is 27.16 Watts/cm².
3. A slug calorimeter can be used to determine the convective heat transfer coefficient in addition to measurement of the heat flux.

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