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Effect of Duty Cycle on Catalytic Thruster Degradation

H. C. Hearn*
Lockheed Missiles & Space Company, Inc., Sunnyvale, Calif.

The thermal cycling and low-temperature operation inherent in three-axis stabilization attitude control can lead to several forms of hydrazine catalytic thruster degradation, including catalyst attrition and voiding, catalyst bed compaction, chamber pressure spiking, and injector tube thermal effects. Each of these mechanisms is influenced by the thruster operating characteristics or firing duty cycle, and the duty cycle plays a major role in determining the type and rate of thruster degradation. Test experience shows that particular thruster designs may be greatly affected by a change in duty cycle and that testing over a variety of duty cycles is required to demonstrate insensitivity to mission application.

Introduction

IT is generally known within the industry that the life of hydrazine catalytic thrusters is dependent on the way they are operated. Total impulse, number of pulses, pulse width and frequency, operating temperature, and the operating environment all contribute to thruster wear and degradation. This duty cycle dependence has become increasingly evident in the application of these thrusters to three-axis stabilization of spacecraft; differences have been observed in the rate of performance degradation and in the type of anomalies experienced. It has become clear, for example, that demonstration of great capability in one application does not necessarily imply a similar capability under a different type of use. These findings have significance with regard to the goal of producing standardized thrusters that will satisfy the requirements of a variety of missions and thus minimize costs for thruster development and qualification.

This paper addresses the effects of duty cycle on performance of 5-lbf (22-N) thrusters used for three-axis stabilization. Some aspects of anomalous thruster behavior and duty cycle effects have been discussed in the literature,[1,2] but there has not been a broad treatment of the subject. Also, understandably, thruster manufacturers are reluctant to discuss problems that may have been encountered in the course of development testing or flight applications. For this study, the information available includes flight and ground-test data involving a number of different designs and mission duty cycles. The intent of this paper is to demonstrate the influence of duty cycle on thruster degradation, and to show how various phenomena are related to the way the thruster is used. Finally, cases will be presented which show that a thruster design chosen for a specific application may be at a distinct disadvantage when evaluated for different requirements. It should be recognized at the outset that it is not possible to cover all the observed anomalies and that different designs may respond differently to the same duty cycle. However, it is hoped that this discussion will reveal something of the sensitivity of hydrazine thrusters to the way they are used, since this can be an important consideration in spacecraft design.

Degradation Mechanisms

The types of degradation discussed will be those which have been observed on 5-lbf (22-N) thrusters. These have been classified as catalyst attrition and voiding, catalyst bed compaction, chamber pressure spiking, and injector tube thermal effects. Catalyst bed poisoning due to aniline or decomposition gases is not included since data relative to 5-lbf (22-N) thrusters are not conclusive. Poisoning has been identified in primarily 0.1-0.2-lbf (0.44-0.89-N) thrusters operating at temperatures below 400°F (478 K), and this phenomenon has been discussed in other papers.[3,4] Following the treatment of these individual effects, the overall interaction between duty cycle and thruster design will be illustrated in the section on duty-cycle sensitivity.

Catalyst Attrition and Voiding

Although a duty cycle can be characterized in terms of cold starts, pulse width, pulsing frequency, thermal cycling, and other variables, the key parameter appears to be catalyst bed temperature. Analyses and experiments dealing with catalyst breakup[5] show that thruster temperature is a significant factor in several mechanisms, including catalyst particle wetting with liquid hydrazine, impingement of liquid hydrazine on a hot particle, and differential thermal expansion effects. In general, a thruster can accommodate very large values of total impulse if it is operated at a high temperature involving a minimum amount of thermal cycling.

In the case of one three-axis stabilization duty cycle, sufficient test data exist to clearly demonstrate the effect of operating a thruster at different temperatures. This duty cycle is primarily a thermal-cycling type with a period of 90 min. All the thermal-cycling pulses have a 0.022-s pulse width and the thrust chamber temperature cycles between approximately 400°F (478 K) and 1000°F (811 K). Interspersed at regular intervals in this duty cycle are sequences involving higher rate pulsing (with pulse widths up to 0.5 s) and some steady-state firings up to 25 s. However, approximately 75% of the impulse and over 90% of the pulses are in the minimum impulse-bit thermal-cycling mode. This duty cycle will be referred to as Type I in this paper.

A number of 5-lbf thrusters have been tested to this duty cycle. One design has a lower bed composed of 14-18 mesh catalyst and an upper bed of 25-30 mesh catalyst; hydrazine is injected over the top of the upper bed by five separate injector elements. The upper bed catalyst is packed into a metallic foam matrix designed to improve catalyst retention and heat transfer. Testing on this design involved several versions of the Type I duty cycle whose only significant differences are in the rate of pulsing during thermal cycling. The rates have ranged from a low of 2500 pulses/day [chamber temperature 400-900°F(478-756 K)] to as high as 6000 pulses/day [700-1000°F temeperature (644-811 K)]. Figure 1 shows the catalyst weight loss in the upper bed as a function of impulse for the different pulsing rates. It is seen that operating the thruster at the higher rates and temperatures reduces the rate of catalyst loss per unit of impulse; this is consistent with other studies.[6]

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*Sr. Research Engineer. Member AIAA.

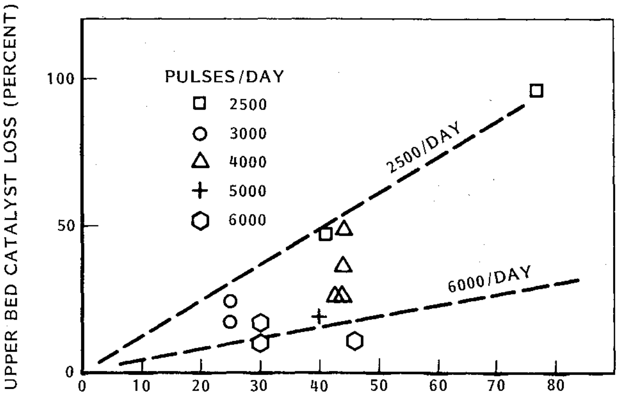

Fig. 1 Effect of duty cycle on catalyst loss.

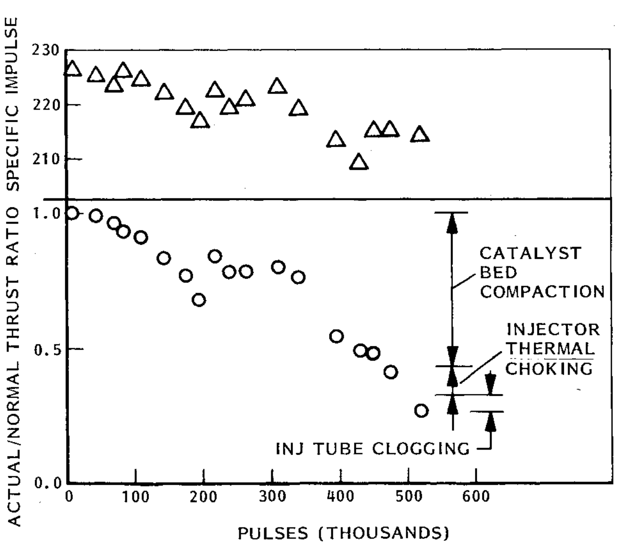

Fig. 2 Thruster performance degradation.

Catalyst Bed Compaction

Catalyst breakup can lead to another degradation mechanism whereby the resulting fine catalyst particles collect in the bed or against screens and plates to create an increased flow impedance. The result is reduced flow into the thruster and lower thrust and pulsing impulse bits. There is also some reduction in specific impulse (I_{sp}) due to increased gas residence time and ammonia dissociation, but this effect is small compared to the flow reduction. Unless sufficient instrumentation is available, it can be difficult to distinguish this mechanism from washout or injector clogging, although ground testing of a particular design can reveal dominant failure modes. Therefore, it is instructive to examine the results of one test where sufficient monitoring was present, and where a post-test disassembly allowed verification of analysis conducted during the test.

The Air Force Rocket Propulsion Laboratory (AFRPL) conducted a long-life evaluation test for 5-lbf thrusters which concluded in 1978.[7] The goal was to accumulate 1,000,000 pulses on a Type I three-axis stabilization duty cycle, and a total of six thrusters were involved in the test. At regular intervals during the test both pulsing and steady-state health check firings were made a a specified feed pressure for performance evaluation. One of the designs was the same as described previously (nickel foam catalyst retention matrix), and previous experience with this duty cycle indicated that catalyst bed compaction would probably cause significant thrust reduction prior to test completion. Analyses using data from a number of tests had revealed a correlation between thrust decay and the quantity of catalyst fines remaining in the engine. Figure 2 shows that performance did steadily degrade until the thruster was shut down after 536,000 pulses. The 73% reduction in steady-state thrust was accompanied by a comparable drop in pulsing impulse bit, and there was also a gradual decrease in steady-state I_{sp}.

The relatively detailed analysis devoted to this thruster during the test revealed that bed compaction was the primary cause of thrust degradation even before disassembly and injector flow were conducted. Since the thruster was receiving a progressively lower than normal flow during the test, the problem was to distinguish between catalyst bed effects and injector tube clogging. It was known that some clogging was occurring based on previous experience, a review of chamber-pressure traces, and the effect of thruster temperature on impulse bit. However, for injector-passage clogging to explain the entire thrust decay would have required a decrease of about 0.012 in. (0.305 mm) in the original 0.017-in. (0.432 mm) diameter injector passages. Since this would have been about three times the reduction experienced in earlier testing, it was considered unlikely. Also, I_{sp} variations during the test were consistent with catalyst effects. For example, following a repressurization from 120 to 200 psia (827-1379 kPa), the next health check at 90 psia (621 kPa) revealed a 25% flow-rate increase accompanied by a 6-s increase in I_{sp}. Subsequent to this event, the flow rate and I_{sp} resumed a steady decrease. Although the I_{sp} is affected by flow rate to a small degree, the magnitude of the changes observed was more consistent with the effect of catalyst fines on bed impedance and ammonia dissociation. In fact, the shifts in ammonia dissociation required (approximately 15-20%) are within the range which has been observed in other thruster testing.

The repressurizations that were a part of the mission duty cycle provided a way in which to separate the effects of bed compaction from thermal choking in the injector passages. When the feed pressure was increased significantly, the increased flow and injector cooling eliminated the hydrazine boiling in the injector which caused part of the thrust reduction at low feed pressures. A catalyst bed flow coefficient (describing the physical state of the bed) can be calculated at high pressure and then used at low pressure to determine the portion of performance loss that can be attributed to two-phase flow.

The post-test disassembly revealed that 47% of the catalyst was lost from the upper bed while the lower bed gained 1.5%. The finding of catalyst packed in support-plate holes and a 1/8-1/4-in. (3.2-6.4-mm) layer of tightly packed fines in the upper part of the lower bed supported the analytical conclusions that flow rate and thrust reduction were primarily due to catalyst bed compaction. The injector flow test that was conducted showed an increased resistance to flow which would account for approximately 6% of the thruster flow reduction. The data would imply an injector passage deposition of about 0.004 in. (0.102 mm) and is consistent with the thermal choking observed at low feed pressure. Figure 2 shows the contribution of each degradation mechanism to the end-of-life thrust reduction.

Chamber Pressure Spiking

Chamber pressure spiking, especially during the start transient, is a phenomenon that has been observed on catalytic thrusters. Early investigations[8] did not satisfactorily explain the mechanism, and it is still not well understood. However, the test experience and information that have been accumulated over the last few years enable a better description of its characteristics and the effects on thruster performance and degradation.

Pressure spiking during a pulse is due to the temporary accumulation of liquid hydrazine that subsequently detonates or decomposes at a very high rate, causing a rapid pressure increase in the chamber. Figure 3 shows a pressure spike somewhat typical of those that have been observed in both the ground and flight environments following a significant ac-

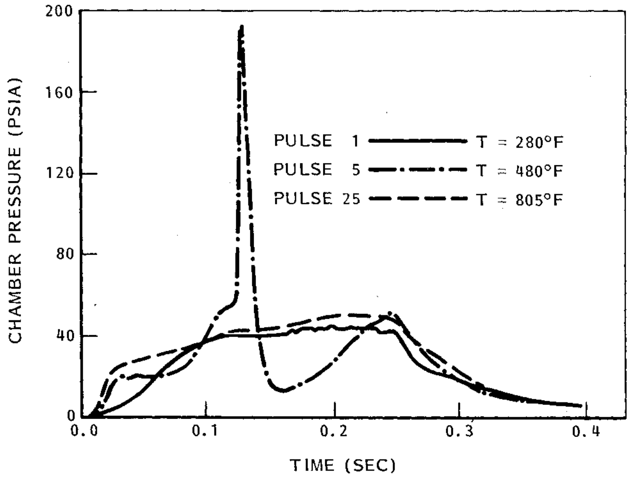

Fig. 3 Chamber pressure spike.

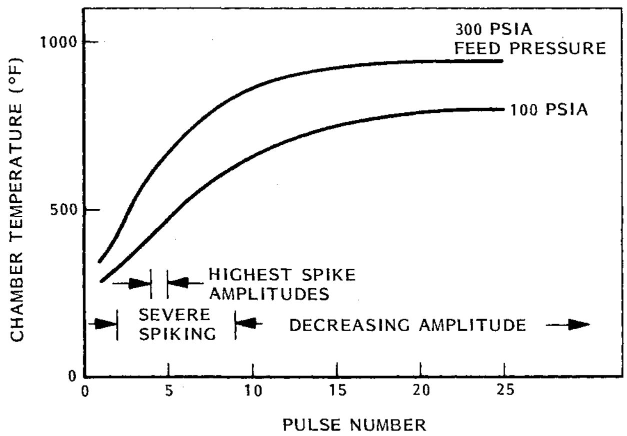

Fig. 4 Effect of thruster temperature on spiking.

cumulation of life on the engine. It was found that spiking did not occur on pulses shorter than 0.040 s, presumably because the pulse width is not long enough to cause a critical accumulation of liquid hydrazine. It was also found that the spiking tendencies and amplitudes were greater during pulsing duty cycles that involved thruster chamber temperatures in an intermediate region. Figure 4 shows the spiking characteristics observed during a 25-pulse health check consisting of 0.240-s pulses every 100 s. The first pulse at a temperature of 300°F (422 K) never spiked, while the most severe spiking occurred in the region of pulses 2-9. As illustrated in Fig. 3, spiking decreased and eventually disappeared as the thruster temperature increased beyond a certain range. It appears that, below the critical temperature range, heat cannot be transferred to the liquid rapidly enough to cause a pressure overshoot, while above the critical temperature range the liquid vaporization and decomposition is rapid enough to prevent an accumulation in the liquid state.

Testing has demonstrated the influence of duty cycle and temperature on spiking. For example, Fig. 5 shows the number of spikes observed for different thrusters on a Type I duty cycle. The data are plotted in this fashion since most of the pulses long enough to spike, and most of the spikes, occur in a particular maneuver type. Almost all the other pulses in Type I are 0.022 s long and are not subject to spiking. It is seen that the 6000-pulses/day duty cycle accumulates spikes at about half the rate of the 3000-4000-pulses/day duty cycles; in addition, the spiking amplitudes were lower. It appears that entering the maneuver sequences at a 100-200°F (311-367 K) higher temperature resulted in fewer spikes and lower amplitudes.

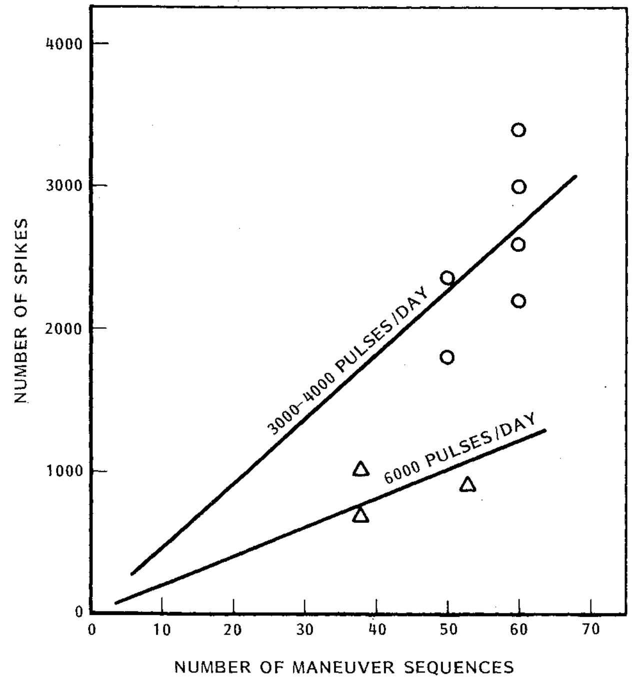

Fig. 5 Effect of duty cycle on spiking.

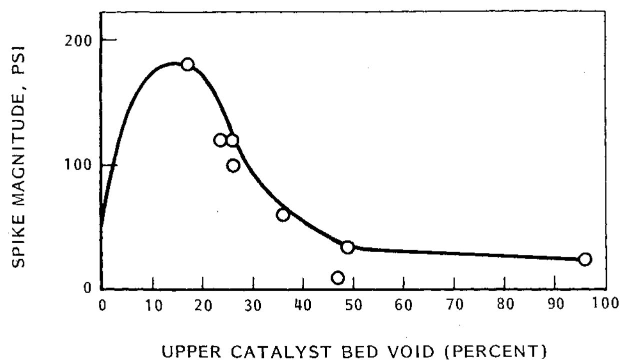

Fig. 6 Effect of catalyst attrition on spiking.

It is also apparent that pressure spiking is influenced by catalyst attrition and voiding as life is accumulated on the thruster. Figure 6 shows the envelope of maximum spike amplitude based on ground and flight data and an assumption of linear void formation with life (which test data indicates is valid). The data points on the plot represent the spiking amplitude at end-of-life and the catalyst loss determined after disassembly for different thrusters. The pressure spiking effects appear to pass through a worst-case condition at about 15% void; however, this conclusion cannot be generalized beyond the Type I duty cycle. Attempts at mathematically modeling the spiking phenomenon have not been completely satisfactory; uncertainty still exits with regard to liquid hydrazine mass and geometry and the relationship between vaporization and reaction rates. Ground testing of this thruster design, which incorporated hydrazine injection at the forward end of the catalyst bed, was conducted in the horizontal, nozzle-up, and nozzle-down attitudes. Spiking was more pronounced in the nozzle-down position where catalyst loss would cause a void to grow between the injector and catalyst; the nozzle-up attitude had the lowest spiking levels. It is apparent that the relationship between the injector element and the catalyst is very important for minimizing void growth and for reducing spiking severity. It would appear that thrusters with injectors penetrating into the catalyst bed would be less subject to liquid hydrazine accumulation and spiking, assuming that void growth at the injector can be inhibited.

Pressure spiking has been shown to be more than just a curiosity; it can have a significant impact on thruster life and performance. Experiments have shown[5] that spiking causes pressure and temperature transients which subject catalyst particles to severe impact loads, pressure crushing, and abrasion. These effects result in particle fracture and generation of fines at a rate dependent on magnitude and number of spikes. The role that spiking can play in catalyst attrition and performance has been clearly demonstrated in thruster testing (discussed in a later section) and by flight experience. In the case of one flight thruster, severe spiking resulted in the rupture of a chamber pressure transducer line. In another case, intermittent thruster valve leakage was attributed to spiking magnitudes greater than the feed pressure. Equations were derived to model the injector tube fluid dynamics resulting from pressure spiking in the catalyst bed and predictions were made regarding the transport of particle contamination back to the valve seat area. The analysis verified that the duration and magnitude of the spikes observed was sufficient to reverse the injector flow and cause valve contamination.

Injector Tube Thermal Effects

A general review of thruster flow anomalies due to contaminants in the propellant and feed system was reported in a recent paper.[9] That review covered instances of tube plugging and flow reduction as well as thruster valve leakage for primarily 0.1-lbf (0.44-N) level thrusters. This paper will examine thermal anomalies that have been observed on 5-lbf (22-N) thrusters and that are associated with contaminant deposition in injector tubes. Most of the deposition is believed to occur after a pulse is completed, as propellant evaporation in the small injector passages leads to an accumulation of soluble contaminants on the tube walls. Hydrazine impurities that have been implicated are the nonvolatiles, with some experience indicating a predominance of silicon compounds. The roughening of the tube surface can lead to an increase in heat transfer to the propellant, resulting in boiling and two-phase flow. This thermal choking can cause sharp reductions in thrust and pulsing impulse bit. This form of degradation appears to get progressively worse as additional pulses are accumulated, and the effects of thermal choking are more severe at low feed pressure where the lower liquid flow rates are least effective in cooling the injector, and where the boiling point is lower.

The previously mentioned life test at AFRPL provided an illustration of injector tube thermal effects. The thruster example used for this discussion is the 5-lbf thruster which consisted of upper and lower catalyst beds (each with 14-18 mesh catalyst) and twelve injector elements that penetrated into the upper bed. While this thruster demonstrated excellent performance and durability over the entire test of 1,014,000 pulses, it did experience effects that are attributed to changes in the interior of the injector tubes. For a new engine, the minimum impulse bit (0.025-s pulse width) varies from about 0.04 to 0.09 lbf-s (0.18 to 0.40 N-s) over the feed pressure range; the impulse bits show an increasing trend as the thruster warms up during a pulsing sequence. For the AFRPL test, Fig. 7 shows the difference between the impulse bit at the end of a thermal cycle [nozzle temperature approximately 775°F (686 K)] and that at the beginning [nozzle temperature at about 450°F (506 K)]. This difference was relatively constant at about 0.01 lbf-s (0.045 N-s) over the pressure blowdown range until the accumulation of about 300,000 pulses, where a decrease in peak chamber pressure and impulse bit began to occur during the hotter part of the duty cycle. Since the steady-state performance of the thruster was normal, tube deposition in conjuction with heat soak back appeared to be causing two-phase flow and thrust reduction as the thruster temperature increased.

After an additional 100,000 pulses were accumulated, thermal effects were also observed in the pulsing health checks

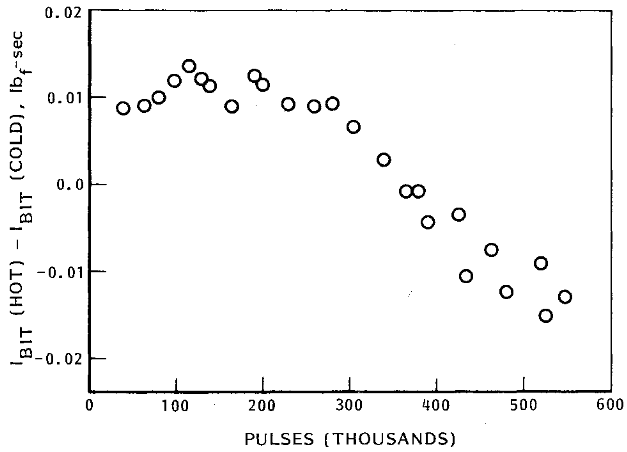

Fig. 7 Impulse bit degradation.

that involved 0.025-,0.050-, and 0.100-s pulsing at a rate of 1 per second. This pulsing was performed subsequent to steady-state firings which resulted in high injector temperatures of approximately 775°F (686 K) prior to the pulsing. On two occasions when the initial temperature was higher than usual [approximately 865°F (736 K)] and the feed pressure was low [approximately 110 psia (758 kPa)], the thruster chamber pressure and impulse bits were sharply reduced during the pulsing; a significantly lower nozzle temperature at the end of each sequence was indicative of reduced flow through the engine. On subsequent pulsing health checks where the initial injector temperature was lower, the chamber pressures and impulse bits returned to normal. It appears that when the initial injector temperature is above a certain level, the pulsing flow rate is reduced by boiling in the passages and thus is not sufficient to cool the injector and allow impulse recovery to normal values. The occurrence of these phenomena illustrates the importance of evaluating each mission application for duty cycles that might cause adverse thruster performance.

The post-test injector flow on this thruster showed less than a 10% flow reduction for a given pressure drop, consistent with observed performance and indicating only a minor flow blockage in the injector tubes. However, the inside walls showed surface deterioration and roughness, and this could explain the increased heat transfer that caused thermal choking under conditions of high temperature and low feed pressure.

Other thrusters in this test also exhibited varying degrees of injector effects. It appears that all the engines experienced some impulse bit reduction while at low feed pressure in the hot part of the 90-min cycle, and the thruster that had severe catalyst bed compaction also had thermal choking in the 24-s health check firings at 90 psia (621 kPa). Post-test injector flow[7] on one of the engines utilizing a nine-element penetrating injector showed a sharp reduction consistent with observed performance prior to shutdown. Both of these thrusters apparently had problems with injector clogging.

The minimization of injector tube thermal effects can be accomplished by maximizing the operating feed pressure. This is related to 1) reduction in the pulse count except for some limit cycling modes, 2) higher flow passage shear stresses that should inhibit the buildup of contamination, 3) higher propellant boiling point, and 4) higher propellant flow velocities that provide increased thermal margin. There are also indications that passage contamination is reversible to some degree. For example, following a 400,000 pulse qualification program, one thruster was experiencing a greater than 50% reduction in thrust at 100-psia (689 kPa) feed pressure, primarily due to thermal choking. A series of six 20-s firings was made at 185 psia (1276 kPa), followed by a return to 100 psia (689 kPa). The result was an 80% improvement in thrust and elimination of most, but not all,

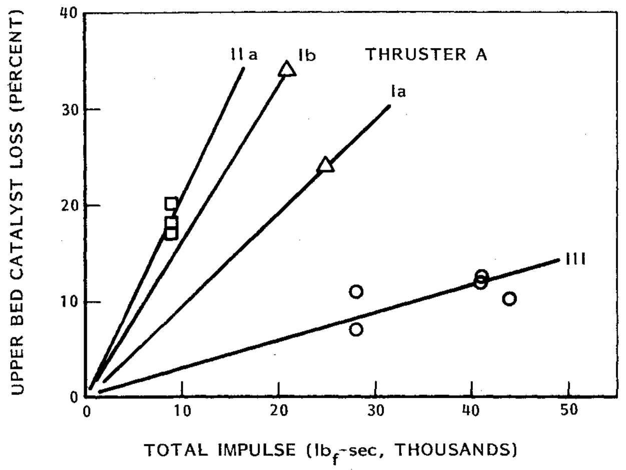

Fig. 8 Duty-cycle sensitivity—thruster A.

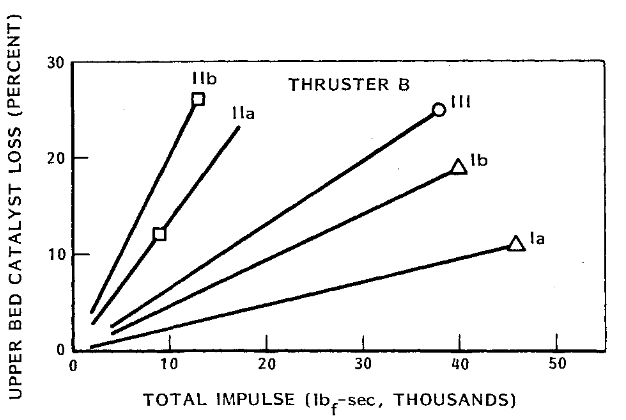

Fig. 9 Duty-cycle sensitivity—thruster B.

thermal choking. Although the possibility of some change in the catalyst bed cannot be discounted, the analysis indicates that the large decrease in thermal choking is probably due to the removal of contaminant buildup in the injector passages.

Duty Cycle Sensitivity

The influence of thruster duty cycle on performance and degradation can best be illustrated by presenting a case history showing the response of different thruster designs to different types of duty cycle. Three thruster designs have been tested over several common duty cycles. Thruster A has an upper catalyst bed divided into three compartments with one injection element per compartment. Thruster B, described earlier in this paper, employs a nickel foam matrix for upper-bed catalyst retention and has five injection elements. Thruster C is like B except that it uses a rhodium-nickel-rhodium coating on the foam matrix. Figures 8-10 show the upper-bed catalyst loss for each thruster and duty-cycle Type. Thrust decay has been due primarily to upper-bed attrition which leads to increased flow impedance; the lower catalyst bed experiences a much smaller change and often gains a slight amount of catalyst weight. The straight-line fits for catalyst loss are consistent with test experience.

The Type I duty cycle has been described earlier as a high pulse-rate cycle consisting of mostly minimum impulse bits with a 0.022-s pulse width. Type Ia averaged 6000 pulses/day and thruster temperatures in the 700-1000°F (644-811 K) range while Type Ib was conducted with 50°F (283 K) hydrazine [vs 95°F (308 K) for Ia] and had an average rate of 5000 pulses/day and lower thruster temperatures of 500-900°F (533-756 K). For these Type I duty cycles, thruster B was demonstrated to be clearly superior to thruster A, which lost catalyst at a much faster rate and suffered serious per-

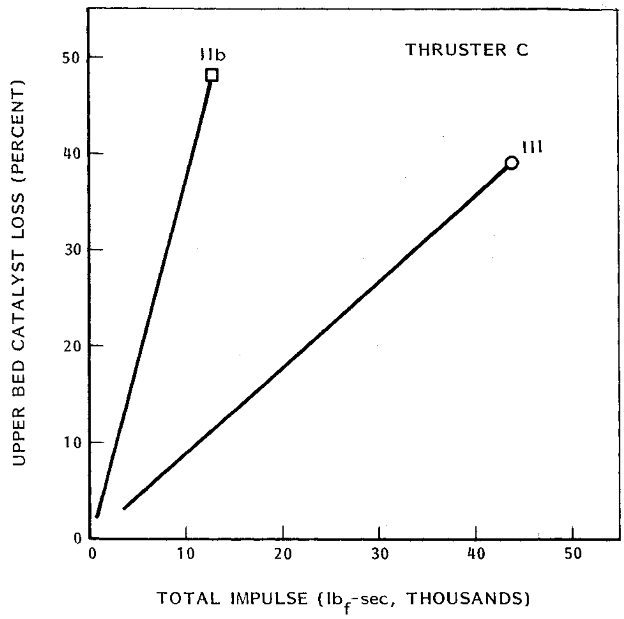

Fig. 10 Duty-cycle sensitivity—thruster C.

formance degradation and early test termination. Although thruster C was not tested to these specific duty cycles, the AFRPL test at 2500 pulses/day showed that it was probably the best of the three thrusters for the Type I duty cycle.

Type II is a 90-min duty cycle involving a mixture of minimum impulse bits and longer pulse widths while the level of activity and thruster temperature is much lower than Type I. Type IIa involved an average rate of about 650 pulses/day and a temperature range of 275-650°F (408-617 K). Type IIb had a rate of 420 pulses/day and a temperature range of 225-350°F (381-450 K). It is first seen from the figures that the thrusters exhibit a higher catalyst loss rate on the Type-II duty cycle than on Type I; this is consistent with the lower temperature operation. Thruster B had a slightly lower loss rate than thruster A, although both successfully completed the testing. In a simultaneous test using duty cycle IIb, thruster B was superior to C in terms of catalyst loss, response time, and chamber pressure spiking characteristics, reversing the results obtained from Type I testing.

The Type III duty cycle is substantially different from the other two in that it involves a minimum pulse width of 0.240 s (vs 0.022 s for Types I and II) and a large number of steady-state firings.[10] The pulse rate is about 300 pulses/day and the average impulse per pulse is an order of magnitude greater than Types I and II. Another difference is that on many of the sequences all the pulsing occurs within a 3-10-min period rather than being spread over a 90-min cycle; this results in greater thermal excursions on the thruster than on Types I and II. By every method of comparison, including thrust level, catalyst loss, roughness, chamber pressure spiking, and post-test condition, thruster A is clearly superior to the other two designs. The thrusters incorporating foam retention, B and C, developed serious problems with chamber pressure spiking that got progressively worse during the testing. Based on sampled data, each accumulated about 5000 spikes (the total number of pulses for the test was only about 12,000) at magnitudes up to 650 psi (4482 kPa). By comprison, thruster A had fewer than 1000 spikes, most of which were below 100 psi(689 kPa). It appears that severe spiking greatly accelerated the catalyst loss on B and C and created a potentially hazardous condition, necessitating a termination of testing on these thrusters. One interesting occurrence was the delivery of higher than normal impulse bits on some pulses. After the valve opened, the chamber pressure would come up to some low value and remain there for 0.100-0.200 s, followed by a rapid pressure rise or spike. On one pulse, 80% of the impulse occurred after valve closure, and the total delivered impulse was 40% greater than normal. Analysis showed that flow into the thruster was higher due to the lower pressure in the chamber and the liquid hydrazine that collected in the thruster subsequently decomposed and resulted in a late and abnormally high impulse bit.

The test results described here reveal a situation in which a different thruster design was more suitable for each of the three types of duty cycle. Conversely, it was not possible to select a single design that would perform satisfactorily for all duty cycles. For example, the change in duty cycle showed that one thruster design was more prone to pressure spiking; this led to a sharp increase in the catalyst attrition rate, creating an increase in flow impedance as well as hazardous operation. Although the results obtained here are not necessarily transferrable to other thruster designs, they serve to illustrate the role that duty cycle plays in thruster performance and life. They also help to explain why claims of duty cycle insensitivity have been greeted with skepticism in cases where a particular thruster design has not actually been tested to a variety of duty cycles.

Conclusions

The degradation and types of anomalies experienced in hydrazine catalytic thrusters are determined by the mission duty cycle and length of operation. Experience with 5-lbf thrusters shows that the thermal cycling and low-temperature operation inherent in three-axis stabilization duty cycles can be a source of concern with regard to catalyst attrition, bed compaction, pressure spiking, and injector tube effects. These degradation modes are influenced by operating temperature, feed pressure, pulse width, and pulse frequency and are themselves interdependent. It is significant that a particular thruster design may be greatly affected by a change in duty cycle, and that a design shown to be superior in one application may not be optimum should requirements change. Therefore, testing over a variety of duty cycles is required to demonstrate relative insensitivity to mission application.

Acknowledgment

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