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Recession Curve Generation for Space Shuttle Solid Rocket Booster Thermal Protection System Coatings

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Ablatable Thermal Protection System (TPS) coatings are used on the Space Shuttle Vehicle Solid Rocket Boosters in order to protect the aluminum structure from experiencing excessive temperatures. The methodology used to characterize the recession of such materials is outlined. Details of the tests, including the facility, test articles and test article processing are also presented. The recession rates are collapsed into an empirical power-law relation. A design curve is defined using a 95-percentile student-t distribution, based on the nominal results. Actual test results are presented for the current acreage TPS material used.

1.0 INTRODUCTION

The following document summarizes the methodology used to determine the design recession rate curves for the United Space Alliance Solid Rocket Booster element (USASRB) Thermal Analysis and Test Programs. Herein, we shall also include information about the test facilities typically used and the basic procedures followed, as well as some typical data.

2.0 RECESSION DATA REDUCTION METHODOLOGY

When data is acquired during material characterization testing for the Space Shuttle Vehicle (SSV) Solid Rocket Boosters (SRBs), it is processed to provide empirical relations to envelope the worst recession rates expected to be experienced by the SRBs during flight.

Recession test data is acquired during material characterization thermal testing at George C. Marshall Space Flight Center (MSFC) Improved Hot Gas Facility (IHGF, building 4554, Figure 1). Typical material characterization data sets include pre-test and post-test/post-scrape test panel thickness measurements, cold-wall heat rates and test duration. All the data is acquired at each of the 20 locations on the Medtherm

calibration plate (Figure 4, H2501-H2520). Thickness measurements are acquired using a deep-throat micrometer. Cold-wall heat rates are computed from the measured hot-wall heat rates acquired during calibration runs at Marshall Space Flight Center (MSFC) Improved Hot Gas Facility (IHGF) using the USA/IHGF data reduction program, REDUCT. The correlation between cold-wall and hot-wall heat rates is defined in the following relation:

$$\dot{q}_{cw} = \dot{q}_{hw} \times [(T_r - T_{cr}) / (T_r - T_w)]$$

where:

\dot{q}_{cw} = cold wall heat rate, [BTU/ft²-sec, BFS]

\dot{q}_{hw} = hot wall heating rate, [BTU/ft²-sec]

T_r = (adiabatic wall) recovery temperature
= $r^* \times T_{total}$ [°F]

T_{cr} = cold wall reference temperature = 0°F

T_w = surface temperature of calibration plate, [°F]

r^* = corrected recovery factor (for M=4, $\gamma=1.4$ gas), [ND], typically 0.92

$$= r + \frac{(1-r)}{1 + \frac{\gamma-1}{2} M^2} \text{ and } r = 0.89$$

Recession rates are defined as the change in the thickness measurement divided by the run duration. The run duration is defined as the time the total temperature measured in the combustor was stable.

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Typically, data from calibration panel locations 7 and 8 (H2507, H2508) are neglected because the flow on the test panel is not fully established at those locations. Point 14 (H2514) may also be ignored, depending on test conditions such as shock encroachment, etc...

2.1 Methodology

The recession data is plotted on a log-log plane. A linear least-squares curve fit to the log of the raw data values results in a recession rate equation of the following power-law form:

$$\dot{r} = k \dot{q}_{cw}^x$$

where:

- \dot{r} = recession rate [mils/sec]
- \dot{q}_{cw} = cold wall heating rate ($T_w = 460^\circ\text{R}$),
[BTU/ft²-sec]
- k = empirical scale factor; least-squares fit y-intercept
- x = empirical exponent; least-squares fit slope

This equation is, of course, linear in log-log space. When the thickness of the TPS required to protect the SRB hardware during flight is calculated, a more conservative recession equation is used, known as the design equation. The former equation is known as the nominal equation. The design equation is based on a calculation of the 95% Upper Prediction limit¹ for each ordered pair of recession rate as a function of cold-wall heating rate. The upper prediction limit is calculated using the following equation:

$$Y = y + t_{\alpha/2} \times S_e \times \left(1 + 1/n + (x_0 - \bar{x})^2 / S_{xx}\right)^{1/2}$$

where:

- y = estimated value of dependent variable based on least-squares fit
- $t_{\alpha/2}$ = constant for t-distribution based on degrees of freedom
(df=number of data points-2) and the width of the prediction interval (95%)
- S_e = SQRT((Slope of Standard Error)/df)
- x_n = independent variable
- \bar{x} = average value of independent variable
- S_{xx} = $\sum (x_i - \bar{x})^2$

This calculation results in a new set of recession rate values for the cold-wall heating rate distribution. A linear, least-squares curve is fit to this adjusted data and the result is the design curve.

If the data is not best fit with a single linear fit, it is subdivided into two or more heat-rate regimes for which the recession is linear in character.

2.2 Implementation

The above methodology is implemented in Microsoft Excel spreadsheets. Curve fitting is completed using the LINEST() function. The student-t distribution extrapolation is completed using the TINV() function.

3.0 THERMAL TESTING

As stated previously, material characterization testing is completed at NASA/ MSFC IHGF, shown in Figure 1. All material characterization testing is completed using constant heat rates of 5 to 15 BFS convectively, with a nominal recovery enthalpy of 600 BTU/lb_m. Higher heat rates are achieved using a radiant arc lamp, which can be using simultaneously with convective heating.



Figure 1: Photograph of IHGF

3.1 Improved Hot Gas Facility

The IHGF is a nominal Mach 4.1 acrothermal tunnel that burns a lean mixture of hydrogen (GH₂) and air to produce temperatures up to 2200°F at total pressures up to 200 psia. The tunnel has a nominal 16x16x40 -inch test section that was primarily designed for the testing of thermal protection materials. However, provisions were made for a support strut and sting so that other aerothermal testing could be accomplished in the facility. In the original design configuration, each of the four walls of the test section could accommodate a blank panel, a viewing panel, or a test panel. However, a model injection system has been added in the bottom wall opening that allows the test panel to be retracted during tunnel start and then injected into the flow at inclination angles from 0 to 15 degrees. The heating rates available in the IHGF with the model injection system are shown in Figure 2. A picture of the test section is shown in Figure 3. A complete description of the tunnel is given by Palko^{2,3}. A database with variables of combustor pressure, combustor temperature, and injection angle from the injection system checkout calibration is available at the facility to

aid in selecting the tunnel control settings for a desired test condition. However, calibration runs are normally made for each test sequence to fine-tune the control settings for the specific test conditions.

Radiant heating is also available by an arc lamp that can be fitted to the test section upper window. With a set-up of mirrors, the radiant heat is applied consistently over a portion of the test panel, as indicated by the shaded zone in Figure 4.

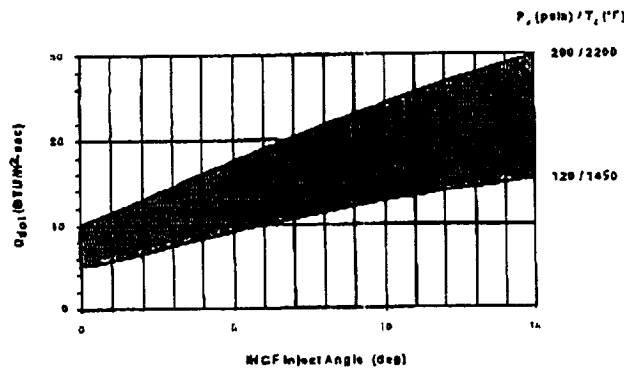


Figure 2: Obtainable Heat rate as a Function of Model Wedge Angle in the IHGF

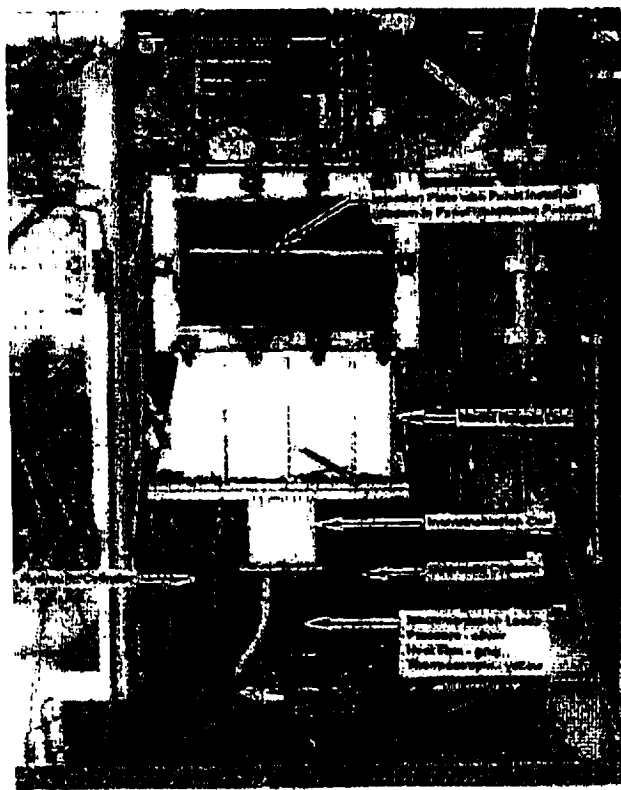


Figure 3: Photograph of IHGF Test Section and Model Injection System

3.1.1 Calibration Test Panel

Test panels do not typically include calorimeters or any other means to measure incident heat flux on the surface. To determine the heat rates on test panels, a calibration run is completed at each test condition. The calibration test panel has a planform of 12×19-inches and includes 20 Medtherm Schmidt-Boelter type transducers located as indicated on Figure 4.

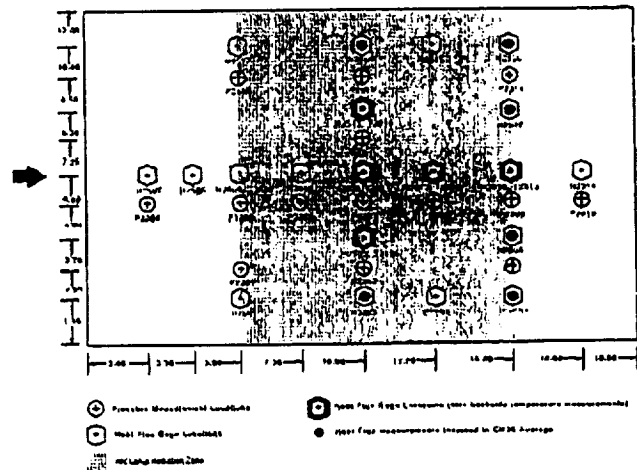


Figure 4: Standard Convective Heating Medtherm Calibration Plate denoted with Radiant Footprint

A separate calibration plate is available for radiant-only testing, which includes radiometers as well as calorimeters.

3.1.2 Test Panels

The test panels, like the calibration panels, have a 12×19-inch planform. Typically, they are ¼-inch thick aluminum. TPS is applied on the surface with typical thickness up to ½-inch. Using a template that matches the locations of the calorimeters on the Medtherm calibration plate, thickness measurements are made, both before and after testing using a deep throat micrometer (0.001-inch graduations). Pre- and post-test panel photographs are in Figure 5 and Figure 6.

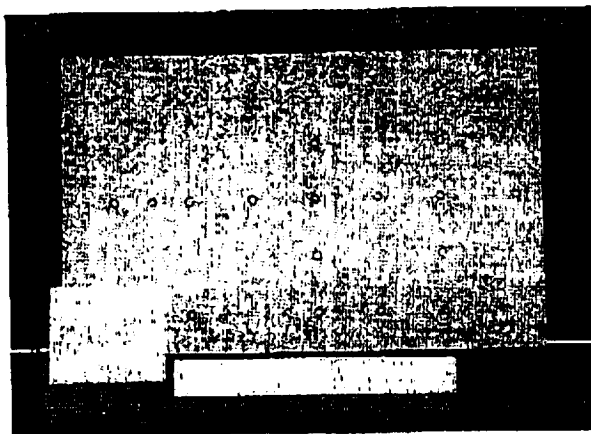


Figure 5: MCC-1 Test Panel Pre-Test Photograph



Figure 6: MCC-1 Test Panel Post-Test Photograph

After testing, the test panels consist of virgin material covered with ablation by-products, defined as a "heat-affected" layer and a char layer. Recession, for USASRB, is defined as the loss of virgin material, thus the char and heat-affected layers need to be removed for final measurements. These layers are removed by scraping the test panels. Depending on the TPS, hand scraping or mechanical scraping are done. Hand scraping is achieved using paint scrapers, while mechanical scraping is completed using coarse or fine Roto-Stripper™ tools in an electric drill (Figure 7).



Figure 7: Roto-Stripper Tool for Removing Char Layer

3.2 Actual Test Data

Within this section, we present typical test data and the resulting recession characterization curves; both nominal and design. The data presented is for an acreage TPS, MCC-1 on the SRB nose cap, frustum, forward skirt and aft skirt. The data is presented in both linear space (Figure 8) and logarithmic space (Figure 9). Both formats are presented to graphically illustrate the non-linear trend of the data set.

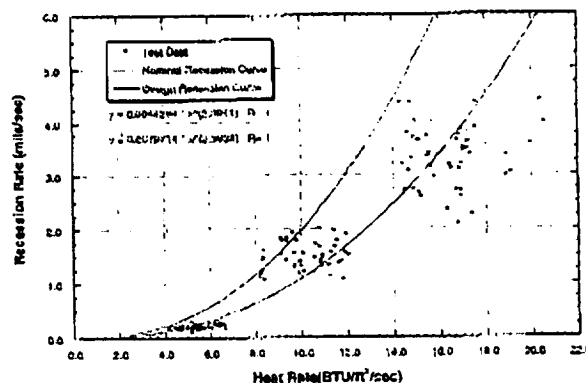


Figure 8: MCC-1 Recession Data in Linear Space

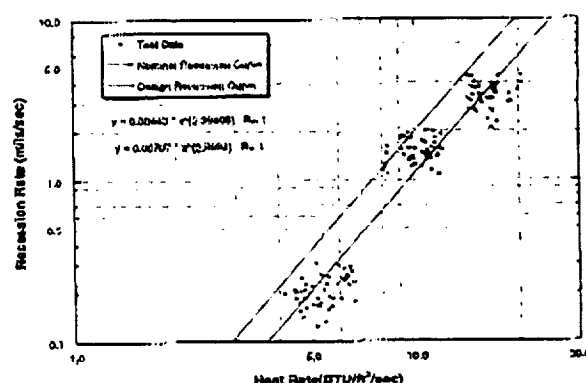


Figure 9: MCC-1 Recession Data in Logarithmic Space

4.0 SUMMARY AND CONCLUSIONS

Material characterization for TPS materials used on the Space Shuttle Vehicle Solid Rocket Boosters are performed at NASA/MSFC IHGF. Constant heat rates are applied to flat panels for fixed durations. The known test duration and the resultant measured recession is then used, with a power-law relationship and a student-t distribution, to define the nominal and design recession rates, where the design rates are such that 95% of all sample recession is represented.

It should be noted that all recession characterization completed by USASRB/Thermal Testing and Analysis is at a fixed recovery enthalpy of 600 BTU/lbm, which is the maximum value to which the SRBs are subject. It is considered conservative to test at this upper limit for this program. Accounting for variations in the recovery enthalpy would be required to use the data below for other applications.

5.0 ACKNOWLEDGEMENTS

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² Palko, R. L., "Technical Design of the NASA/MSFC IHGF," REMTECH Report RTR 170-03, February 1988.

³ Palko, R. L. "NASA/MSPC IHGF Calibration Report, Volume 1 - Performance and Operation", REMTECH Report RTR-210-01, August 1989.