Flight Performance of a High-Impulse Monopropellant Thruster

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A discussion of flight experience obtained on a 250 lb_f thrust monopropellant hydrazine thruster is presented. Consistent and highly predictable performance was achieved over the full range of operating conditions, and the catalyst bed resistance parameter was employed successfully in performance prediction. An unexpected decline in catalyst bed resistance, not observed in previous ground testing, caused initial concern over possible engine washout, although eventual stabilization occurred. Analysis of ground and flight data indicates incomplete simulation in ground testing, and suggests caution in the extrapolation of flight thruster life expectancy from ground test results.

Nomenclature

C^* = characteristic exhaust velocity
g = standard gravitational acceleration
I_{sp} = specific impulse
P_B = upper catalyst bed pressure
P_c = chamber pressure
T_B = catalyst bed temperature
T_N = nozzle temperature
$\dot{w}$ = propellant flowrate
σ = standard deviation

Introduction

FLIGHT experience which represents a significant increase in the available data for orbit adjust thrusters has been obtained on a 250-lb_f thrust monopropellant hydrazine thruster developed by Walter Kidde and Co. The propulsion system includes a propellant tank which uses nitrogen pressurant over a 3:1 blowdown ratio, and a cavitating venturi for precise flow control. The design requirements for the system specify successful operation over at least 47 ambient temperature starts and 675,000 lb_f-sec total impulse while providing an impulse predictability within $\pm 4.5\%$.

Since the impulse delivered by the thruster is high relative to previous monopropellant experience, extensive evaluation was conducted to characterize the flight performance. Since it is known that catalyst attrition, void formation, and other forms of degradation limit the operational life of monopropellant thrusters, analytical investigations were conducted to identify physical mechanisms which might be responsible for the observed flight characteristics. These concerns over possible catalyst bed washout tendencies prompted changes in the operational use of the engine, although no performance degradation was actually observed.

Another area of investigation involved the applicability of ground test results to the prediction of actual flight performance and engine life; this aspect is being given increasing emphasis in the monopropellant field. Evaluation of flight data revealed significant differences between ground and flight engine performance and pointed out the need for a better understanding of the phenomena involved, and a better simulation of the flight environment.

Engine Design and Testing

Figure 1 shows the thruster schematic and the locations of the flight instrumentation. The pressure transducers at the upper end of the catalyst bed and in the chamber are used to determine the catalyst bed pressure drop and associated catalyst bed resistance. The temperature probe in the bed and the thermocouple on the nozzle are also part of the diagnostic instrumentation. Upon entering the propellant manifold, the flow branches into tubes leading to 37 individual flow distributor tubes surrounded by cartridges containing 20-25 mesh Shell 405 ABSG catalyst. Figure 2 shows more detail of the distributor tube (covered by a screen) and the fine catalyst assembly. The flow exits each tube through slots in the side and at the end, with approximately 50% of the hydrazine injected through the side slots. Ground flow testing as well as engine firings were conducted to investigate the relative flow distribution between the side and end slots; the selected distribution was a compromise between washout susceptibility and high performance (high end-flow) and high catalyst bed pressure drop and manifold temperatures (high side-flow). The cartridges are embedded in 8-12 mesh coarse catalyst for the purpose of insuring complete hydrazine decomposition. The nozzle itself has an 85:1 expansion ratio.

Ground testing was conducted to simulate the operating conditions and firing duty cycles expected during flight operations. Testing on the final design showed it to be capable of a large number of starts and large total impulse. One engine exhibited satisfactory performance following 130 cold starts (80°F catalyst bed) and over 3,000,000 lb_f-sec total impulse. The thruster successfully underwent a 5000 sec firing which was an attempt to obtain washout. Although standard performance parameters were evaluated (I_{sp}, C^*, etc.), one parameter used to characterize internal engine operation was the catalyst bed resistance factor, defined as catalyst bed pressure drop divided by flowrate to the three-quarters power ($\Delta P / \dot{W}^{3/4}$). This is an empirically derived relationship which provides results similar to other normalization techniques. Since the propulsion system involved a blowdown feed pressure mode this parameter was intended to measure catalyst bed changes while compensating for the flowrate effects. A point 20 secs into a burn was chosen at which to measure the pressure drop, which continuously decreases during a burn and also changes from burn-to-burn, Fig.3. One theory for the continual decrease is that active catalyst surfaces are temporarily covered by decomposition gases, reducing the total available area, and causing the reaction to progress downstream with operating time.[1] The observed pressure drop recovery following a 3-5 sec shutdown and immediate restart seems to support the theory, since the gases would vent out of the engine prior to the restart.

The usefulness of the catalyst bed resistance factor has been demonstrated in the analytical model of engine performance where the factor is employed as a variable in the prediction of thruster burn times. The monitoring of the internal catalyst bed state is most useful in situations requiring high accuracy. For this thruster, the use of the bed resistance factor provides

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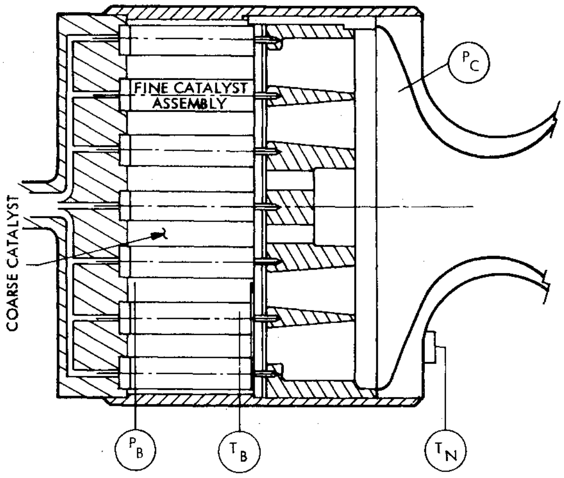

Fig. 1 Hydrazine thruster.

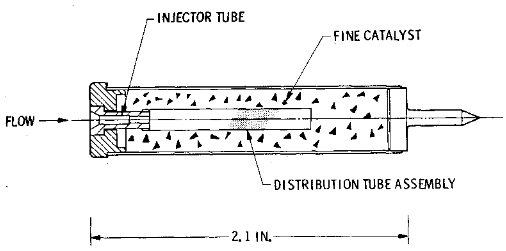

Fig. 2 Fine catalyst assembly.

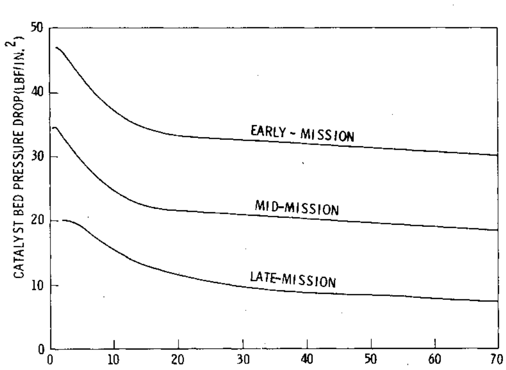

Fig. 3 Catalyst bed pressure drop transient.

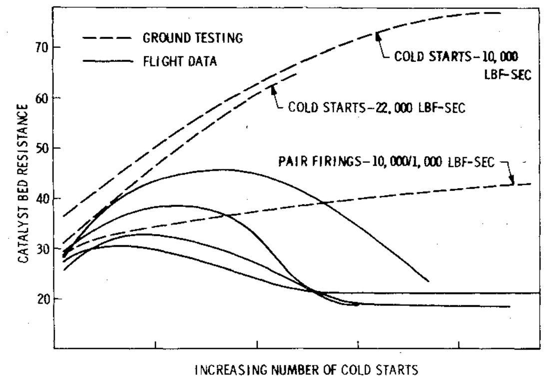

Fig. 4 Catalyst bed resistance history.

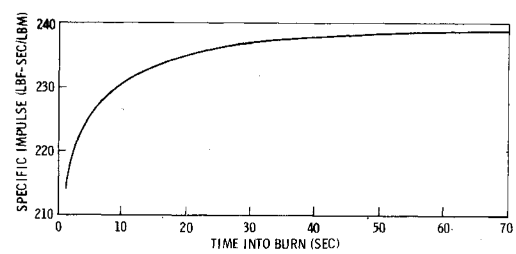

Fig. 5 Specific impulse transient.

an improvement in impulse predictability accuracy of approximately 2% over that obtained using an average value for thruster operation. Physically, for example, a decreasing resistance factor implies a shorter gas residence time and less ammonia dissociation, thus increased specific impulse. It should be noted that the chosen normalization method is not necessarily the most accurate technique; other relationships have been employed, but they provide similar results concerning catalyst bed state and performance.

In order to bracket the expected flight use of the thruster, two general types of firing duty cycles were employed. One consisted of entirely single cold starts of a given impulse (10,000, 22,000, or 35,000 lb_f-sec). The other duty cycle consisted of a succession of pair firings, the first a 10,000 lb_f-sec cold start followed by a hot restart of 1000 lb_f-sec. The thruster was shown to be duty cycle sensitive, as the bed resistance factor of Fig. 4 shows. The three ground test curves are representative of the results obtained. It is seen that the pair firing duty cycle resulted in a much lower bed resistance profile. This effect has been rationalized in terms of the generation and movement of catalyst fines in the bed. It is postulated that each start generates fines and also forces a certain amount out of the engine through the retainer screens. However, a hot start generates less fines relative to the amount forced out of the engine, resulting in a lower accumulation in the downstream end of the catalyst bed. The primary concern involved the single cold start duty cycle, where a high bed resistance could possibly result in dangerously high manifold temperatures and also preclude flow cavitation through the venturi, resulting in degradation of impulse predictability. Besides demonstrating satisfactory operation of the thruster, one result of the ground testing was an envelope which would be expected to contain the future flight engine catalyst bed resistance data.

Flight Experience

Performance

When a thruster firing is required, the burn time is computed through use of an analytical model[2] which accepts as inputs the required impulse, current feed pressure, propellant temperature, and the catalyst bed resistance factor from the previous burn. Most of the cold starts have involved propellant temperatures of 70°-95°F (294-308K) and catalyst bed temperatures of 120°-140°F (322-333K) over a feed pressure range from 300 down to 80 psia (2.06×10^6—$5.59 \times 10^5 N/M^2$). One of the significant features of the is the use of the catalyst bed resistance to characterize internal engine changes with life for the purpose of making performance corrections. As a result of unexpected bed resistance changes, this parameter assumed a greater significance than was expected.

The primary measures of thruster performance are specific impulse and impulse predictability. For this thruster, the range of average mission I_{sp}'s has been 234.2-239.9. This average is an integrated value including all the burns and is a function of not only the individual thruster but also the feed pressure profile and burn durations. Due to the transient nature of monopropellant hydrazine thruster operation, the longer burns exhibit the highest average I_{sp}. This effect is illustrated in Fig.5, which shows the instantaneous I_{sp} as a function of time into the burn based on ground firing data. One unique aspect of this thruster is that due to a decrease in the catalyst bed resistance, the flight I_{sp} at the end of the tank blowdown generally equals or exceeds the value at the beginning. This effect occurs in spite of large decreases in feed pressure and propellant flowrate, which resulted in a decreasing I_{sp} for ground engines. The thruster has exhibited instantaneous I_{sp}'s calculated to be higher than 245 lb_f-sec/lbm at 120 psia feed pressure, which is very high for a monopropellant hydrazine thruster. The average impulse predictability for the flight engines for burns exceeding 10,000 lb_f-sec impulse is $+0.77\% \pm 1.64\%$ (2^σ). This predictability accuracy has been consistent over the full range of operating conditions. The only postflight adjustment made in the analytical model was in the region of low catalyst bed resistance, where no ground data were available for the original model.

Unexpected Thruster Characteristics

As the number of starts on the flight engines increased, a condition was observed which caused concern over the eventual life of the thruster. This concern involved a very rapid decline in catalyst bed pressure drop (and thus resistance factor). This decline, at the rate of approximately 1-2 psi per cold start, raised the possibility that engine washout might occur, involving the passage of liquid hydrazine through the bed in an undecomposed state with associated performance degradation. This occurrence was completely unexpected, since the actual flight duty cycles would have suggested a relatively high catalyst bed resistance, based on previous ground test results. Figure 4 shows the catalyst bed resistance history for several flight engines as well as the range of ground test results.

Two other parameters, nozzle temperature and average specific impulse, were involved in the analysis of declining catalyst bed resistance. Ground testing had shown that the nozzle temperature (measured at T_N) at a given time into the burn follows a decreasing trend until the end of testing. The decreasing temperature is due to the decreasing propellant flowrate (caused by tank blowdown mode) and the increasing pressure drop, implying more ammonia dissociation and lower chamber temperatures. However, later flight engines began to show a plateau followed by an upturn in nozzle temperature which seemed to coincide with the sharp decline in bed resistance; Fig. 6 shows typical flight vs ground characteristics for the nozzle temperature at 40 sec into a burn, the point chosen for purposes of thruster-to-thruster comparison. A similar upturn was later discovered on an earlier ground test engine which had experienced a washout. The average I_{sp} for burns in the area of low bed resistance was also higher than expected, and did not show the declining trend expected from ground data. As a whole, the data suggested that the hydrazine decomposition was occurring farther and farther downstream in the bed, resulting in hotter chamber temperatures and higher performance. The concern was that the performance would peak during some burn, followed by a gradual washout and performance degradation. This situation might place a limit on the number of starts which could be made with the thruster.

The concerns expressed above resulted in a change in the way the thruster was operated. It was decided that when long burns were required (greater than about 200 sec) during the time of low catalyst bed resistance, the burn would be split into segments, with 5 sec off between firings. This precautionary procedure was implemented in order to minimize the total pressure drop decay during the burn, presumably averting any tendency to go into a washout condition. The decision was also based on a theory involving the hydrazine decomposition gases built up inside the catalyst pores during a burn. It was reasoned that shutting down the engine would result in the rapid venting of these gases to the vacuum environment. This would expose more active catalyst sites at the start of the next burn, resulting in greater use of the upstream portion of the bed, higher pressure drops, and an increased resistance to washout. This technique was suc-

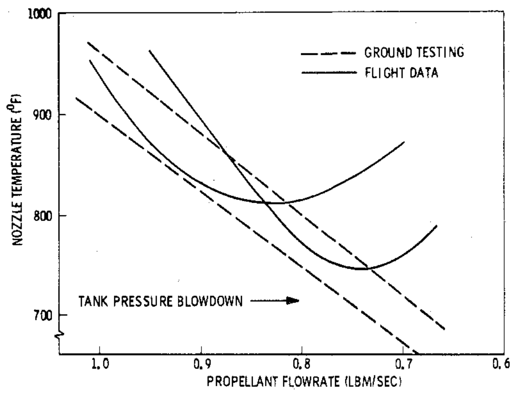

Fig. 6 Nozzle temperature characteristics.

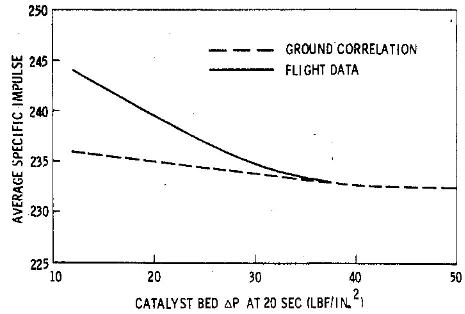

Fig. 7 Pressure drop/specific impulse relationship.

cessfully employed with engine burns involving catalyst bed pressure drops as low as 5 $lb_f/in.^2$ late in the run.

On later flight engines, the increased number of starts made it possible to determine if an engine life limitation was indeed being approached. However, as shown in Fig. 4, continued operation following the period of bed resistance decline did not result in engine washout, but a stabilization of bed resistance and a continuation of successful engine firings. The implications of this characteristic are still being studied.

Analytical Investigations

Data Analysis

Although the catalyst bed resistance stabilization was encouraging, increased requirements on the engine made it desirable to understand the internal changes. The disparity between ground test results and flight data also made it necessary to determine the meaningfulness of the ground results. Therefore, analytical investigations were pursued in an effort to understand the relationship between various engine parameters and operating conditions.

While ground testing had shown a relation between performance and catalyst bed pressure drop, the flight results revealed a much more dramatic effect on I_{sp} when the bed resistance reached low values. A correlation of average I_{sp} (normalized for 15,000 lb_f-sec impulse and 0.8 lbm/sec-flowrate) as a function of pressure drop at 20 sec was developed; Fig. 7 shows the result. The dashed line represents the correlation based on ground data alone (most of the data were above $\Delta P = 30$ psi) while the solid line represents the flight data and reveals a significant effect on I_{sp}. Since there has been no performance degradation on a flight engine, it is assumed that this plot represents normal operation over a wide range of internal catalyst bed changes. This higher-than-expected performance was apparently due to the inability of the previous ground testing to completely simulate the flight conditions. It should also be noted that since these values are averages over the entire burn, the steady state I_{sp} would be higher by about 4 lb_f-sec/lbm.

Completely satisfactory correlations have not yet been obtained for the nozzle temperature reading, but it is apparent that it is related to the catalyst bed resistance. In fact, at low values of bed resistance, the nozzle temperature during a long duration firing (≈ 150 sec) has sometimes exceeded that of the catalyst bed probe. This is another indication of a downstream movement of the reaction zone and hotter gas temperatures in the chamber. Attempts at correlating data from the catalyst bed probe have not been successful. It is believed that the influence of localized reactions plus the individual thruster differences at that location have not made it possible to measure overall thruster changes. However, the readings from the probe confirm the successful operation of the thruster, and large fluctuations or declines indicative of washout tendencies have not been observed.

The attempt to develop flight performance predictions for a given thruster based on ground test data has pointed out the need to better understand the relationship between ground test simulation and actual flight conditions. For example, hot-fire engine acceptance test data were studied for its usefulness in predicting flight performance. Evaluation of the data showed slight shifts in performance (e.g., I_{sp}, C^*) between acceptance testing and actual flight firings – the ranking of engines in terms of flight I_{sp} was also significantly different than on the basis of ground testing. At this time, it is concluded that these minor differences in flight performance cannot be predicted from acceptance test firings. However, it is not possible to tell whether the zero-*g* flight environment, transportation/handling or some other factor is the most significant reason for the differences.

It is known that the performance and life of small hydrazine thrusters (≤ 5 lb_f thrust) are influenced by the firing duty cycle; both ground and flight results have demonstrated this fact. It was therefore expected that larger thrusters would also exhibit a duty cycle dependence, and this was demonstrated in ground testing of this thruster. The flight data have been evaluated in an effort to determine if the performance and catalyst bed resistance changes are a function of the individual firing duty cycles. At this time correlations have not been obtained, and it is apparent that the reasons behind the different flight engine bed resistance histories have not been isolated. The significant aspect is that the thrusters seem to arrive at a common, stabilized condition (in terms of bed resistance and performance), regardless of the duty cycle.

Physical Mechanisms

The hypotheses concerning the observed changes in flight catalyst bed resistance and performance center around two broad categories – changes in the hydrazine flow distribution and physical changes in the catalyst bed. The first category is concerned with the flow injection characteristics of the distribution tubes. Water flow testing showed that some of the tubes exhibit a tendency to suddenly change their hydraulic characteristics, causing an increase in the percentage of the flow which is injected at the end of the tube. Evaluation of manifold pressures during ground hot-fire testing indicates varying degrees of this occurrence during the mission duty cycle and also differences between thrusters. It was therefore suggested that the rapid decline in catalyst bed resistance might be due to higher end-flow injection on the part of an increasing number of distribution tubes, possibly due to physical distortion within the thruster or a feed pressure effect. However, investigations into this area show no correlation between ground engine catalyst bed resistance and the calculated change in injection characteristics. Secondly, it is difficult to rationalize the in-flight trends (initial build-up, rapid decline, and stabilization) in terms of flow distribution changes alone.

It has also been suggested that the flow distribution in the low-*g* flight environment may differ from that in ground testing since the injection velocities can be lower than one ft/sec. The direction of the *g*-field in the horizontal ground testing would give the flow a velocity component in that direction, resulting in a longer flow path to the end of the catalyst bed, a longer residence time, and a higher catalyst bed pressure drop. The shorter effective flow path in the flight engines, in conjunction with the increasing end-flow from the distribution tubes, could result in a decreasing bed pressure drop.

It is believed that the catalyst bed pressure-drop characteristics can be explained more reasonably in terms of physical changes in the catalyst bed. The effects involved are catalyst particle breakup, migration of fine particles down the bed, and ejection of catalyst fines during engine burns. The flight engine catalyst bed resistance history during the initial five to ten cold starts is similar to the ground test results. It seems apparent that some factor in flight contributes to the loss of fine catalyst particles which in ground testing build up in the catalyst bed at the retainer screen. It is postulated that the initial flow impedance build-up is due to the high catalyst breakup/particle generation rate resulting in accumulation of catalyst near the retainer screen. Disassembly of ground test engines has shown that the amount of fines generated and catalyst loss is 5-10% of the initial load; analysis shows that this quantity is sufficient to account for the observed impedance build-up in the aft section of the bed. During this period the catalyst packing proceeds at a faster rate than the particle ejection during burns. After a number of firings the loosened catalyst bed would allow for easier particle migration in the zero-*g* field plus a higher ejection rate during each burn. This high catalyst loss rate in conjuction with a decreasing particle generation rate (partly due to the tank pressure blowdown and decreasing hydrazine flowrate) would cause a very rapid decline in the bed impedance. The decline would continue until nearly all the generated fine particles had been expelled, whereupon the impedance would stabilize at a low value (actual flight data show this to be approximately 75% of the initial value). Beyond this point, the pressure drop would decline very slowly due to decreasing flowrate and a reduced rate of particle breakup and ejection.

It may be surprising that the thruster will run for extended periods with a bed pressure drop as low as 5 psi, which is only slightly more than the drop across the retainer screen. It is suggested that perhaps, after a certain time into a burn, a thermal equilibrium has been reached on this thruster whereby sustained hydrazine decomposition near the end of the catalyst bed is made possible by both the catalyst and also the high thruster temperature existing at that time. This would indicate the capability for additional engine starts, at least at the low feed pressure.

Ground Test Simulation

Although the thruster has not experienced performance degradation in flight, some of the observed engine parameters are different enough to warrant concern with regard to proper ground test simulation. Until recently, the ground/flight comparisons were based almost entirely on engine testing in the horizontal attitude. This type of testing did not provide duplication of the flight results in terms of catalyst bed resistance, I_{sp}, and nozzle temperature trends. The increasing requirements on flight thruster impulse, starts, and feed pressure profiles (repressurization of propellant tank) made it necessary to reevaluate the ground test results which had shown sufficient thruster life margins, but were associated with higher values of catalyst bed resistance and presumably greater washout resistance.

The effect of engine attitude was investigated by firing a ground engine in a vertical attitude over a flight-type duty cycle at propellant and hardware temperatures representative of the flight environment. The engine was also allowed to cool down naturally after each firing rather than be force-cooled as in previous ground testing. The test was designed to simulate as many of the flight variables as possible, with zero-*g* felt to be the most significant one which could no be duplicated. An analysis of the vertical test results is not yet complete, but the indications are that the catalyst bed resistance history, while not duplicating the flight trends, is closer than on the horizontal tests. Although the characteristics of this particular thruster may not apply to others, the testing results indicate that thruster orientation and thermal realism may be very important, and that caution should be exercised in extrapolating flight performance and lift expectancy from ground testing of large hydrazine thrusters. This observation is based on the hypothesis that the zero-*g* environment plays an important role in the catalyst particle migration and possibly hydrazine flow distribution.

Conclusions

As a result of flight experience and analytical investigation, the following conclusions can be made regarding the thruster: 1) successful and highly predictable operation was achieved over extensive duty cycles, 2) the catalyst bed resistance factor proved to be a useful parameter in predicting thruster performance, 3) factors not simulated in ground testing resulted in a sharp decline in flight catalyst bed resistance, 4) the engine life is greater than the design requirement but probably less than ground testing would indicate, and 5) the techniques for proper ground simulation testing of large hydrazine thrusters should be further investigated.

References

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