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Effect of Internal Physical Change on Catalytic Thruster Performance

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Instrumentation has been used to identify physical change occurring inside a catalytic hydrazine thruster. Techniques were developed to measure changes with life in the catalyst bed and relate these changes to effects on performance. It is shown that the quantity of catalyst fines that accumulate in the bed directly affects performance; differences in firing duty cycle, thruster orientation, and acceleration field influence the retention of these particles. The results obtained are directly applicable only to this particular thruster, however, testing of other designs should consider possible differences between ground and flight operation in order to provide a realistic simulation.

Nomenclature

a	= average catalyst particle radius
g_c	= gravitational constant
G	= mass flow rate per unit area
I_{sp}	= specific impulse
K	= constant
L	= catalyst bed length
$\dot{m}$	= mass flow rate
P	= pressure in catalyst bed
$\overline{P}$	= average catalyst bed pressure
P_c	= chamber pressure
P_B	= upper catalyst bed pressure
ΔP	= pressure drop
ϵ	= void fraction
μ	= gas viscosity
ρ	= gas density

Introduction

CATALYTIC hydrazine thrusters have been used successfully for a number of years for attitude control, orbit adjust, and stationkeeping. Although thruster life has continued to increase, the design of these thrusters is certainly not an exact science, as evidenced by the various flow injection and catalyst bed retention techniques used in the industry. Testing over specific firing duty cycles is still required before a new or existing design can be considered qualified for a particular application. The usual procedure is to either terminate the testing after a stated goal has been achieved or test until the thruster has experienced performance degradation beyond a useful life; at this point the thruster is disassembled to evaluate its physical condition and arrive at conclusions concerning the cause of degradation.

Since catalytic thrusters experience continual change during use, it would be desirable to evaluate their condition prior to testing termination. Moreover, waiting until the end of testing can make it difficult to relate observed changes in thruster performance to physical changes, since more than one degradation mode may exist; the disassembly procedure itself also disturbs the catalyst bed and compromises an objective evaluation. Unfortunately, most catalytic thrusters are too small to allow the appropriate instrumentation required to follow the transient nature of thruster operation or to characterize internal physical change as life is accumulated. A chamber pressure transducer is incorporated in some cases, and temperature sensors have been attached to the nozzle and injector areas. There is, generally, no instrumentation inside the catalyst bed, and this limits the performance analysis. For example, thrust degradation may be due either to washout involving undecomposed hydrazine or to a flow restriction in the injector tubes or catalyst bed. Distinguishing between these mechanisms can be difficult, especially in orbit, without additional instrumentation.

This paper discusses various phenomena that have been identified and analyzed on a large 250-lb_f thruster that is heavily instrumented and has an extensive ground and flight performance history. It is recognized that not all catalytic thrusters will experience the same types of change since there are differences in both design and duty cycle. The intent here is to present some of the phenomena that do occur and to show that the awareness of physical change is important in the evaluation of performance and the determination of test conditions.

Thruster Design and Operation

A schematic of the thruster is shown in Fig. 1, which also shows the locations of flight instrumentation plus some of the ground test internal temperature probes and pressure transducers that are used to evaluate performance. Hydrazine is injected from a slotted tube into the fine catalyst assembly containing 20-25 mesh shell 405 catalyst. These 37 individual assemblies are surrounded by 8-12 mesh coarse catalyst. The flight instrumentation includes chamber (P_c) and upper bed (P_B) pressure transducers, two internal temperature probes (T_B) near the end of the bed, and external temperature sensors on the thruster wall (T_w) and nozzle (T_N). Additional ground data are obtained from internal bed temperatures (T_u, T_m), exhaust gas temperature (T_G), and two additional pressure transducers (P_A, P_D) in the aft region of the bed.

A large number of ground tests have been conducted, and disassembly data are available on 15 thrusters. All of the acceptance testing and most of the mission testing have been in the horizontal orientation; however, more recent testing on two engines has involved the nozzle-down attitude in an attempt to establish a closer correlation with on-orbit performance.[1] The total flight experience on a number of thrusters includes over 500 cold starts (120-140°F) and a delivered impulse of over 8,000,000 lb_f-s without a flight

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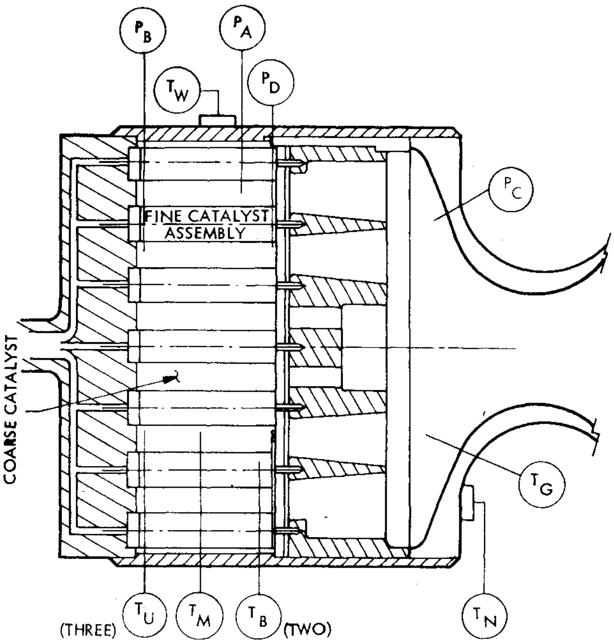

Fig. 1 Hydrazine thruster.

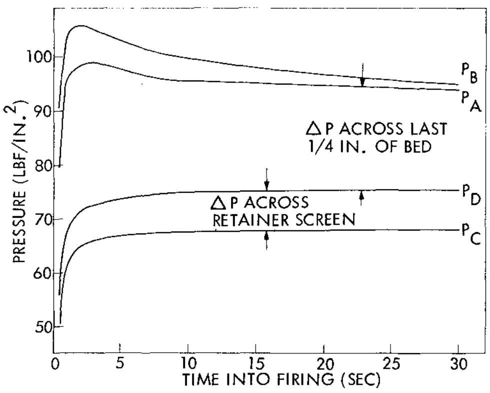

Fig. 2 Internal pressures.

failure. The longest single flight firing has been approximately 1000 s.

The operation of the thruster is characterized by the transient nature of internal pressures, temperatures, and performance. Equilibrium conditions are not achieved until over 200 s of firing, and even then the decomposition inside the bed experiences slow but continual change. The operating characteristics are illustrated on Figs. 2 and 3. It can be seen that most of the pressure drop occurs in the extreme aft portion of the catalyst bed, indicating that this is where most of the decomposition gases are generated. This is not entirely unexpected, since approximately 50% of the hydrazine flow is injected from the end of each tube in the fine catalyst assembly. The temperatures also reflect this situation; the lower temperatures exist in the upper part of the bed which has the least hydrazine decomposition. The difference in temperature between the two forward bed probes (located at different circumferential positions) illustrates the existence of two-phase conditions and lack of homogeneity in this region. The highest temperatures are recorded in the chamber downstream of the bed, an indication that most of the hydrazine decomposition occurs near the end of the bed and probably some in the chamber itself prior to entering the nozzle.

The total pressure drop across the catalyst bed decreases with time in conjunction with a slowly increasing exhaust temperature and specific impulse. The interpretation is that

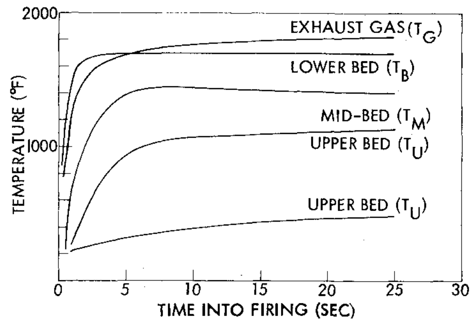

Fig. 3 Internal temperatures.

this represents a gradual downstream movement of the region of hydrazine decomposition, resulting in lower ammonia dissociation and higher exhaust gas temperatures. While alternatives have been suggested for this declining pressure drop (e.g., radial reorientation of the flow throughout the bed), perhaps the most convincing evidence for the downstream movement of decomposition is obtained from hot restarts 5 s after shutdown of long steady-state firings. The observed initial increase in pressure drop in conjunction with lower exhaust gas temperatures that result in a slight cooling of the nozzle is consistent with a more upstream generation of the decompsition gases. The exhaust gas temperature then steadily increases to its original level as the bed pressure drop again decreases.

Measuring Changes with Life

Chamber pressure transducers are commonly used on hydrazine thrusters to evaluate health and thrust level and to allow predictions of remaining life. When thrust degradation occurs, its cause may be inferred from previous ground test experience under the assumption that flight thrusters perform in the same manner. In practice, however, it may be difficult to distinguish between various modes of degradation; an accurate determination of specific impulse, for example, is usually not possible since thruster flow cannot be directly determined. The 250-lb$_f$ thruster has a cavitating venturi which makes the flow dependent only on tank pressure and independent of thruster changes unless a high catalyst bed impedance develops. The availability of accurate flow rate determination plus internal catalyst bed pressure transducers makes possible the monitoring of internal catalyst bed impedance. This parameter, called catalyst bed resistance, makes use of the total catalyst bed pressure drop for the purpose of characterizing the internal bed condition and flow penetration while normalizing for flow rate.

Various expressions for flow through packed beds have been used in hydrazine reactor design and analysis; for this application, the parameter is based on the Ergun equation, written as

$$\frac{dP}{dL} = \left(\frac{1-\epsilon}{\epsilon^3}\right)\left(\frac{G^2}{2a\rho g_c}\right)\left(1.75 + \frac{150(1-\epsilon)\mu}{2aG}\right)$$

After simplification, the equation becomes

$$\frac{L}{a}\left(\frac{1-\epsilon}{\epsilon^3}\right) = \frac{K\bar{P}}{\dot{m}^2}(P_B - P_c)$$

The above expression assumes a constant gas temperature and ammonia dissociation in the catalyst bed; while this is not always the case, changes in these two parameters are compensating, so that only minor changes in gas density result. Changes in the value of the right-hand side of the equation (measured variables) are interpreted in terms of the physical parameters on the left-hand side. The effective gas flow length

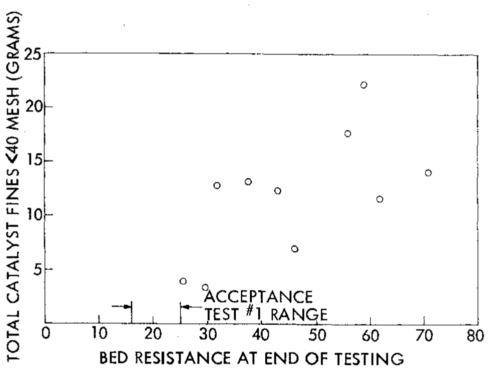

Fig. 4 Effect of catalyst fines on bed resistance.

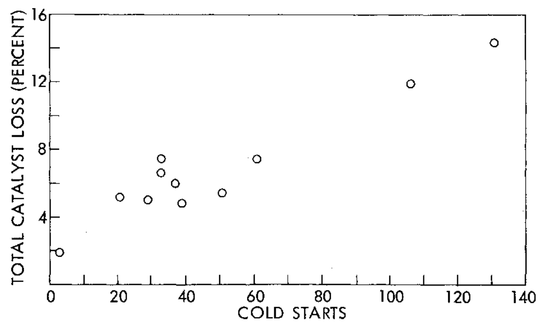

Fig. 5 Total catalyst loss.

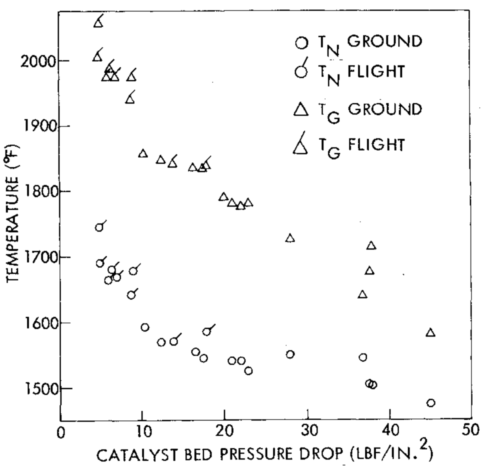

Fig. 6 Effect of bed resistance on temperature.

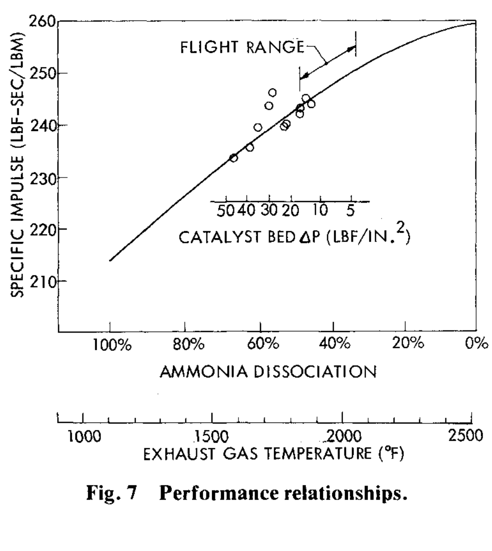

Fig. 7 Performance relationships.

through the bed, L, is a function of the point of hydrazine injection and its penetration into the bed prior to decomposition. It is affected by feed pressure, catalyst attrition and activity, and time into the firing. The average particle radius a is a measure of catalyst wear and the particle size distribution in the bed; it is affected by number of starts and thruster operating conditions. The void fraction ϵ is a measure of catalyst loss, migration, and packing; it is affected by number of starts and firing duty cycle.

The declining pressure drop and catalyst bed resistance during a typical firing is ascribed to increasing hydrazine penetration, since the physical parameters a and ϵ should experience little change. However, theoretical considerations and analysis indicated that changes in the bed resistance from firing to firing are primarily a function of physical change inside the bed. Enough thruster disassembly data are now available to show fairly conclusively that the bed resistance for a given firing is a function of the amount of catalyst fines that accumulate in the aft part of the coarse bed near the retainer screens. Figure 4 illustrates the effect of catalyst fines on bed resistance 20 s into the final mission firing test for a number of different engines. Since it is known that the ground test bed resistance history is dependent on the firing duty cycle, this is confirmation that duty cycle affects the internal physical condition of the bed. Some of the data scatter is ascribed to differences in flow injection, number of starts, and total hydrazine usage.

It has been found that this thruster has a relatively low rate of catalyst loss, which can be correlated in terms of number of cold starts, as shown in Fig. 5, which represents data for different engines; the total impulse has been shown to be a secondary variable. Disassembly data have also shown that of the total catalyst fines generated, no more than 20% of these remain in the bed. It is the degree of catalyst retention (determined by duty cycle and thruster orientation) that is crucial in determining the catalyst bed resistance and performance.

Internal Physical Phenomena

Influence of Catalyst Bed Impedance

A previous paper[2] discussed the use of catalyst bed resistance in performance prediction and presented the hypothesis that changes in bed resistance are a function of accumulation and loss of catalyst fines in the aft region of the coarse bed. Changes in the bed condition would be expected to affect the degree of ammonia dissociation; Fig. 6 shows that exhaust gas and nozzle temperatures are closely related to measured total bed pressure drop. These data were obtained from long (>250 s) steady-state firings on different engines at approximately the same flow rate after thermal equilibrium was attained on the nozzle. Confirmation is thus provided that changes in the catalyst bed condition directly affect exhaust gas temperatures. All the data on Fig. 6 are from actual measurements, except the flight gas temperature, since this probe is not part of the flight instrumentation. However, a correlation obtained between the nozzle and gas temperatures was used to estimate the flight gas temperature values based on actual measured values of nozzle temperature. These estimates of 2000°F temperatures may appear high for a hydrazine thruster, but they are consistent with actual values of average specific impulse for flight burns when the bed resistance is low. Since an accurate instantaneous I_{sp} measurement is not available, a good estimate can be obtained from use of the integrated average for the entire burn (which is available) in conjunction with the known shape of the I_{sp} transient.

Figure 7 shows the relationship between actual measured performance on the thruster and gas temperature, ammonia dissociation, and total catalyst bed pressure drop for the long firings. A theoretical curve for this thruster has been passed through data points taken from different ground test firings

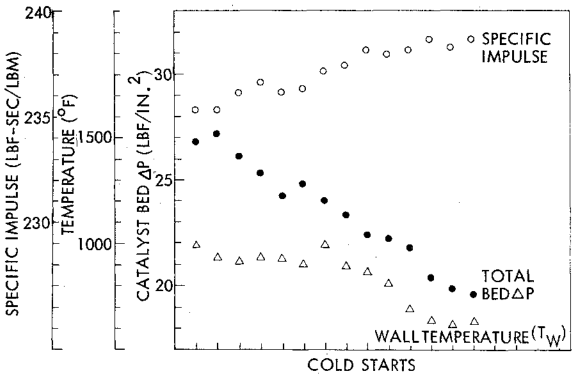

Fig. 8 Decreasing pressure drop phenomenon.

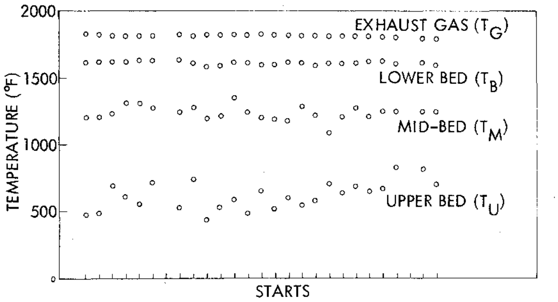

Fig. 9 Internal temperature variability.

where both specific impulse and exhaust gas temperature were available. The range of ammonia dissociation values over which the thruster has operated in steady state has thus been determined to be from about 67 down to 33%. Of course, it is probable that values higher than 67% existed early in a firing before equilibrium had been achieved, since the decreasing pressure drop characteristics indicates a rearward movement of the decomposition region. It appears unlikely that values significantly lower than 33% will ever be attained, or are physically possible, since catalyst bed pressure drops lower than currently measured (5 psi) would seem to be precluded except in the case of thruster washout. Even these extremely low values make it probable that some fraction of the liquid hydrazine is not decomposed until after passing through the catalyst bed. It is conjectured that the high temperatures in the retainer screen and chamber regions in conjunction with the large support mass downstream of the catalyst bed promote the thermal decomposition of hydrazine penetrating the bed, resulting in very high performance without washout.

Transient Effects—Loss of Catalyst Fines

As described in the earlier paper,[2] flight thrusters exhibit an increase in catalyst bed resistance early in the mission (like ground testing) followed by a sharply decreasing trend (unlike ground testing) until a lower plateau value is reached. These decreasing trends raised concerns regarding washout until sufficient data and experience were gained to alleviate the fears. Two engines were subsequently tested in the nozzle-down attitude in an attempt to duplicate the flight results. A similar decay in catalyst bed resistance was obtained by using a particular firing duty cycle which was somewhat different from flight but still provided similar changes in performance and temperature. Figure 8 illustrates the changes that occurred during a time when the feed pressure was nearly constant. The pressure drop data are at 20 s into the firing while the specific impulse and temperature are at 40 s, as is customary for data analysis on the thruster.

The interpretation of Fig. 8 is consistent with the hypothesis that declining pressure drop is due to the loss of catalyst fines that had previously accumulated in the aft region of the

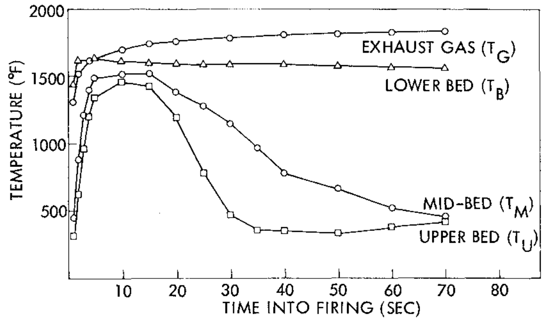

Fig. 10 Thruster temperature anomaly.

coarse catalyst bed. Additional evidence that the impedance changes were a result of the changing population of catalyst fines was in the pressure drop reversibility observed when the firing duty cycle was altered; disassembly data had previously related firing duty cycle to the physical condition of the bed. The downstream movement of the high-temperature region can be clearly seen in the increasing specific impulse trend due to decreases in gas residence time in the bed and lower ammonia dissociation. The external wall temperature monitor provides a measurement upstream of the major area of hydrazine injection; the decreasing temperature trend reflects the downstream movement of the high-temperature region away from this location.

Local Effects—Thruster Temperatures

It has been found that thruster performance can be reliably correlated in terms of exhaust gas temperature; however, in moving upstream in the thruster, the temperatures experience an increasing degree of fluctuation. Figure 9 illustrates this effect for data taken at the 40-s point into the firing for a particular ground test engine. The temperature probes at the forward end are cooler and are subject to the local effects of variable flow distribution and regions of two-phase flow. If a thruster-to-thruster comparison is made, the variability relative to the exhaust gas temperature (even for the lower bed probe) is even more pronounced. One reason for this upstream temperature variability lies in the flow characteristics of the individual flow distribution tubes in each of the 37 fine catalyst assemblies. Water flow testing has shown that a single tube can abruptly change from one run to the next so as to greatly alter the percentage of flow exiting at the various slots along the tube. This phenomenon has been related to the point of flow attachment along the distribution tube wall of the entering hydrazine.

Figure 10 shows what appears to be the effect of large changes on the part of more than one flow distribution tube in the same general area of the thruster. This change caused the upper and middle bed probes, which are almost in-line axially, to decay rapidly to values significantly below those for previous firings. It is believed that a sudden decrease may have occurred in the quantity of liquid hydrazine injected into the upstream part of the bed in this region, resulting in the lower temperatures. The effects extended at least halfway down the bed; however, neither the lower bed nor exhaust gas temperature probes reflected this disturbance, indicating that the increased downstream hydrazine flow was accommodated and decomposed before reaching the end of the bed. The important thing is that the flow injection variability demonstrated here did not affect thruster performance, probably because the total flow through the bed was dispersed due to the large number of injection elements. It should be noted that the temperature profiles returned to normal on the next firing.

Effect of Operating Conditions

The effect of firing duty cycle on the internal catalyst bed condition has been discussed; this corroborates the evidence already available on smaller attitude control thrusters that performance and thruster life are very strongly related to the particular application (e.g., spinning vs three-axis stabilization). Both catalyst bed voiding and bed packing are phenomena influenced by duty cycle, which can lead to severe thrust degradation.

Conditions not often addressed are those of thruster orientation and acceleration field. Experience with this thruster has shown that these are significant variables affecting the internal catalyst bed condition. Mission testing in the horizontal, nozzle-down, and near-zero-g (flight) conditions has confirmed a relationship with catalyst bed resistance, with horizontal testing resulting in the highest values and zero g the lowest. Changes in orientation from acceptance testing (all horizontal) to mission testing and on particular engines during mission testing appear to rule out significant effects due to flow distribution differences (for this engine), leaving catalyst bed changes as the primary mechanism.

The hypothesis is that the retention of catalyst fines in the bed, and thus catalyst bed resistance, is determined by the degree of catalyst freedom of movement in the aft region near the retainer screens. In the horizontal attitude, for example, loss of coarse catalyst causes a void to form at the top of the engine along the wall; this void at least partially accommodates the relative movement between catalyst and shell due to thermal expansion during a firing. The minimization of radial and axial disturbances in the catalyst bed then minimizes the sifting action, which would cause catalyst fines to migrate toward the end of the bed and out of the engine. Therefore, a relatively high level of impedance results from the collection of fines in this region. In the nozzle-down orientation, the void will be in the forward end of the bed; thermal effects will create radial disturbances and induce an axial movement due to the constraining effect of the shell. The resulting catalyst movement allows fine particles to work their way through the bed somewhat more easily in this orientation, thereby reducing the impedance to flow. It is in flight, however, that the sharpest declines and lowest values of bed resistance are encountered. In addition to the thermal expansion effects, the near-zero-g field allows the catalyst particles to assume a looser state (higher ϵ) than in 1 g; in fact, the low acceleration that does exist is directed away from the retainer screens, further impeding the catalyst packing process near the end of the bed. As noted earlier, most of the catalyst fines that are generated pass out of the engine regardless of orientation. However, the quantity that is retained is very important in determining operating performance, and the indication is that the orientation and acceleration field are significant variables in this regard. While the results reported here apply only to a particular thruster, the recognition that there are differences between the ground and flight environments should be a subject of consideration for future thruster design and testing.

Conclusions

Instrumentation has been used to relate observed changes in performance and operating characteristics to physical change inside the thruster catalyst bed. It has been shown that exhaust gas temperature and specific impulse are functions of the flow impedance caused by the accumulation of catalyst fines. A flight anomaly involving a rapid decline in bed impedance was analyzed and explained in terms of loss of catalyst fines from the aft region of the bed. Differences in thruster orientation and acceleration field do not significantly affect the total catalyst loss but do influence the degree of retention of catalyst fines inside the engine; differences between ground testing and on-orbit operation reflect this phenomenon. Internal temperature probes were used to confirm flow distribution variability and assess the effect on thruster performance. Techniques were developed whereby exhaust gas temperature and ammonia dissociation percentage could be determined for flight engines lacking direct performance monitors.

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