Development Of FIAT-Based Thermal Protection System Mass Estimating Relationships For NASA's Multi-Mission Earth Entry Concept

Extended Abstract
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Mass Estimating Relationships (MERs) have been developed for use in the Program to Optimize Simulated Trajectories II (POST2) as part of NASA's multi-mission Earth Entry Vehicle (MMEEV) concept. MERs have been developed for the thermal protection systems of PICA and of Carbon Phenolic atop Advanced Carbon-Carbon on the forebody and for SIRCA and Acusil II on the backshell. How these MERs were developed, the resulting equations, model limitations, and model accuracy are discussed herein.

Nomenclature

a,b,c	=	power-law fit parameters
x	=	entry flight path angle, absolute degrees
y	=	heat load, J/cm^2
z	=	TPS thickness, cm
i	=	index of data point
n	=	total number of data points
V	=	velocity, km/s
R	=	residual
TH	=	TPS thickness, cm
HL	=	heat load, J/cm^2
EFPA	=	entry flight path angle, absolute degrees
MER	=	mass estimating relationship
SD	=	standard deviation

I. Introduction

Part of NASA's In-Space Propulsion Technology (ISPT) program is the development of a multi-mission Earth Entry Vehicle[1] (MMEEV) for any sample return mission. For MMEEV, the Program to Optimize Simulated Trajectories[2] II (POST2) was employed as a tool for solving atmospheric ascent and reentry problems. Part of POST2's evolution required the development of mass estimating relationships (MERs) to determine the vehicle's required Thermal Protection System (TPS) for safe Earth entry. For this analysis, the heat shield was made of a constant thickness TPS on its forebody and backshell. Once the required TPS thickness was known, then its pre-flight mass would be determined.

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A typical re-entry problem requires computational aerothermodynamics to understand the flow conditions around the vehicle and to determine the convective and radiative heating to its surface. Once the surface heating was known, than a TPS material response model would be used to determine the amount of heat shield material required to keep its bond line temperature below a specified value, and to know the amount of surface recession if heating was high enough to cause ablation. The traditional approach for this coupled problem would be to first use a high fidelity computational code such as DPLR[3] or Laura[4] for the aerothermal component and then FIAT[5], CMA[6], or STAB[7] for the TPS response. However, this coupled approach usually has a very slow turnaround time and is highly dependent upon analyst availability. To circumvent these issues, POST2 employs correlations to bypass these codes with as minimal loss in accuracy as possible.

To determine the aerothermal environment, POST2 uses the Sutton - Graves[8] correlation for the convective heating, and Tauber - Sutton[9] for radiative heating. To date, however, no correlations based on high-fidelity FIAT modeling have been determined. The current work was to develop MERs using FIAT-based correlations with as high an accuracy to FIAT prediction as possible. Four MERs have been developed. For the vehicle forebody the ablators were Phenolic Impregnated Carbon Ablator[10] (PICA) and Carbon Phenolic[11] atop Advanced Carbon-Carbon. For the vehicle backshell the insulators were Silcone Impregnated Reusable Ceramic Ablator[12] (SIRCA) and Acusil[13] II. Insulators are used on the backshell because the aerothermal environment was so mild to warrant the use of an insulative material. As will be shown, the MERs were accurate to FIAT prediction within 6 to 13% at one standard deviation.

With the development of these MERs, MMEEV can now use POST2 to perform trade studies involving entry velocity, ballistic coefficient, vehicle geometry, entry flight path angle, etc. and now include TPS thickness as an output variable. Design turnaround times for a possible Earth entry configuration have been reduced from weeks to minutes for a set of proposed flight conditions. For these MERs, no margins were added to the calculated TPS thickness requirement.

II. Comparison of DPLR and POST2 Aerothermal Environment Calculations

Before developing the MERs, it was decided to compare POST2 aerothermal environment predictions to those of the high-fidelity DPLR. This was done using the Mars Sample Return[14] (MSR) flight conditions[§] given in Table 1, for the forebody stagnation point. The results are shown below for surface pressure (Fig. 1) and heat flux (Fig. 2). The CFD DPLR point considered was at peak pressure along the trajectory. As shown in the figures, the difference in pressure was 0.3% and in heat flux was 15%. Both values confirmed good agreement between POST2 and DPLR.

Table 1. MSR flight conditions.

Item	Value
MSR EEV Diameter	0.9 meter
Entry mass	44 kg
Hypersonic ballistic coefficient:	46.7 kg/m^2
Ballistic coefficient at terminal velocity with the lower drag coefficient	94.57kg/m^2
Entry velocity	11.56 km/s
Entry flight path angle	-25 deg
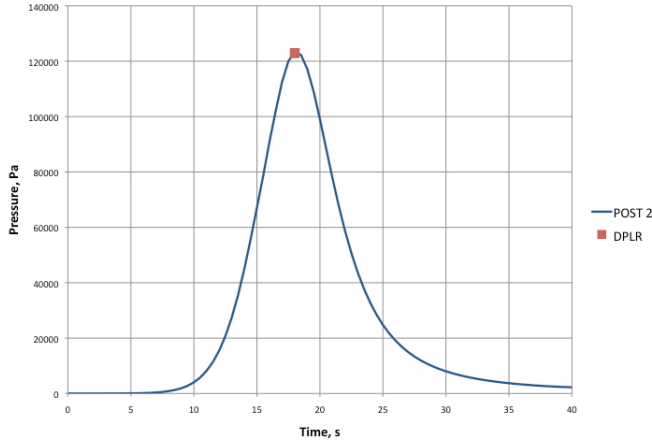
Figure 1. Comparison of POST2-derived pressure pulse and DPLR stagnation point peak pressure. The difference is about 0.3%.
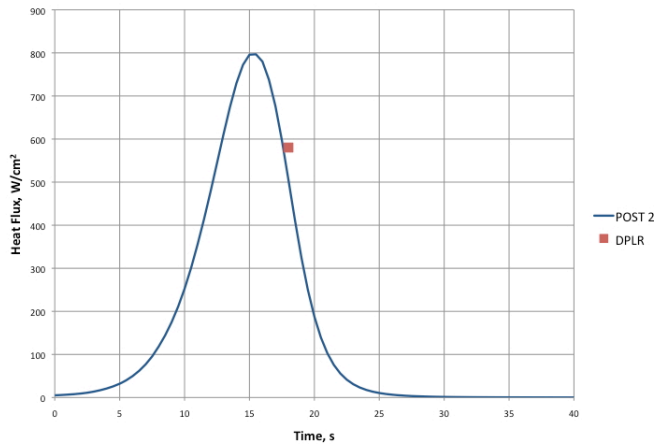
Figure 2. Comparison of POST2-derived convective heat pulse and DPLR stagnation point peak heating. The difference is ~15%.

III. MER Model Development

A. Concern Regarding the Application of MERs

The MERs presented in this paper are statistical correlations developed to predict FIAT output. Each MER has with it a listed accuracy to FIAT prediction, which was found by taking the standard deviation of the MER/FIAT value for all the trajectories. These correlations are only valid only for the FIAT TPS thickness range that is given with each MER. If the MER were to predict a required TPS thickness greater than this range, then the model is not appropriate and FIAT or some other high-fidelity material response code should be used to do the proper analysis. It is emphasized that the MER TPS maximum thickness is <u>not</u> the manufacturing limit of the material's thickness or the limit to a TPS material's applicability for a proposed flight path. For example, Stardust flew with a PICA thickness[15] of 5.816 cm (2.29 inch), which is much greater than the 4.445 cm allowed by the PICA MER (to be shown below). POST2 has correctly implemented the MER TPS prediction limits into its code.

Finally, it should also be noted that as for any statistical analysis, there exist trajectories for which the ratio of MER/FIAT prediction can far exceed the listed MER accuracy. It is for this reason that full datasets are presented showing MER/FIAT data with FIAT predicted thickness. POST2 utilizes these MERs as a "rough approximation" to determine flight trajectories of interest, but always maintains that a true high-fidelity analysis is a requirement as proposed sample return mission moves forward in its development.

B. Flight Trajectory

Found in Table 2 is the flight trajectory range that was considered for the present study.

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Table 2. Flight trajectory space considered for the MERs

Flight Trajectory Parameter	Range of Values	Resolution
Entry Velocity [km/s]	10-16	1
Entry Flight Path Angle [abs. deg.]	5-25	5
Ballistic Coefficient [kg/m^2]	41.95 – 128.74	15.5 (max)
Total number of trajectories	840	-

C. FIAT modeling constraints

FIAT was run for each trajectory with the following constraints that were common for each developed MER:

1. The maximum temperature at the bottom face of the top material was 250°C.
2. An adiabatic back face of the material stack up.
3. A surrounding environment temperature of 21.3°C (for radiation from the spacecraft surface).
4. 1D planar geometry
5. FIAT v2.6.1

It should be noted that FIAT, being a 1D code, was most applicable for regions on the heat shield that did not change shape quickly, such as along the flank or any other acreage location. For regions that do change shape quickly, like at the shoulder, the material response code TITAN[16] would be more appropriate because it includes 2D effects. In addition, PICA's heat conduction was orthotropic, which also necessitates the use of TITAN along regions of the heat shield that change shape quickly. Shown in Table 3 are the range of heating rates, heat loads, and surface pressure that were found from the FIAT analysis of the 840 flight trajectories.

Table 3. Surface heating and pressures ranges found by running FIAT over the 840 trajectories.

FIAT Range	Forebody	Backshell
Maximum heat flux [W/cm^2]	151 – 3767	2.3 – 58.1
Heat Load [J/cm^2]	3855 – 34453	59.4 – 531.0
Maximum pressure, atm	0.03 – 3.182	0.005 – 3.182

D. Vehicle Forebody: MERs for PICA and Carbon Phenolic

Sensitivity studies were conducted by plotting required TPS thickness against a variable of interest and looking to see if any correlation existed. Variables of interest included: peak heat flux, peak surface pressure, heat load, ballistic coefficient, entry velocity, and entry flight path angle. Of these, heat load and entry flight path angle showed the greatest sensitivity to required TPS thickness and were chosen as the variables to use in a power-law correlation.

The results given in this section are listed by material stack up. Each MER correlations was a power-law fit to the following equation, with the required TPS thickness, TH, (given in centimeters):

$$ TH = a\left(HL^b \times EFPA^c\right) \tag{1} $$

No margins were added to the thickness. Goodness of fit (GoF) was defined as the ratio of MER prediction to FIAT output.

When FIAT ran all 840 trajectories, 123 of them that were so mild as to produce little or no recession/ablation for either PICA or Carbon Phenolic. For such mild, non-ablating environments, the proper heat shield material would be an insulator rather than an ablator. However, the lower limit of the MER TPS thickness range can be used as a bound for the minimum thickness needed to keep the bond line temperature below 250°C, with the following exception. Three of the mild trajectories (entry velocity = 11 km/s, EFPA = 5° (absolute), ballistic coefficient 97.8 – 128.7 kg/m^2) required a slightly higher MER minimum thickness (PICA = 2.1437 cm and Carbon Phenolic = 1.458 cm). The FIAT-predicted heat load for these three cases was 13.32 – 13.95 kJ/cm^2, nearly twice the amount (or more) as the other 120 mild trajectories.

The upper limit of the MER thickness range was chosen to give as small an error as possible to FIAT prediction while having as large a range of flight trajectories as possible.

1. PICA MER

The material stack up for this MER consisted of PICA with an adiabatic back wall. This MER had an accuracy to FIAT prediction of 13.1% at one standard deviation subject to the constraints given in Section IIIA. Specifics of the flight trajectory space and correlation model are given in Table 4. Scatter plots of GoF with heat load, entry flight path angle, and FIAT predicted TPS thickness are given in Figure 3. The correlation shows generally good agreement. Scatter increases with EFPA and required TPS thickness and decreases with heat load. This MER was good for the FIAT prediction range of 1.919 cm (0.755 inch) to 4.445 cm (1.75 inch), after which the model diverges rapidly.

Table 4. Flight trajectory space and correlation details for the PICA-only MER

Variable	Values
Recession [cm]	0.468 – 3.620
a	1.993062
b	0.13189
c	-0.34152
Accuracy to FIAT at one SD	9.7%
Trajectories with TPS thickness greater than 4.445 cm	48
Number of FIAT non-convergent trajectories	8
Trajectories with recession less than 0.1778 cm	123
Trajectories used for correlation	661
FIAT TPS thickness range, cm	1.919-4.445
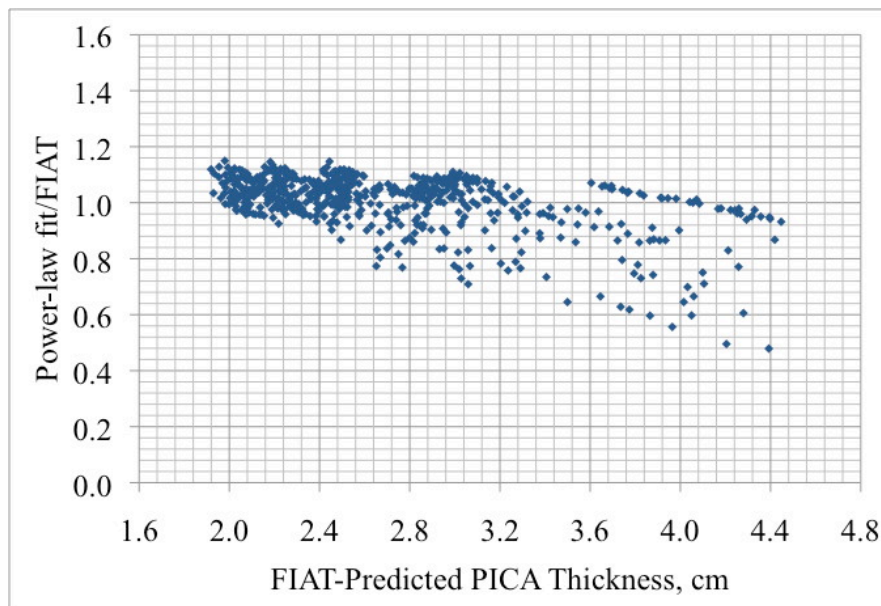
Figure 3. PICA-only MER goodness of fit versus FIAT-predicted PICA thickness. Goodness of fit is given as the ratio of FIAT to correlation prediction. A GoF value of 1.0 indicates a perfect fit.

2. Carbon Phenolic Atop Advanced Carbon-Carbon 6 MER

The material stackup is given in Table 3. The ACC6 was the carrier structure.

Table 5. Material stackup

Material	Thickness, cm
Carbon Phenolic	variable
HT-424 (adhesive)	0.0381
Advanced Carbon-Carbon (ACC) version 6	0.250

This MER had accuracy to FIAT prediction of 8.6% at one standard deviation subject to the constraints given in Section IIIA. No margins have been added to the thickness. Specifics of the flight trajectory space and correlation model are given in Table 5. A scatter plots of GoF with FIAT predicted TPS thickness are given in Figure 4. This MER was good for the FIAT prediction range of 1.245 cm (0.490 inch) to 4.304 cm (1.694 inch).

Table 6. Flight trajectory space and correlation details for the Carbon Phenolic atop ACC MER

Variable	Values
Recession [cm]	0.458 – 2.713
a	2.366755
b	0.107048
c	-0.374326
Accuracy to FIAT at one SD	8.6%
Trajectories with TPS thickness greater than 4.304 cm	5
Number of FIAT non-convergent trajectories	8
Trajectories with no recession	123
Trajectories used for correlation	712
FIAT TPS thickness range, cm	1.245-4.304
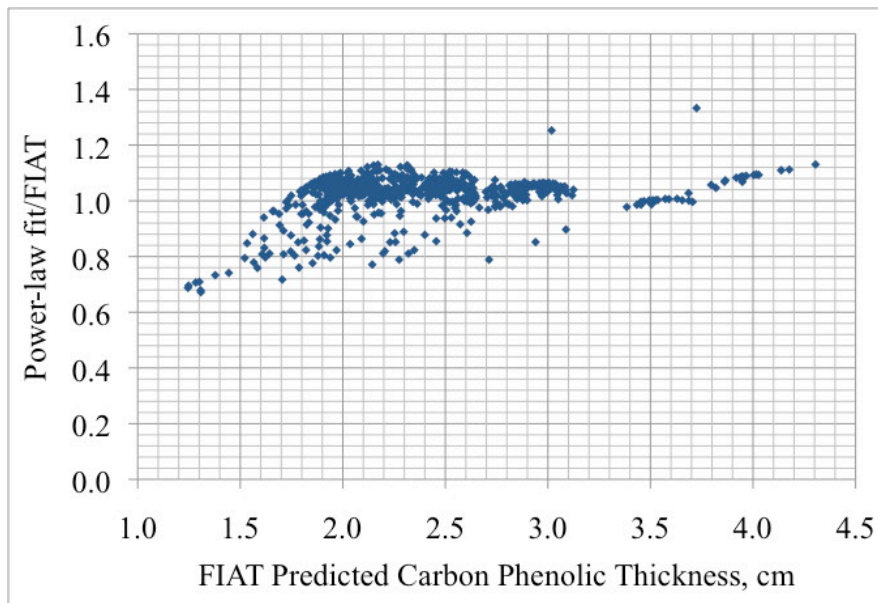
Figure 4. Carbon Phenolic over ACC6 MER, goodness of fit versus FIAT-predicted PICA thickness.

E. Vehicle Backshell TPS: SIRCA and Acusil II

For the backshell, each MER correlation had a power-law fit given in Eqn. 19, with the required TPS thickness, TH, (given in centimeters):

$$TH = a\left(\frac{HL}{V^2}\right)^b \tag{2}$$

No margins were added to the thickness. Goodness of fit (GoF) was defined as the ratio of MER prediction to FIAT output. Out of the 840 trajectories considered, only six cases occurred where the surface energy balance in FIAT did not converge. There were no MER modeling cutoffs based on FIAT predicted TPS thickness like those found for MER forebodies.

1. SIRCA MER

The SIRCA MER had accuracy to FIAT prediction of 7.4% at one standard deviation subject to the constraints given in Section IIIA. No margins have been added to the thickness. Specifics of the flight trajectory space and correlation model are given in Table 5. Scatter plots of FIAT predicted thickness with heat load/velocity[2], and of GoF with FIAT predicted TPS thickness are given in Figure 5. This MER was good for the FIAT prediction range of 0.387 cm (0.152 inch) to 1.332 cm (0.524 inch)

Table 7. SIRCA MER parameters

Variable	Values
Recession [cm]	none
a	0.6597
b	0.5053
Accuracy to FIAT at one SD	7.4%
Number of FIAT non-convergent trajectories	6
Trajectories used for correlation	834
FIAT TPS thickness range, cm	0.387-1.332
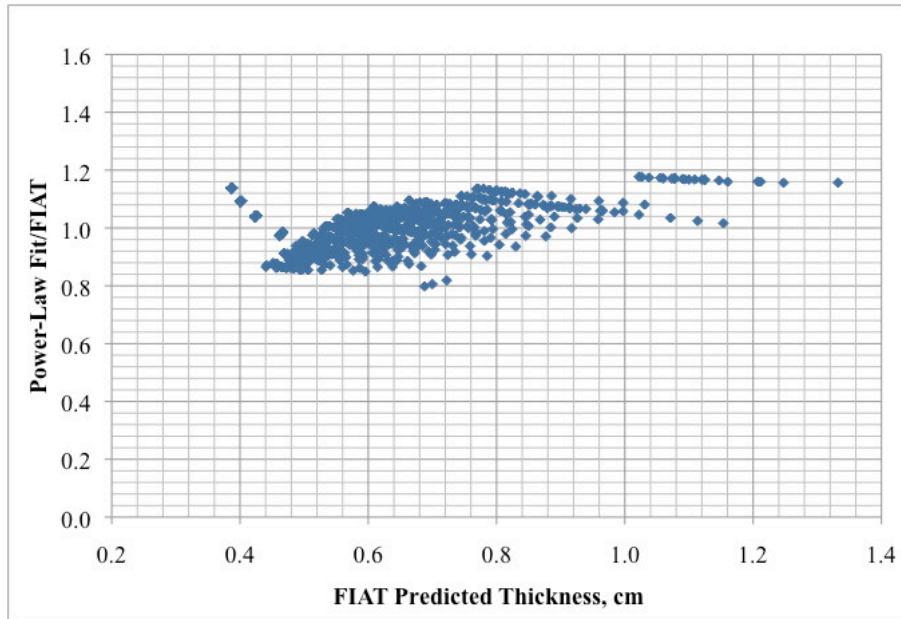
Figure 5. SIRCA Goodness of Fit

2. Acusil II MER

The Acusil II MER had accuracy to FIAT prediction of 6.2% at one standard deviation subject to the constraints given in Section IIIA. No margins have been added to the thickness. Specifics of the flight trajectory space and correlation model are given in Table 5. Scatter plots of FIAT predicted thickness with heat load/velocity[2], and of GoF with FIAT predicted TPS thickness are given in Figure 6. This MER was good for the FIAT prediction range of 0.403 cm (0.159 inch) to 1.672 cm (0.658 inch)

Table 8. Acusil II MER parameters

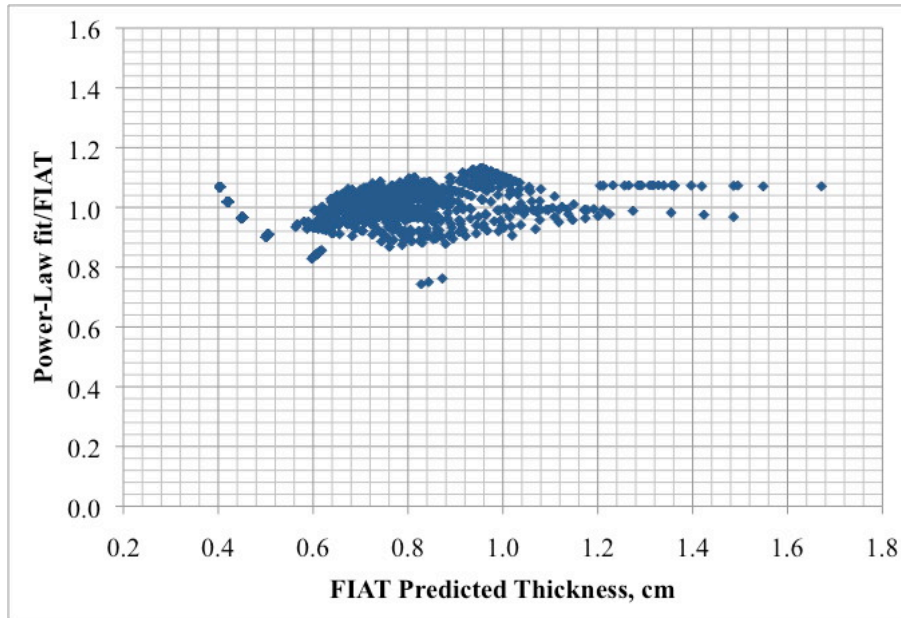| Variable	Values
Recession [cm]	none
a	0.8159
b	0.5886
Accuracy to FIAT at one SD	6.6%
Number of FIAT non-convergent trajectories	6
Trajectories used for correlation	834
FIAT TPS thickness range, cm	0.403-1.672

Figure 6. Acusil II Goodness of fit

IV. PICA Arcjet Testing Database

The PICA correlations that have been developed are for a trajectory space that includes a peak heat flux of over 3700 W/cm^2 as part of its applicability range. PICA has never been tested under such high heating, and it is unlikely to be able to withstand such conditions, so caution must be used when considering a trajectory for use with a PICA MER. It was estimated that a peak heat flux of about 1220 W/cm^2 was experienced on the PICA heat shield of the Stardust[17] capsule. A summary of arcjet tests form 2007-2010 is shown in Figure 7. For these tests, no material failure (spallation) was observed.
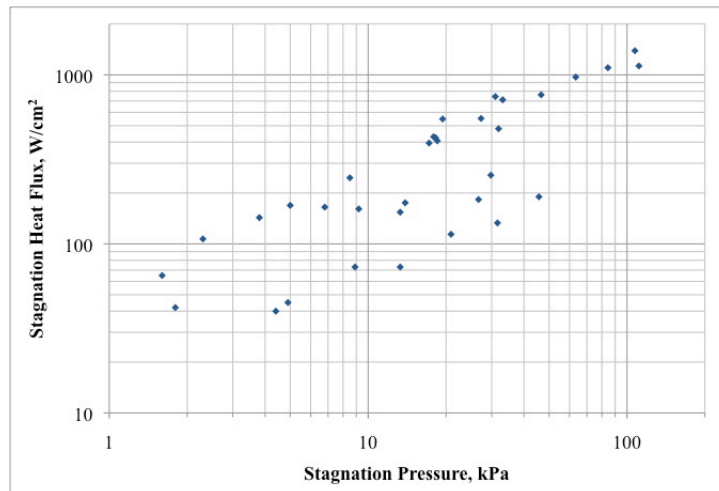
Figure 7. Stagnation tests of PICA in which no spallation was observed. Heat flux values are cold-wall.

V. Conclusion

MERs have been presented for PICA, Carbon Phenolic atop Advanced Carbon-Carbon, SIRCA, and Acusil II with accuracies ranging from 6 – 13% at one standard deviation. These MERs will be into POST2 in a first-generation process to estimate TPS mass. With subsequent revisions, it is likely that these MERs will be replaced with FIAT embedded into POST2.

Acknowledgments

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