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Space Shuttle Reusable Solid Rocket Motors**

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REAL-TIME INHIBITOR RECESSION MEASUREMENTS IN THE SPACE SHUTTLE REUSABLE SOLID ROCKET MOTORS

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ABSTRACT

Real-time char line recession measurements were made on propellant inhibitors of the Space Shuttle Reusable Solid Rocket Motor (RSRM). The RSRM FSM-8 static test motor propellant inhibitors (composed of a rubber insulation material) were successfully instrumented with eroding potentiometers and thermocouples. The data was used to establish inhibitor recession versus time relationships. Normally, pre-fire and post-fire insulation thickness measurements establish the thermal performance of an ablating insulation material. However, post-fire inhibitor decomposition and recession measurements are complicated by the fact that most of the inhibitor is designed to erode away as the propellant web burns back during motor operation. It is therefore a difficult task to evaluate the thermal protection offered by the inhibitor material. Real-time measurements would help this task. The instrumentation program for this static test motor marks the first time that real-time inhibitor char line recession was measured on an RSRM. This report presents that data for the center and aft field joint forward facing inhibitors. The data was primarily used to measure char line recession of the forward face of the inhibitors which provides inhibitor thickness reduction versus time data. The data was also used to estimate the inhibitor height versus time relationship during motor operation.

INTRODUCTION

A propellant grain inhibitor is an insulation material designed to insulate a solid propellant grain surface so that the insulated portion will not burn. In this context, the surface is said to be "inhibited". By inhibiting certain grain surfaces, the solid propellant rocket designer can more easily create the desired thrust-time relationship. On the Space Shuttle Reusable Solid Rocket Motors (RSRM), the forward facing inhibitors are composed of the same material used to insulate the internal case wall. Figure 1 illustrates the RSRM propellant grain and inhibitor geometry. As indicated on the figure, the RSRM has three forward

facing inhibitors – one for each field joint. The RSRM chamber pressure is generated from the exposed, uninhibited, propellant surfaces as the propellant undergoes combustion and produces gas. Figure 2 illustrates the direction of the propellant burn back and the change in propellant grain shape as the propellant burns from the exposed surfaces. The inhibited propellant surface will not recede. The propellant grain recedes only from the exposed surfaces.

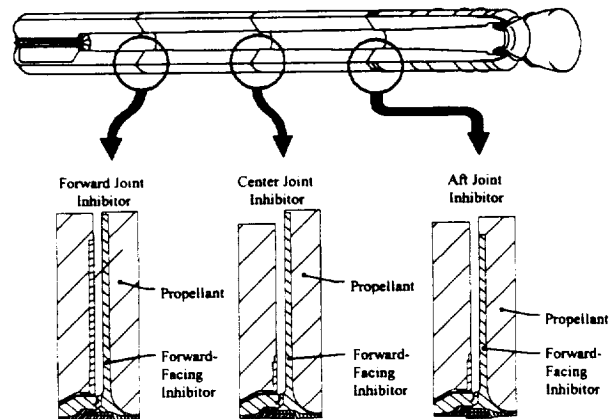


Figure 1. RSRM propellant and inhibitor configuration.

During motor operation, the inhibitor will erode from all exposed surfaces (as indicated in Figure 3). As the propellant grain combusts and recedes, the inhibitor tip (defined by its inner diameter) will recede, or erode, radially outward toward the case wall. This inhibitor tip will recede with the propellant, but at a slower rate. As the inhibitor tip erodes, the inhibitor will also erode from its forward face that is exposed to the propellant gases. This forward face erosion (or recession) will reduce the inhibitor thickness over the propellant surface it is insulating. It is desired that the inhibitor maintain enough insulation thickness over the propellant such that the propellant/inhibitor interface will remain below 200°F. This limit helps maintain the integrity of the propellant/inhibitor bondline and prevents premature auto-ignition of the propellant.

With the RSRM, it is also desired to have the inhibitor tip erode so that the inhibitor will not obstruct the flow of the chamber gas, nor enhance pressure oscillations. The main goal of the inhibitor, however, is to maintain an insulation layer over the propellant surface so that the propellant will not ignite.

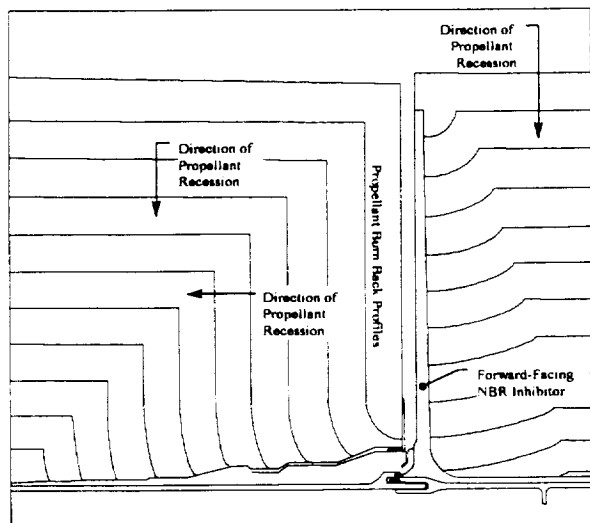


Figure 2. General directions of RSRM propellant recession.

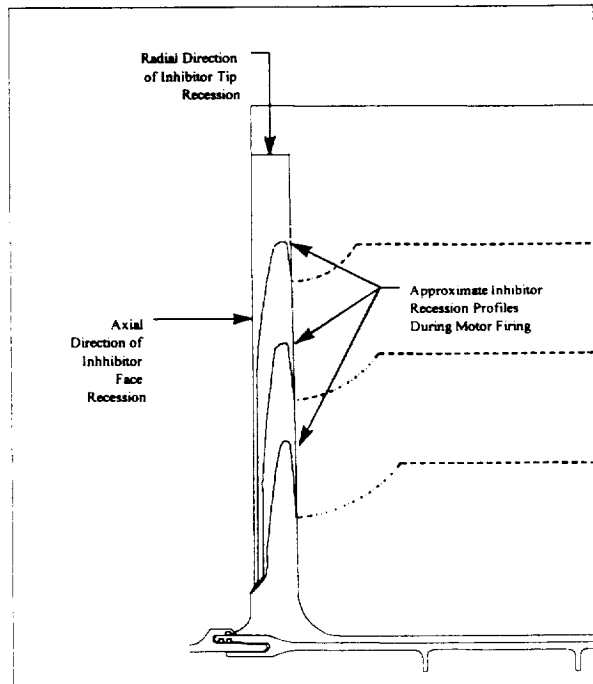


Figure 3. General directions of RSRM inhibitor material recession.

THE PROBLEM WITH VERIFICATION OF INHIBITOR PERFORMANCE

The effectiveness of the RSRM case wall insulation is directly related to the ability of the insulation material to withstand thermal decomposition and maintain its thickness over the internal case wall. The thermal diffusivity of the material is, of course, also important. However, the real trick in finding a good insulation material is finding one that will resist thermal decomposition and erosion in the harsh internal motor environment. In this thermal environment, the insulation materials will thermally decompose and erode (or ablate). The designer must insure that an adequate amount of insulation thickness, which protects the motor case, will last throughout motor operation. Analyses can be performed to theoretically show that an insulation thickness will be adequate, however, most solid rocket programs rely on test data to demonstrate and verify the performance of the insulation. For the RSRM, this data is obtained from post-fire measurements of full scale static tests and flight motors. Thus, the case wall internal insulation thermal performance is measured directly from the post-fire static test and flight data. No motor operation real-time data is needed.

The RSRM propellant inhibitors present a different problem. By design, most of the RSRM center and aft inhibitors will erode away during motor operation. Obviously then, there is no post test inhibitor thickness that can be measured to verify that the inhibitors have insulated the propellant properly. Since the center and aft inhibitors are mostly eroded away by the time of the post-test inspections, the inhibitor thickness that did overlie (protect) the propellant during motor operation has to be determined by a combination of post-test inhibitor stub measurements and thermal analysis. The physics of the ablation environment and ablation process is complicated. Thus, an accurate inhibitor thermal analysis is difficult, and therefore these analyses have usually been conservative. However, it is not necessarily advantageous to design an overly thick inhibitor. Aside from the extra inert weight that might be designed into the system, the inhibitor stubs resulting from an overly thick inhibitor may protrude into the chamber causing undesired effects on the flow, pressure, and acoustics of the chamber gases.

THE ERODING POTENTIOMETER

It has been desirable for some time to have more data than what is normally available at post-test inspection to verify inhibitor performance. The ability to verify inhibitor performance could greatly reduce the risks associated with new designs or material changes. The RSRM Asbestos-Free program is investigating a Kevlar® EPDM (Ethylene Propylene Diene Monomer) replacement for the asbestos fiber filled NBR – the present material for RSRM internal insulation. For this program, an effort to instrument the RSRM inhibitors during a static test was initiated. The goal was to measure inhibitor recession during motor operation. This effort generated the development of an instrument called an "eroding potentiometer." This instrument was developed to approximately measure the real-time recession (recession versus time) of the insulation material. In actuality, it measures the char line recession, which approximates the surface recession of the material as explained below. The testing and verification of this instrument was presented in an earlier paper.¹

Figure 4 schematically illustrates the eroding potentiometer and how it functions. The instrument consists of two small (about 3 mils in diameter) twisted wires that are composed of an electrically resistive alloy and are polyimide insulated. The wires are placed into the rubber insulation of a rocket motor during manufacturing insulation lay-up. It is preferred to have the wires oriented in the insulation so that they will be parallel to the direction of erosion that will occur during motor firing. During the rocket motor firing, the insulation decomposes and ablates, exposing the tips of the wires to the heat of the internal motor environment, causing the wires to recede as well. The wire pair form an electrical circuit that shortens in length as the recession occurs. With this recession, the electrical resistance of the wire pair decreases. A constant current of about 20 mA is passed through the wire and the resulting voltage is measured. With a pre-measured and known resistance (ohms/inch) of the twisted wire pair, the real-time length, and therefore the recession, of the wire can be determined. This recession may also cause frequent "making" and "breaking" of the electrical junction at or near the tip of the wire pair which makes the signal discontinuous and a little difficult to measure. Special amplifiers, signal conditioners, and recording instruments record the voltage as a function of time.

The desired effect is for the wire recession to occur concurrently with the recession of the motor internal insulation. The polyimide insulation of the twisted wire electrically insulates each wire from the other until the

polyimide breaks down at or near the tip, making an electrical junction. This breakdown starts to occur at about 900°F. The electrical junction will occur when the polyimide insulation is mostly decomposed at a temperature higher than 900°F. In tests performed at Thiokol,² the electrical junction between the two wires appeared to occur just into the char layer near the char/pyrolysis interface, which is somewhere between the 1200°F isotherm and the 1650°F isotherm.

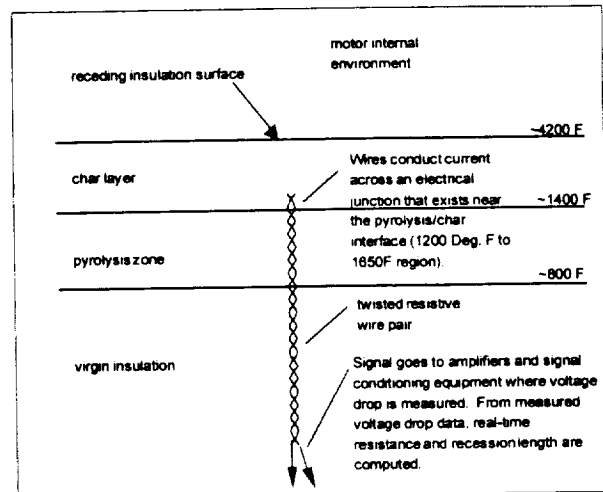


Figure 4. Schematic of the eroding potentiometer and how it functions.

If the above conditions exist, the electrical junction of the twisted wire pair will occur near the pyrolysis/char interface of the decomposing rocket motor internal insulation, and thus the eroding potentiometer is measuring the insulation char line recession verses time with decent accuracy. Rapid pyrolysis of typical internal insulation usually begins at approximately 900°F. The insulation elastomer is usually 100% char (decomposition is mostly complete) at 1300° to 1500°F - depending on the heating rate. If the insulation location of interest is eroding rapidly enough, the temperature gradient from the pyrolysis/char interface (or char line) to the eroding insulation surface is usually steep, and the distance between the char line to the eroding insulation surface is usually less than 0.1 inch. Thus, the electrical junction of the resistive wires, although leading the erosion surface, is usually within 0.1 inch of this surface. The instrument therefore will also approximately measure the recession of the insulation surface if the surface is eroding at a rapid enough pace so that the temperature gradient remains high.

INSTRUMENTATION OF THE RSRM FSM-8 STATIC TEST MOTOR

The RSRM static test designated as FSM-8 was the first RSRM motor to incorporate eroding potentiometers. The eroding potentiometers were installed to approximately measure the inhibitor forward face recession (by measuring the char line recession as explained above). The forward face recession results from the thermal decomposition and erosion of the char material. The recession of the forward face of the inhibitors is essentially in the axial direction. Figure 3, referred to earlier, shows the general direction of the inhibitor material recession. The eroding potentiometers were oriented so that they would measure the axial direction of the char line recession at three radial locations on the inhibitors. Figure 5 illustrates these locations as radial stations 1, 2, and 3.

For added insurance that recession data could be obtained, the FSM-8 inhibitors were also instrumented with thermocouples. Figure 5 illustrates the locations for the thermocouples. Two radial locations (stations 1 and 2) were instrumented with thermocouples. At each radial location, the thermocouples were installed at several depths into the thickness of the inhibitor – as measured from the forward face axially towards the propellant. This type of thermocouple placement will give a sharp temperature rise at the time when the insulation char front passes through the location of the thermocouple. So, by knowing the depth of the thermocouple and measuring the time of the char front passing, the char line recession versus time is approximately measured.

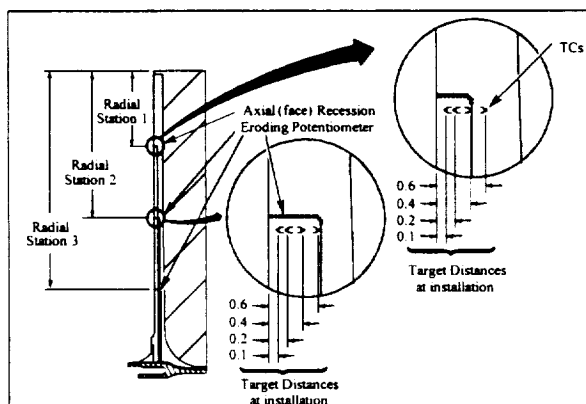


Figure 5. Locations of the eroding potentiometers and thermocouples in the FSM-8 inhibitors.

This instrumentation was primarily installed to provide data on the char line recession of the forward face of the inhibitor. Figure 3 illustrates the general

direction of inhibitor material recession. With inhibitor forward face char line recession versus time measurements, the inhibitor thickness over the propellant during motor operation can be calculated from the data. The effectiveness of the thermal protection offered by the inhibitor for the propellant can then be evaluated.

FSM-8 MEASURED DATA

The RSRM FSM-8 static test was fired on February 17, 2000. The instrumentation worked well, and char line recession data was obtained with both the eroding potentiometers and thermocouples. With this data, partial recession profiles (approximated by char line recession) of the inhibitors at different times could be constructed. These measurements were used to verify that the inhibitor thickness remained adequate to insulate the propellant during motor operation and that the safety factor requirements were met.

Figure 6 shows inhibitor forward face char line recession for the RSRM FSM-8 center inhibitor at radial station 1 (see Figure 5 for an illustration of the radial locations). Each point plotted represents a reading from the eroding potentiometers. The thermocouple points plotted represent the time at which the temperature of the thermocouple reached 1500 °F. This is the temperature of the material when it is fully charred and represents the time when the char line reaches the location of the thermocouple. A curve fit was made to this data. This curve is also shown on Figure 6 as a line that approximates all of the measured data for this radial location on the inhibitor.

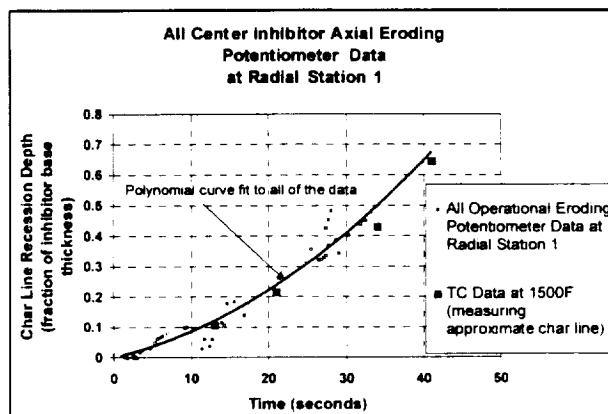


Figure 6. Forward face char line recession versus time for the FSM-8 center inhibitor at radial station 1.

The curve fit process was repeated for the measured data at radial station 2 on the center inhibitor.

Figure 7 shows curves for both radial stations 1 and 2. These curves represent an approximation of the forward face char line recession.

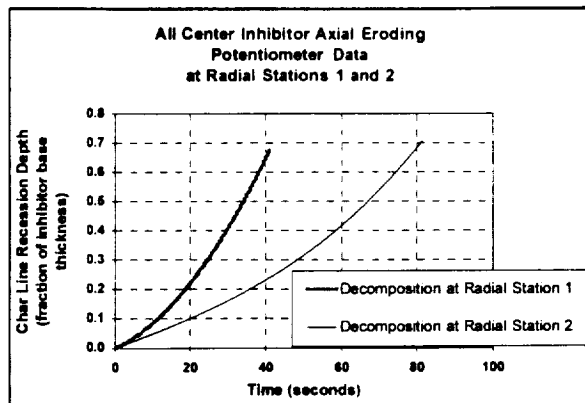


Figure 7. Forward face char line recession versus time, curve fit to all data, for the FSM-8 center inhibitor.

Data was also obtained for radial station 3 on the center inhibitor. However, the erosion rate was slow for this location. As a result, the eroding potentiometer did not work well at this location. There were no thermocouples at this location either. Therefore, there is no accurate data available for radial station 3 on the center inhibitor.

Figure 8 shows inhibitor forward face char line recession for the RSRM FSM-8 aft inhibitor at radial station 1 (see Figure 5 for an illustration of the radial locations). Each point plotted represents a reading of the eroding potentiometers. Again, the thermocouple points plotted represent the time at which the temperature from the thermocouple reached 1500 °F. A curve fit was made to this data. This curve is also shown on Figure 8 as a line that approximates all of the measured data for this radial location on the inhibitor.

The curve fit process was repeated for the measured data at radial stations 2 and 3 on the aft inhibitor. Figure 9 shows curves for radial stations 1, 2, and 3 on the aft inhibitor. These curves represent an approximation of the forward face char line recession of the aft inhibitor.

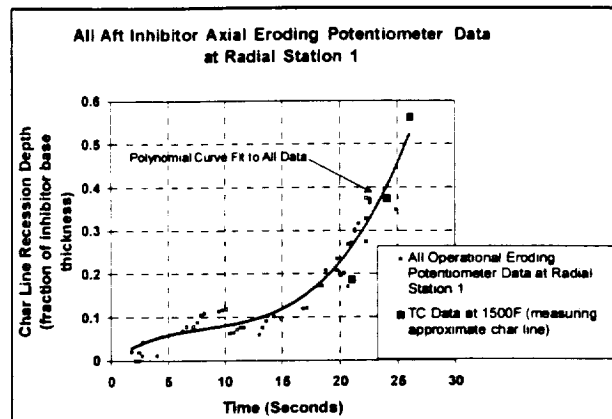


Figure 8. Forward face char line recession versus time for the FSM-8 aft inhibitor at radial station 1.

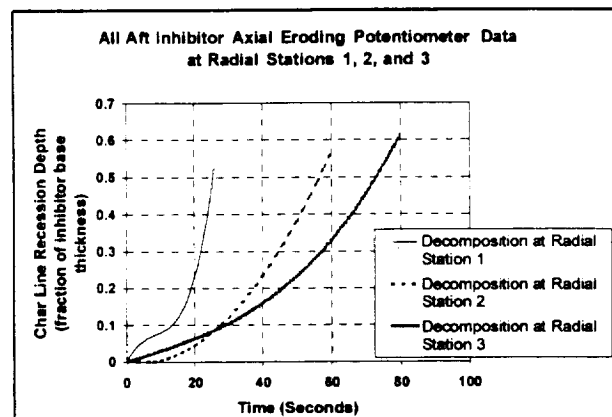


Figure 9. Forward face char line recession versus time, curve fit to all data, for the FSM-8 aft inhibitor.

Data for the forward joint inhibitor was also gathered, but is not shown here. The forward inhibitor is exposed to a relatively mild environment compared to the center and aft inhibitors. Since the erosion rate is a great deal slower for the forward inhibitor, the eroding potentiometer data was more scattered and less reliable. However, positive thermal margins of safety for the forward inhibitor are easy to prove since most of the forward inhibitor stub does remain after motor operation. So its discussion is of less importance.

ESTIMATION OF INHIBITOR RADIAL HEIGHT RECESSION

In addition to determining inhibitor thickness versus time, the data was used to estimate the inhibitor radial height versus time.³ The radial height versus time is the real-time dynamic distance from the inhibitor outer radius to the inhibitor inner radius. In this discussion, the reader is reminded that the main purpose of the instrumentation was to measure inhibitor thickness versus time – not height. So, the real-time

radial height measurements, being of secondary importance, had to be estimated from the thickness data.

Figures 10 and 11 present partial inhibitor profiles constructed from the FSM-8 data. The figures show the recession of the center and aft inhibitor forward faces during motor operation. It was estimated that the inhibitor radial height for a few different times was approximately at the locations noted on the figures. Figure 12 shows this estimated inhibitor radial height versus time for the center and aft inhibitors.

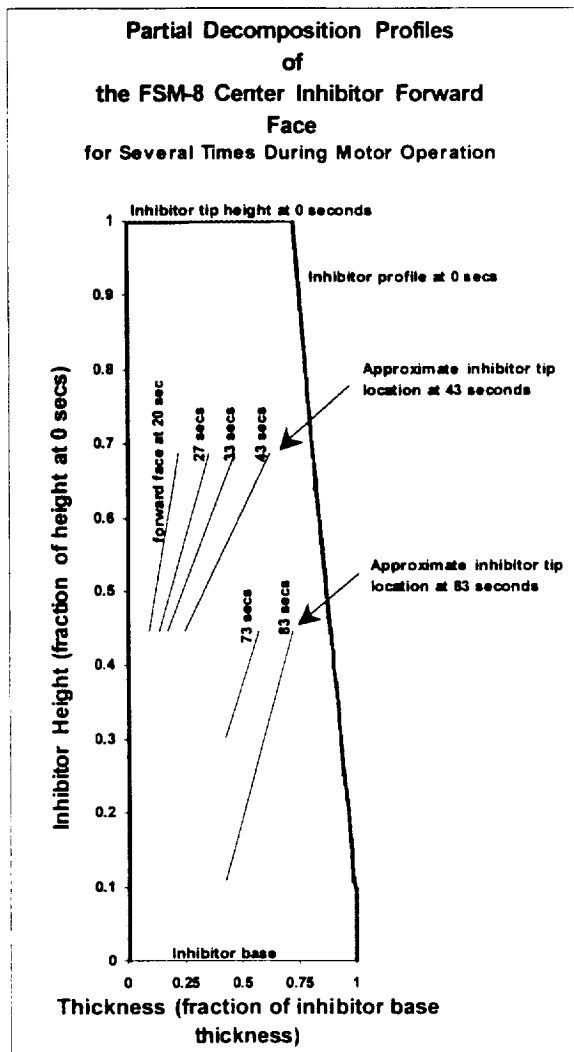


Figure 10. Partial recession profiles at different times for the FSM-8 center inhibitor.

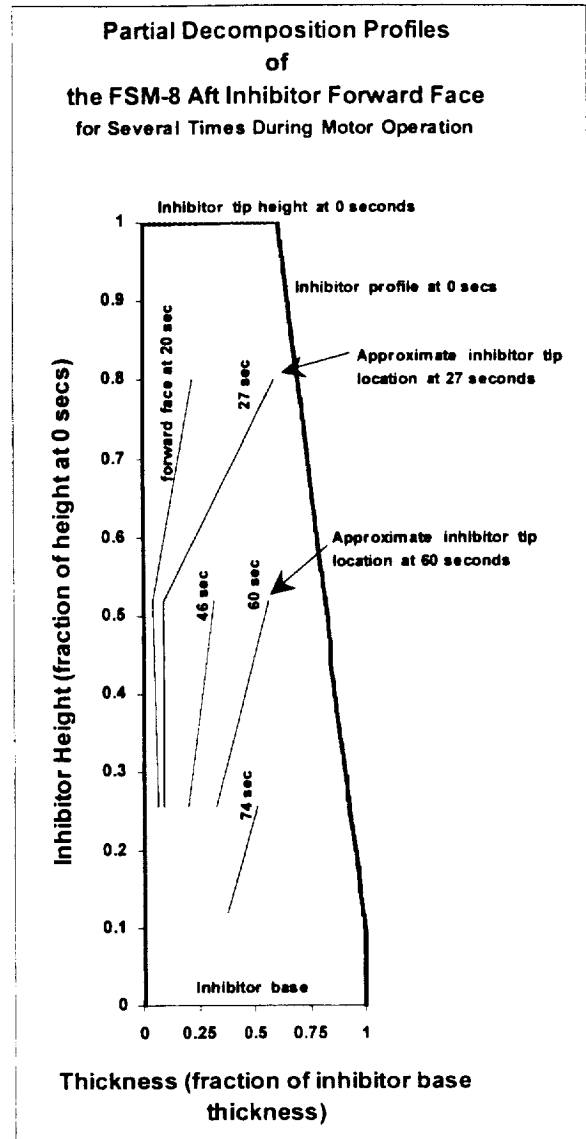


Figure 11. Partial recession profiles at different times for the FSM-8 aft inhibitor.

EMPIRICAL MODEL FOR INHIBITOR HEIGHT

Using this data, an analysis was performed to develop a simple empirical model of inhibitor tip recession versus time. The analysis is based on correlating the measured inhibitor recession data with the propellant gas mass flux (which varies with time). A power function was used for the empirical model.

Inhibitor recession was correlated against mass flux, where the mass flux, G , is defined as the mass flow rate per unit area defined by the inhibitor port.

$$G = \frac{\dot{m}}{\pi(R_c - H)^2} \quad (1)$$

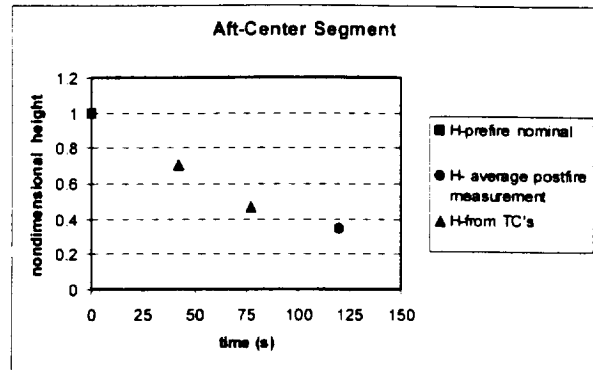
In Equation (1), \dot{m} is the total mass flow rate through the inhibitor port, R_c is the radius from the centerline to the inboard clevis tip, and H is the inhibitor height also measured from the inboard clevis tip. The inhibitor recession rate, \dot{H} , was correlated with mass flux as follows

$$\dot{H} = cG^n \quad (2)$$

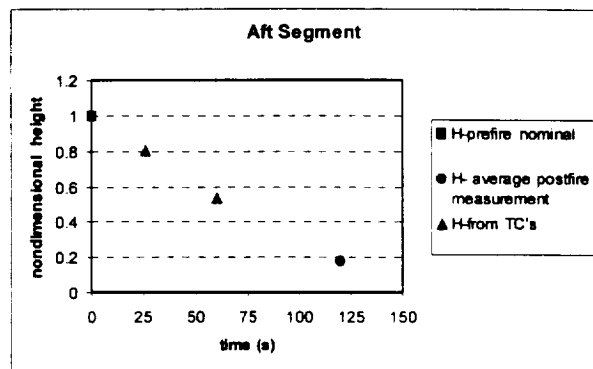
where c and n are empirical constants to be determined using the measured data. The inhibitor height at any time, τ , is then

$$H = H_0 - \int_{t_0}^{\tau} c[G(t)]^n dt \quad (3)$$

where H_0 is the initial height and t_0 is the time at which erosion begins. For the center joint inhibitor, a value of $t_0 = 2.0$ was used (the approximate time for full tip exposure), and for the aft joint, a value of $t_0 = 6.0$ was used (the approximate time for the upstream propellant bore to coincide with the inhibitor height). The parameters, c and n , were determined using the measured data described above. The parameter, n , defines the shape of the H vs. t curve. It is determined by finding the value giving the best fit with respect to the FSM-8 data from Figure 12. Several values of n are selected for consideration. For each value of n , c is forced to the value which gives the final average (post-fire) measured inhibitor height for FSM-8. This results in a table of c and n values, each pair giving the correct final average height for the FSM-8 motor. The one which best matches the values from Figure 12 is then selected to establish the best n value.



a) Center joint inhibitor



b) Aft joint inhibitor

Figure 12. Estimated inhibitor radial heights for the FSM-8 center and aft inhibitors.

Assuming recession rates to be linked to flow conditions in a manner similar to heat transfer coefficients, values of the parameter, n , near 0.5 would be expected; 0.5 for low Reynolds number boundary-layer-type flow and 0.8 for high Reynolds number and pipe-type flow. Because of the short flow length over the inhibitor tip, the flow behavior is more similar to lower Reynolds number boundary layer flow, and values closer to 0.5 should be expected.* The exponent, n , was fit using the FSM-8 data of Figure 12. Values in the range of $0.2 < n < 0.9$, in increments of 0.1, were considered. For each value of n , the coefficient, c , was determined for each inhibitor by forcing the final height from Equation (3), with numerical integration, to match the average post-fire measurement value for FSM-8. Resulting values for c and n are given in Table 1. Note that the c values for the aft and center inhibitors are similar indicating similar behavior with respect to mass flux.

* Flow separation and mechanical oscillation of the inhibitor actually make the flow dynamics much more complicated than this implies, which is why the empirical approach is used.

Table 1. Values of the parameter c for the FSM-8 data

n	Center Joint	Aft Joint
0.2	0.25	0.27
0.3	0.25	0.28
0.4	0.26	0.28
0.5	0.27	0.29
0.6	0.27	0.29
0.7	0.28	0.30
0.8	0.29	0.30
0.9	0.30	0.31

The goodness of each n value was quantified using the intermediate values of Figure 12 by summing the square differences between the correlated and the estimated intermediate values. The value of $n = 0.5$ was found to provide the best fit. The values for c were found to be 0.27 for the center inhibitor and 0.29 for the aft inhibitor. The resulting correlations are shown graphically in Figure 13.

CONCLUSIONS

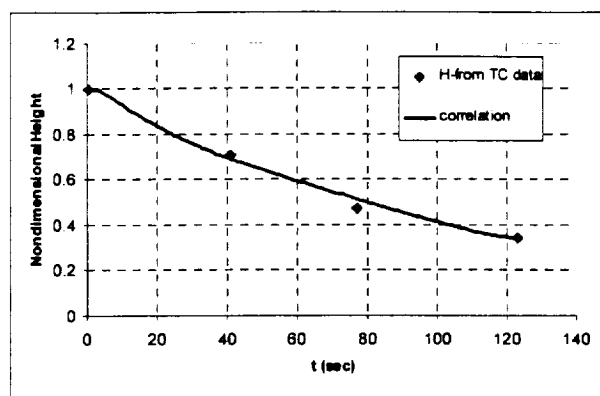
Real-time propellant inhibitor char line recession measurements can be accomplished with eroding potentiometers and thermocouples. The RSRM FSM-8 static test motor propellant inhibitors were successfully instrumented with eroding potentiometers and thermocouples. The data was used to establish forward face char line recession versus time relationships. This report presents that data for the center and aft field joint forward facing inhibitors. The eroding potentiometers worked well to measure insulation material char line recession versus time.

The inhibitor height recession rates have been shown to correlate well with the mass flux through the area defined by the inhibitor port.

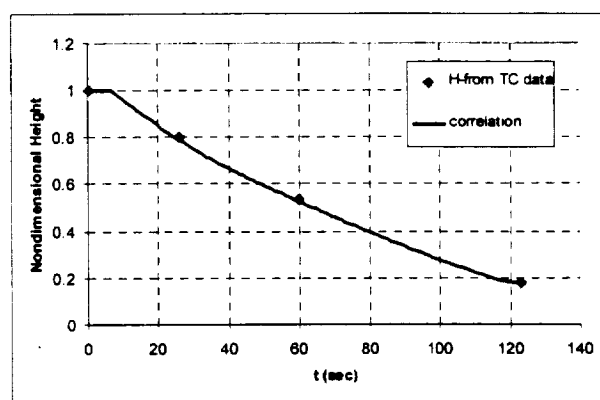
FUTURE WORK

Improvements to the eroding potentiometer are being investigated. The most promising improvements involve the use of new resistive wire materials.

Additional RSRM static test motors are being instrumented. This additional experience will improve installation techniques. Although the instrumentation was a success on FSM-8, some of the instrumentation did not work. Most of the instruments that failed on FSM-8 were damaged during manufacturing of the motor. It is hoped that modifications to the installation process will increase the survivability of the instrumentation wires.



a) Center joint inhibitor



b) Aft joint inhibitor

Figure 13. Calculated versus measured values of estimated inhibitor radial height for the FSM-8 center and aft inhibitors.

ACKNOWLEDGEMENTS

The ultimate use of this data has been for thermal analysis of RSRM inhibitors. However, to make the project successful, many other engineering disciplines were involved. The writers thank the Thiokol Propulsion Insulation Work Center and all of the manufacturing technicians involved with installing the insulation and instrumentation materials. The installation required careful handling and layup of the materials.

The writers thank the Thiokol Propulsion Test Transducer Development Lab. The success of this instrumentation program absolutely would not have been possible without the extreme dedication and professionalism of these workers. The thermal analysts are in deep gratitude to all of the Test Transducer Development Lab personnel. Thanks goes to Lloyd Johnson for his enthusiasm and "can do" attitude during the building and installation of this instrumentation. Thanks especially goes to Boyd Bryner, the main inventor of the eroding potentiometer.

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