IAC-04-S.1.09

THE USE OF THE AEROJET MR-103H THRUSTER ON THE NEW HORIZONS MISSION TO PLUTO

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The New Horizons spacecraft is designed to be the first mission to Pluto and its moon Charon, the last unexplored planetary system in our solar system. The planned New Horizons science payload drives the requirement for a 3-Axis stabilized spacecraft that has the ability to maintain tight pointing requirements with very low body rates. Due to the extreme power constraints of the mission, reaction wheels would not provide a viable control option, and thus 3-Axis attitude control should be maintained by thrusters. Similarly, mission lifetime and mass constraints drove the design to a blowdown hydrazine system that would serve as both the velocity control and as the only method of attitude control on board the spacecraft. The Aerojet MR-103H thruster was chosen as the New Horizons attitude control thruster for its minimum impulse bit performance, and for its heritage from the Voyager and Cassini missions. Spacecraft attitude control would be maintained by a total of 12 MR-103H thrusters, arranged in pairs to produce coupled torques about any given axis. Instrument performance and the subsequent science return would rely heavily on the spacecraft's ability to accurately control spacecraft body rates, and thus performance matching of each of the sets of thrusters is of paramount importance to mission success. The requirements that drove the design of the liquid propulsion system and that led to the selection of the MR-103H thruster will be discussed in detail. Also, the measured performance of the New Horizons MR-103H thrusters will be analyzed, and the methods used to pair thrusters and meet spacecraft control requirements will be discussed.

INTRODUCTION

The New Horizons mission is funded under the NASA New Frontiers Program, and is being designed, built and operated by the Johns Hopkins University Applied Physics Laboratory (APL).

New Horizons is scheduled to launch January 11, 2006 from Cape Canaveral Air Force Station aboard an Atlas V 551. During its planned 10-year mission, New Horizons would fly by Jupiter on its way to a rendezvous with the Pluto/Charon system in July 2015. The New Horizons spacecraft is designed to continue its mission past the Pluto/Charon encounter to investigate up to three Kuiper Belt Objects (KBOs).

As designed, the New Horizons science payload consists of three core instruments, and four supplementary instruments. The core payload consists of the Alice UV Spectrograph, the RALPH visible and IR imager, and the REX radio experiment. The secondary payload consists of the LORRI long-range imager, the PEPSSI energetic particle spectrometer, the SWAP solar wind experiment, and the SDC dust counter that would count interstellar dust particles during the flight to Pluto and beyond.

PROPULSION SYSTEM REQUIREMENTS

The primary requirements for the New Horizons LPS are to provide velocity control and spin- and 3-Axis attitude control for the observatory. Some measure of velocity change would be required to correct the injection errors introduced by the Atlas Launch Vehicle and the Boeing 3rd Stage, and also to provide along-track and cross-track targeting adjustments for the Jupiter, Pluto/Charon and Kuiper Belt Object (KBO) flybys. However, as is shown in Table 1, the majority of the ΔV capability of the New Horizons observatory would be reserved for the large maneuver required to target KBOs after the Pluto/Charon encounter.

	2006 (Primary Mission)	2007 (Backup Mission)
Primary Mission	92	77
Primary Mission Margin	30	30
KBO Navigation	120	95
Total	**242**	**202**

Table 1: Proposed New Horizons Navigation ΔV Budget

The ΔV requirements shown in Table 1, coupled with the attitude control propellant requirements of approximately 21.6 kg dictate that the New Horizons LPS carry a minimum usable hydrazine propellant load of 68.4 kg. Since the system must also meet the nutation time constant (NTC) requirements levied by the spinning Boeing 3rd Stage, significant testing was performed to measure the NTC of the system at various propellant loads and observatory/3rd Stage stack mass properties. It was found that to meet the 3rd Stage NTC requirements, the observatory could carry a maximum propellant load of 80 kg.

To perform the majority of its observations, the New Horizons science payload would require either a 3-Axis stabilized bus, or that the observatory rotate about a certain axis at a specified rate. Due to the extreme power limitations of this outer planetary mission, reaction wheels did not pose a viable option for attitude control on the New Horizons observatory. Consequently, attitude control would have to be maintained by thrusters alone.

In particular, the RALPH instrument requires that the observatory be capable of setting up and maintaining a scan rate of +/- 34 μrad/s about any given axis. This attitude control requirement, along with the ΔV budget shown above, is the primary driver for the design of the New Horizons LPS.

The RALPH scan mode would require that the LPS be capable of delivering a minimum impulse bit no greater than 0.0066 N-s from each ACS thruster at the time of the planned Pluto/Charon encounter. This led to the selection of two candidate thrusters to meet the requirements of the mission: the Aerojet Minimum Impulse Thruster (MIT), and the Aerojet MR-103H thruster. At the time the program was proposed, the MIT thruster was still under development and awaiting qualification testing, whereas the MR-103H thruster was already qualified and had recently been produced for the Cassini and Deep Impact missions. Consequently, in order to minimize the total schedule and cost risk to the program, APL chose to baseline the MR-103H thrusters for use on the New Horizons observatory.

PROPULSION SYSTEM DESCRIPTION

The schematic for the planned New Horizons LPS is shown below in Figure 1. Spacecraft attitude control would be maintained using twelve Aerojet MR-103H 0.2 lbf thrusters, and spacecraft velocity change would be achieved primarily through the use of four Aerojet MR-111C 1.0 lbf thrusters. The arrangement of the thrusters on the spacecraft is shown in Figure 2. The thrust directions of the MR-103H ACS thrusters are shown as red arrows, and the thrust directions of the MR-111C ΔV thrusters are shown as blue arrows in the figure.

The system would be fed from a single titanium propellant/pressurant tank (manufactured by PSI) through six latch valves and a single system filter. Propellant and nitrogen would be loaded through three-seal service valves. The pressure of the system would be monitored by redundant pressure sensors, and the system fully instrumented with temperature sensors.

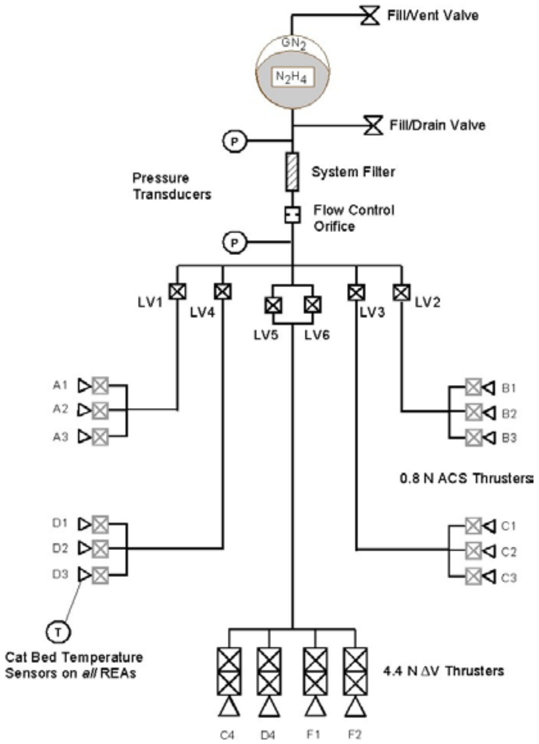

Figure 1: New Horizons LPS Schematic

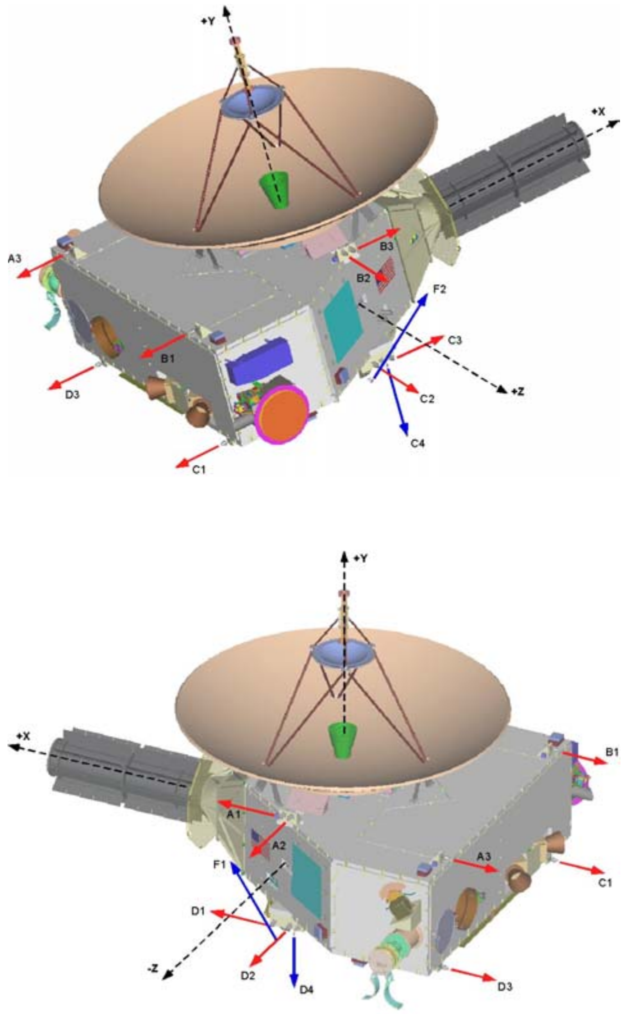

Figure 2: New Horizons Observatory and LPS Thruster Lines of Action (MR-103H thrusters shown in red).

The blowdown curves for the New Horizons LPS are shown below in Figure 3. Selection of the maximum expecting operating pressure (MEOP) was a particular challenge for the New Horizons system. On the one hand it was desirable to maximize the pressurant load and MEOP, thereby maximizing thruster performance (thrust and Isp) throughout the mission and ensuring that the end of life (EOL) operating pressure would be above the minimum qualified operating pressure of the thrusters. On the other hand, the thrusters are required to deliver a minimum impulse bit no greater than 0.0066 N-s during the planned Pluto/Charon encounter, which drives the decision toward a lower MEOP.

Ultimately, the selection of MEOP was made based on a detailed estimate of the propellant that would be used before the Pluto/Charon encounter. The G&C requirement to provide an impulse bit of less than 0.0066 N-s at Pluto/Charon essentially fixes the maximum system pressure at the time of the encounter. The MEOP was then determined using a worst-case estimate of the propellant usage – which in this case corresponds to the *least* possible propellant usage - prior to the encounter. Finally the mission propellant budget analysis was re-run using this derived MEOP to ensure the end of life system pressure would still be within the qualified range of the thrusters.

The results of this analysis, presented in Figure 3, show three sets of curves:

1. The maximum pressure blowdown curve – with an MEOP set by the maximum qualified inlet pressure for the MR-103H and MR-111C thrusters.
2. A minimum pressure blowdown curve – with an MEOP set by the minimum qualified inlet pressure of the MR-103H thrusters.
3. The nominal pressure blowdown curve set (including minimum and maximum tank and ullage temperature effects) – set by expected maximum minimum impulse bit at Pluto/Charon encounter as described above.

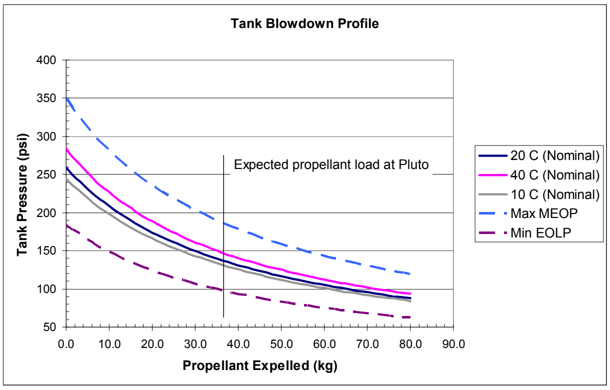

Figure 3: New Horizons LPS Nominal Blowdown Profile

MR-103H DESCRIPTION

The MR-103H 0.2 lbf rocket engine assembly (REA) was originally developed for and flown on NASA's Voyager mission. The REA is a monopropellant hydrazine thruster, with a single solenoid valve, a catalyst bed and catalyst bed heaters and thermocouples.

The thruster was next produced for the Cassini mission, during which time it again went through a full qualification program. The same model thruster is set to launch on the Deep Impact spacecraft in December 2004. With one exception, the Voyager thrusters continue to operate successfully, after 27 years in operation.

The MR-103H is currently qualified to operate between 420 psia and 80 psia, and can be operated with command pulse widths as low as 4 ms. The MR-103H produces a nominal impulse bit of 0.0066 N-s at 240 psia feed pressure and 0.0040 N-s at 100 psia feed pressure, and is capable of producing impulse bits as low as 0.0026 N-s at 100 psia and 4 ms commanded on-time. The nominal thrust, Isp and impulse bit performance curves for the thrusters over the New Horizons blowdown pressure range are given below in Figures 4 through 6.

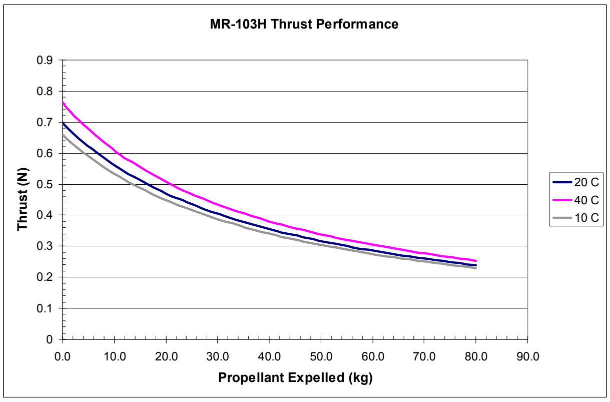

Figure 4: MR-103H Predicted Thrust Performance

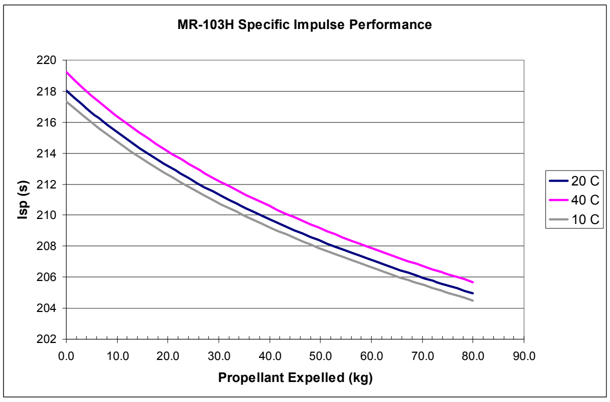

Figure 5: MR-103H Predicted Isp Performance

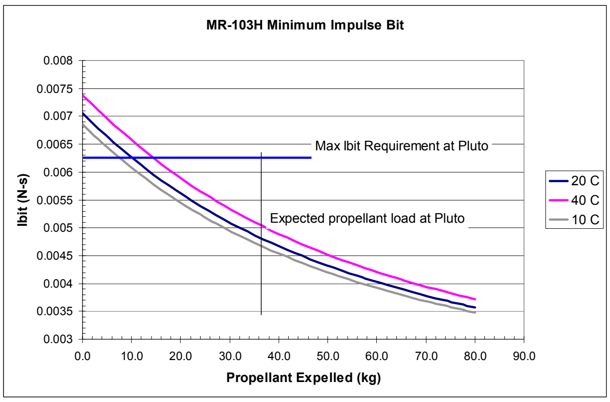

Figure 6: MR-103H Predicted Impulse Bit Performance (5 ms commanded on-time)

MR-103H ACCEPTANCE TEST PERFORMANCE

A total of fourteen MR-103H thrusters were procured and tested to select the twelve flight thrusters planned for the New Horizons program. The remaining two thrusters would be carried as spares through launch. As part of the Acceptance Test Program (ATP) of the New Horizons LPS, each of the MR-103H thrusters underwent numerous hot-fire tests. For all tests, thruster chamber pressure (and thereby thruster performance) were measured directly through chamber pressure (Pc) tubes. In all cases, the thrusters were fired in both steady-state and pulse-mode operation.

To measure baseline performance, each of the thrusters was fired for 100 seconds at each of three feed pressures: 350 psia, 265 psia and 175 psia. Thrust and Isp were measured for each of these tests and were compared against nominal and specified performance. The steady-state thrust and Isp performance of each of the fourteen New Horizons MR-103H thrusters is shown below in Figures 7 and 8.

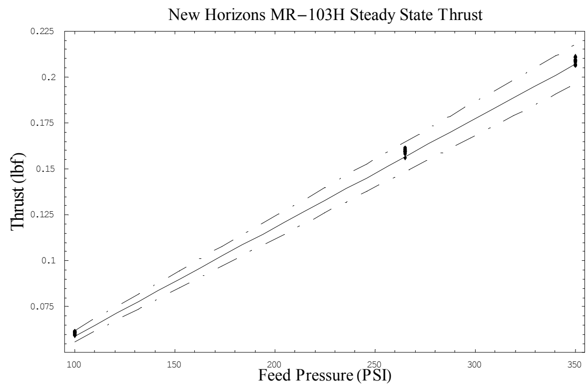

Figure 7: New Horizons MR-103H Measured Thrust Performance

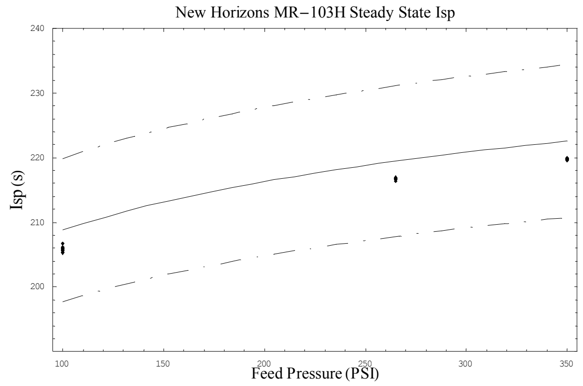

Figure 8: New Horizons MR-103H Measured Isp Performance

The MR-103H thrusters used on the New Horizons mission would also operate in pulse-mode through much of their life. As such numerous pulse-mode tests were conducted during thruster ATP. Each of the New Horizons thrusters was tested for pulse-mode performance at four feed pressures: 350 psia, 265 psia, 175 psia and 100 psia. The specific duty cycles and durations tested are given below in Table 2. In all cases thrust, impulse bit, response times and pulse centroids were measured.

Duty Cycle		# Cycles
On-Time	Off-Time	
0.100	12	50
0.020	0.020	50
0.005	60	10
0.020	60	10

Table 2: New Horizons Pulse-Mode ATP Duty Cycles

The duty cycles shown in Table 2 were chosen to mimic the expected in-flight operation of the system, but also to bound the worst-case duty cycles from a thruster degradation standpoint. These duty cycles were chosen with significant input from the spacecraft G&C team.

The pulse-mode performance of the New Horizons MR-103H thrusters is shown below in Figures 9 and 10. In all cases the commanded on-time was 5 ms.

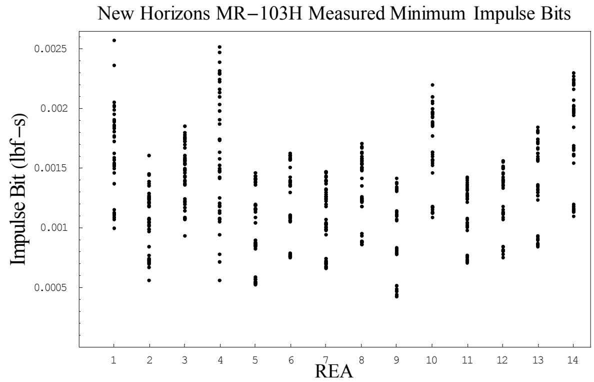

Figure 9: New Horizons MR-103H Measured Impulse Bit Performance (by Thruster)

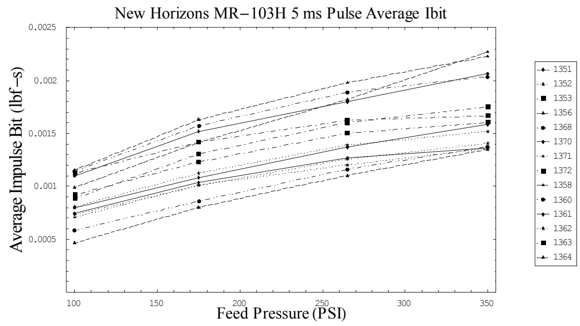

Figure 10: New Horizons MR-103H Measured Average Impulse Bit Performance (by Feed Pressure)

The limit duty cycle (with a 5 ms commanded on-time) performance of the New Horizons thrusters does meet the requirements specified by the program. However, it is also important to note that the impulse bits achieved in this operating mode have appreciable roughness that must be accounted for. The roughness of the New Horizons thrusters is illustrated below in Figures 11-15.

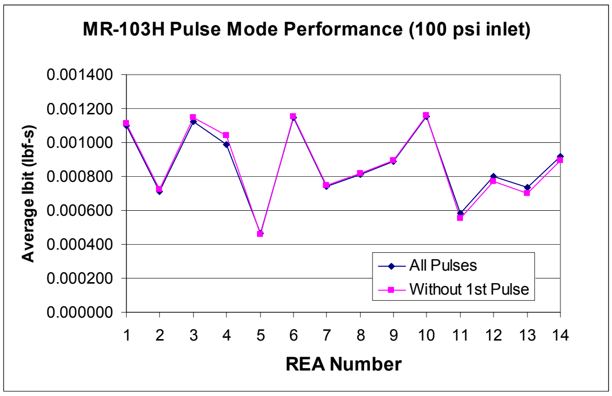

Figure 11: New Horizons MR-103H Limit Duty Cycle Impulse Bit (100 psi inlet pressure)

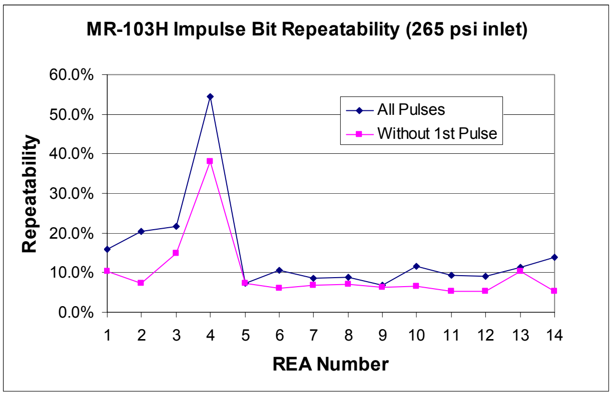

Figure 14: New Horizons MR-103H Limit Duty Cycle Bit Roughness (265 psi inlet pressure)

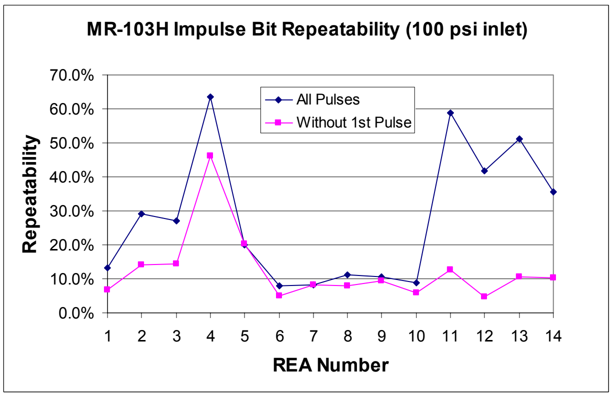

Figure 12: New Horizons MR-103H Limit Duty Cycle Bit Roughness (100 psi inlet pressure)

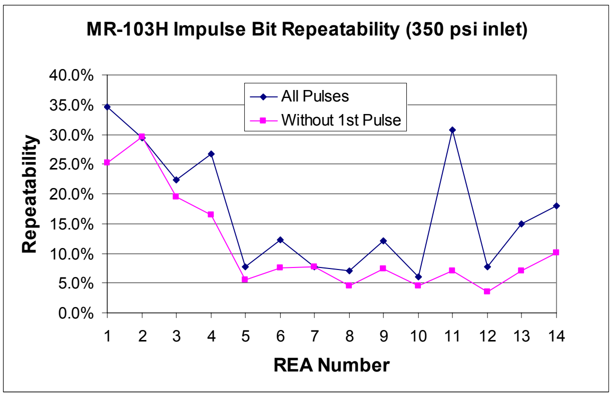

Figure 15: New Horizons MR-103H Limit Duty Cycle Impulse Bit Roughness (350 psi inlet pressure)

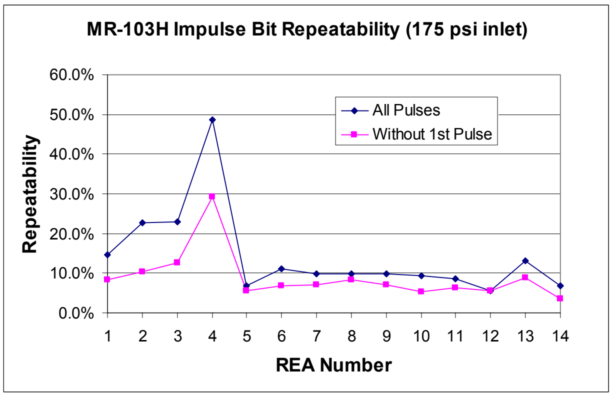

Figure 13: New Horizons MR-103H Limit Duty Cycle Bit Roughness (175 psi inlet pressure)

Impulse bit roughness was evaluated with and without the first pulse in each test sequence. Because the thruster catalyst beds are allowed to cool fully in between tests, the first pulse in each sequence is prone to transient warm-up effects, which can significantly affect the impulse bit of that pulse. However, the thrusters will typically be operated in a limit duty cycle during science operations, and analyses that include this first pulse are more representative of the flight condition.

It is clear from the data shown in Figures 12-15 that REA 4 displayed significant roughness throughout its minimum impulse bit testing, with roughness typically in the range of 50-

65%. This performance fluctuation can be seen easily in the limit duty cycle test results of REA 4, shown below in Figure 16. The limit duty cycle performance of this thruster varied widely across inlet pressure ranges, and as a result this specific thruster has been designated as the number 2 spare for the program, and would not fly aboard the New Horizons spacecraft.

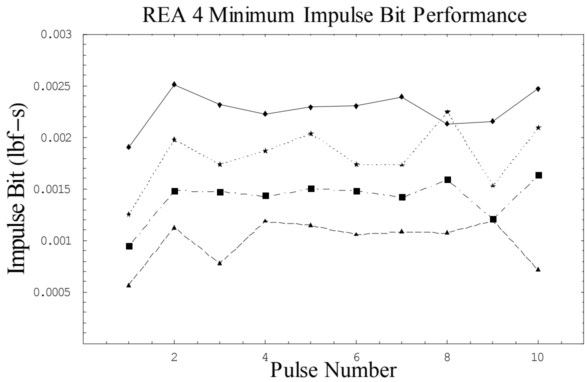

Figure 16: REA 4 Limit Duty Cycle Impulse Bit Performance

THRUST MATCHING

Because the New Horizons thrusters would be operated as couples, it was important to match the performance of each of the thrusters as closely as possible. This task was complicated by the fact that a single thruster can be operated with any of several other thrusters depending on the required torque to be imparted to the spacecraft. For example, from Figure 2 it can be seen that thruster A1 can be used with thruster B1 to provide torque about the +Y axis. Thruster A1 can also be combined with thruster D3 to provide torque about the +Z axis.

Both steady-state and pulse-mode performance were considered during the thruster matching analysis. A set of curves similar to those shown in Figures 17 and 18 were generated for each possible thruster combination, and these were used as the basis for an exhaustive comparison of the best possible thruster locations.

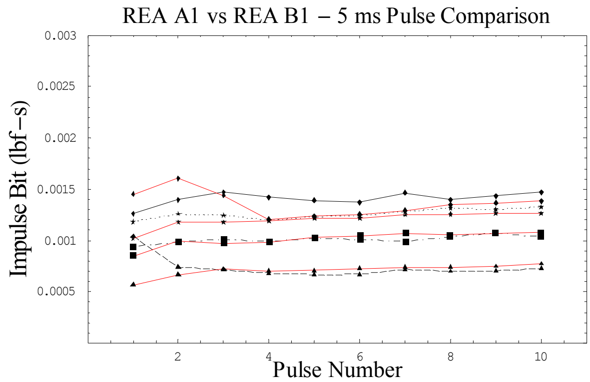

Figure 17: Example of Thruster-to-Thruster Pulse-Mode Performance Comparison

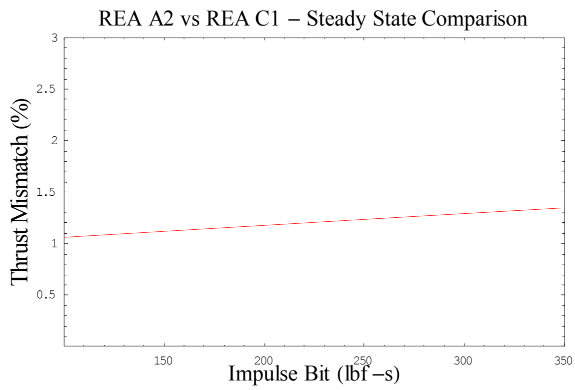

Figure 18: Example of Thruster-to-Thruster Steady-State Performance Comparison

The MR-103H thrusters were tested in four groups: one group of two and three groups of four. Pulse-mode performance was found to vary quite a bit from thruster to thruster, with no strong correlation to test group or any test parameters. One extreme example of thruster-thruster performance is shown below in Figure 19. It was clear from the acceptance test data of the New Horizons thrusters that the MR-103H thrusters are operating near the limit of traditional solenoid valve hydrazine thrusters. Consequently, care must be taken in designing attitude control system algorithms to operate with thruster-only control in this difficult performance regime.

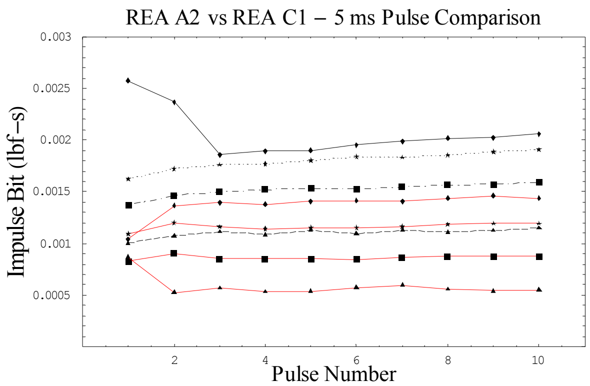

Figure 19: Example of Poor Thruster-to-Thruster Pulse-Mode Performance Matching

It is recognized that ground test performance does not always match in-flight performance. As such, in-flight performance of the New Horizons MR-103H thrusters would be monitored continuously, and comparisons to ground predictions and the resultant impacts on Guidance & Control models and performance would be regularly updated.

PULSE COUNTS

Another significant challenge in analyzing the New Horizons LPS was the assessment of the total number of cycles that will be seen by each of the thrusters during the course of the mission. Because the thrusters are the only source of attitude control on board the spacecraft, they will each see a significant number of total cycles, particularly during science operations.

A thorough study was undertaken to investigate the expected thruster usage throughout the nominal mission. This analysis incorporated inputs from the full mission team, and included all expected spacecraft maneuvers, including detailed science checkout, rehearsal and encounter operations as well as all expected guidance and control, navigation and communications operations. These inputs were coupled with modeling results from the spacecraft guidance and control simulator to produce estimates of the worst-case thruster pulse counts for each thruster throughout the course of the mission.

Early results from the thruster pulse counts analysis indicated that the expected thruster counts would far exceed qualified levels for the MR-103H thrusters. As a result, several aspects of the baseline mission and science operations were reworked to reduce the total number of thruster cycles. The results of the updated mission analysis are shown below in Figure 20. A comparison of the New Horizons expected worst-case thruster cycles versus previous MR-103H experience is shown in Figure 21.

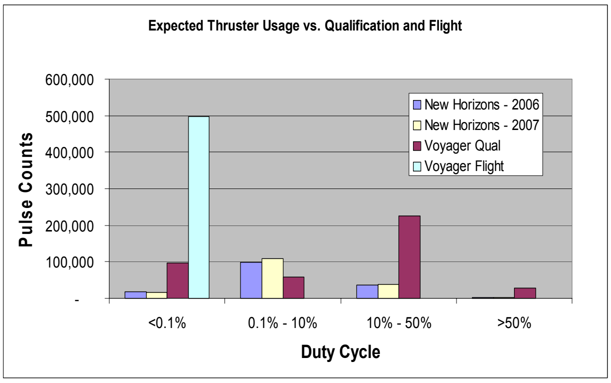

Figure 20: New Horizons Worst-Case Predicted Thruster Counts

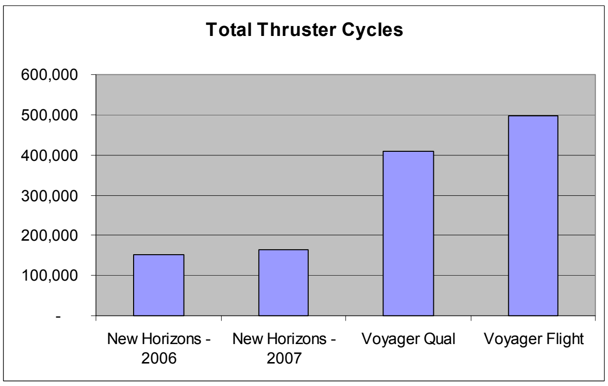

Figure 21: New Horizons Thruster Count Comparison to Previous Qualification

As is illustrated in Figure 20, it was found that the New Horizons thrusters are expected to exceed previous mission cycling in the 0.1%-10% duty cycle range. Aerojet has performed a detailed analysis to show that operation in this duty cycle range does not stress the thruster - and in particular the catalyst bed - as the <0.1% duty cycle range does. This analysis, coupled with the significant margin shown on total thruster cycles led to the conclusion that the expected use of the MR-103H thrusters on the New Horizons mission is sufficiently bounded by their previous use on the Voyager mission.

CONCLUSIONS

Mission and science operations requirements and extreme power constraints drove the New Horizons spacecraft design to a dual-mode spinning and 3-axis stabilized platform that is controlled only by thrusters. The tight pointing and rate requirements dictated by the science goals of the mission led to the selection of the Aerojet MR-103H thruster.

The MR-103H thrusters used on the New Horizons LPS were put through a thorough hot-fire test program designed to characterize the performance of the thrusters across the expected operating range of the system. The thrusters were found to meet the expected New Horizons performance requirements, although the thrusters demonstrated significant roughness when operating in a limit duty cycle mode. The spacecraft Guidance & Control system will have to be designed to accommodate the roughness demonstrated by the thrusters during test.

An extensive analysis was performed to determine the optimal thruster locations that provided the best coupled-torques about all spacecraft axes. Significant effort was also expended to estimate the worst-case total number of thruster cycles that will be seen by each thruster during flight. A detailed assessment of this prediction relative to previous thruster qualification and flight history was performed, and the thrusters were determined to have sufficient margin on the total number of expected cycles.

According to mission plans, performance of the thrusters will be monitored continuously after launch to account for ground-to-flight effects and to track and trend performance changes throughout the mission. Thruster counts and duty cycles would also be recorded on board the spacecraft, and tracked and reported throughout the mission.

The extensive analysis and test efforts performed to date on the New Horizons LPS indicate that the MR-103H thrusters are performing within specification and provide a satisfactory solution for the demanding control requirements of the New Horizons spacecraft.