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Life Test Results of a MONARC 5 1 lbf Monopropellant Thruster with Heraeus Catalyst

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The Jet Propulsion Laboratory (JPL) will be launching the Soil Moisture Active Passive (SMAP) satellite in the fall of 2014. The spacecraft propulsion subsystem includes eight MONARC 5 monopropellant hydrazine thrusters. These thrusters are the first flight thrusters to contain Heraeus catalyst instead of Shell 405. The SMAP thruster performance requirements were such that a Life Test was conducted over 57 days by, the JPL Propulsion and Fluid Flight Systems Group, to demonstrate that the thruster performance met the Project requirements and that the thruster performance was comparable to the Shell 405 heritage.

Nomenclature

AT = Acceptance Test
DC = Duty Cycle
Isp = Specific Impulse
$\dot{m}$ = Mass flow rate
Pc = Chamber Pressure
Pf = Feed Pressure
PTL = Propulsion Test Laboratory
SMAP = Soil Moisture Active Passive
T90 = Time to reach 90% thrust level

I. Introduction

The Jet Propulsion Laboratory (JPL) will be launching the Soil Moisture Active Passive (SMAP) satellite in the fall of 2014. This is an Earth orbiting satellite with a two year nominal mission. The propulsion subsystem for the satellite is a monopropellant hydrazine blow down system that provides delta –v and three-axis control. The system includes eight 1 lbf (4.45 N) MONARC 5 thrusters manufactured by MOOG – ISP. These thrusters are unique in that they are the first flight MONARC 5 thrusters to contain Heraeus catalyst (all previous models contained Shell 405). Additionally, the JPL mission requirements are such that the thruster must demonstrate 36,000 pulses, 15 cold starts and 132.3 lbm of propellant throughput. These combined requirements had not been demonstrated by this thruster with this catalyst. In order to verify these requirements, the JPL Propulsion and Fluid Flight Systems Group conducted a 57 day Life Test at the JPL Propulsion Test Laboratory (PTL) during the fall of 2012. The test parameters were chosen according to the mission operations plan and applicable JPL margins for Life Testing. During the test, thruster degradation was monitored via Health Checks (baseline performance tests) that were conducted at four significant Life Test milestones. First a Health Check was conducted to provide a thruster performance baseline. Then the thruster was hot-fired at inlet pressures of 350, 200 and 120 psia to simulate a nominal mission, followed by a health check. Then the thruster was tested over 350, 250, and 120 psia to

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demonstrate 100% performance margin followed by a Health Check. Finally the thruster was tested over 350, 200 and 120 psia followed by a final fourth Health Check to demonstrate 200% performance margin. During the nominal and margin testing, the thruster was hot fired at duty cycles (DC) from steady state to limit cycles (0-5% DC), provided with a total propellant throughput of over 132.3 lbm, and a total impulse of 28,571 lbf-sec (127,143 N-sec). This paper outlines the Life Test and provides an analysis of the results of the test as conducted at JPL for the SMAP mission.

II. Soil Moisture Active Passive Project

The SMAP Project will be launching in the fall of 2014. It will be launching from Vandenberg Air Force Base into a 685 km polar orbit. The 6 m antenna will spin at a rate of 15 rpm and measure the soil moisture content of Earth’s land masses. The spacecraft bus is three-axis controlled and relies on thrusters for orbit insertion, orbit trim maneuvers, orbital collision avoidance maneuvers, fault protection in the case of reaction wheel fault and deorbit maneuver at mission completion in accordance with the NASA deorbit requirement (Fig. 1).

The propulsion subsystem consists of a diaphragm propellant tank, with a capacity for 176.4 lbm of propellant in a 3:1 blow-down ratio. The system also contains a gas service valve, liquid service valve, system filter, and redundant latch valves. Most importantly, it contains eight 1 lbf (4.45 N) MONARC 5 thrusters to perform all spacecraft maneuvers (Fig. 1).

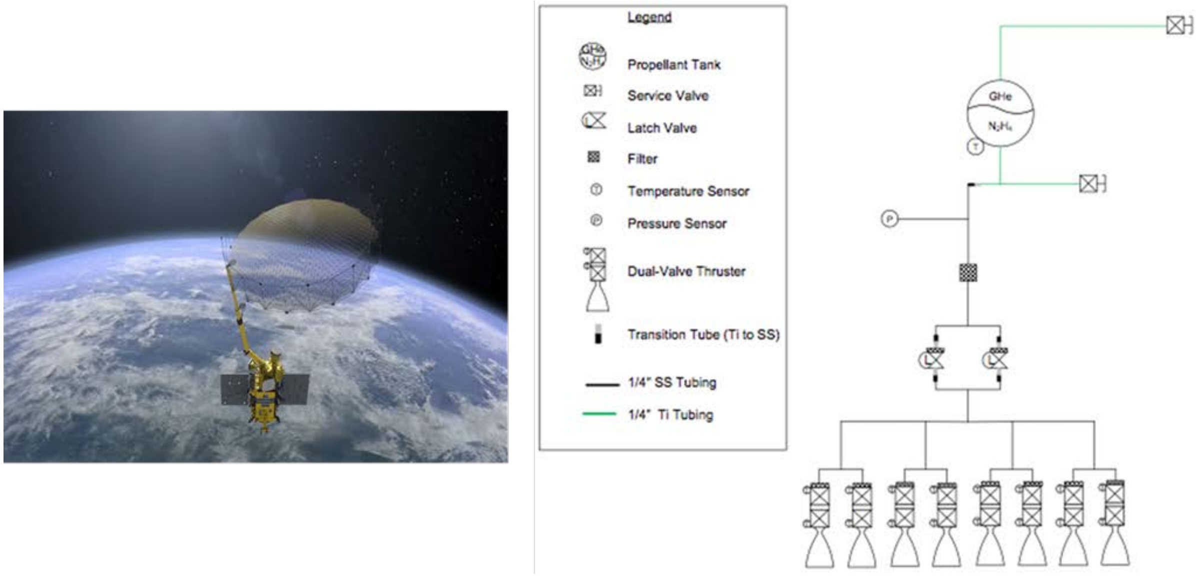


Figure 1. SMAP spacecraft in orbit (left). SMAP propulsion block diagram (right).

III. Test Objectives

The MONARC 5 thrusters have a successful heritage with the Shell 405 catalyst substrate. However, with the dwindling supply of Shell 405, MOOG-ISP now manufactures the MONARC 5 with Heraeus catalyst manufactured in Germany. The change in catalyst supplier caused the SMAP Project to select a thruster Life Test for the MONARC 5 given the paucity of performance data for the thruster with Heraeus catalyst.

The test objectives we based on the SMAP spacecraft performance models generated by the Guidance Navigation and Control Group. Based on worst case performance values, a qualification margin was added to yield the test objectives for the SMAP Life Test (Table 1).

Table 1. Test objectives for the SMAP Life Test.

Test Objectives
Demonstrate at least 36,000 on-pulses
Demonstrate at least 24,000 off-pulses
Demonstrate total cumulative impulse of at least 31,010 lbf-s
Demonstrate 15 cold starts
Demonstrate 132.3 lbm throughput
Demonstrate 445 hot starts
Demonstrate 7,145 limit cycle pulses

The pulsing behavior is divided between an on-pulse and an off-pulse. On-pulse behavior is a duty cycle between 5% and 50%. An off-pulse is between 99.99% and 50% and specifically for the SMAP mission, the pulse has a total duration of 1 second including on and off time. A limit cycle pulse is defined as a duty cycle of 0% to 5%. All pulsing test objective values were determined by adding 50% margin to mission worst case values. Prior to the SMAP Life Test the MONARC 5 thruster with Heraeus catalyst had not demonstrated a cold start. A cold start is defined as the catalyst bed temperature between 46 degrees F and 160 degrees F. A total of 15 cold starts were completed to satisfy a worst case of 1 planned cold start and an additional 8 possible over the mission life as contingency (i.e. collision avoidance maneuvers). The nominal throughput of one thruster on the SMAP spacecraft is 44 lbm, and a 200% margin was included for this value to yield 132.3 lbm. The number of hot starts, defined as a catalyst bed temperature of greater than 160 degrees F at the start of hot-fire, were calculated by adding 200% margin to the mission nominal value to yield 445. Finally, the cumulative impulse was determined based on the modeled thruster behavior over the mission life with an additional 50% margin.

IV. Test Matrix

The test matrix addressed each of the Test Objectives of Section III, with a planned 38,365 on- pulses, 24,300 off-pulses, 31,091 lbf-sec cumulative impulse, and 7,245 limit cycle pulses. There were 15 planned cold starts and the 132.3 lbm throughput requirement was met via the 24,300 off-pulses and the 25,560 seconds of steady state on time. A total of 445 hot starts were planned to meet the pulsing and steady state test objectives.

The test matrix for the Life Test was generated based on the thruster performance requirements predicted by the JPL Guidance Navigation and Control Group. The matrix was designed to qualify the thruster to provide performance margin for the nominal required steady state and pulsing performance. A matrix was designed with a nominal life performance and additionally for 100% and 200% margin. Testing was performed at three pressures over the pressure blow down range, 350 psia, 200 psia, and 120 psia, to demonstrate performance at beginning of mission, mid-mission and end of mission. During thruster testing, the thruster health was assessed through health checks. These were performed prior to the start of the nominal life sequence of testing, prior to the 100% margin sequence of testing, prior to the 200% margin testing and the fourth and final health check was performed at the completion of 200% margin testing. The health checks provided a snapshot of thruster health after approximately 11,108 pulses and 9,660 seconds of on-time. Decisions to proceed with testing were also based on the results of the health checks. They also provide data to determine the root cause of potential degradation/failure (low risk). The Health Check portion of the test matrix is provided in Table 2. The pressures differ slightly from the Life Test pressures of the test matrix in order to allow the comparison of the health check data to the MOOG-ISP Acceptance Test (AT) data for the thruster. The thruster underwent a complete shock, random vibration and acceptance hot-fire prior to the JPL Life Test. A sample of the Life Test matrix is located in the Appendix. A pulse train map is provided in Figure 2 for reference for the duty-cycles and associated on-times performed during the Life Test.

Table 2. Health Check portion of the Life Test Matrix

Health Check Test Matrix			
Test Run Description	**Inlet Pressure (psia)**	**On-Time (ms)**	**Off-Time (ms)**
Steady State	355	60,000	0
Off Pulse	355	950	50
Long Pulse Train	355	150	850
Long Pulse Train	355	150	850
Short Pulse Train	355	20	4,980
Short Pulse Train	355	20	4,980
20 ms baseline	355	20	980
Steady State	225	60,000	0
Long Pulse Train	225	150	850
Long Pulse Train	225	150	850
Short Pulse Train	225	20	4,980
Short Pulse Train	225	20	4,980
20 ms baseline	225	20	980
Steady State	120	60,000	0
Long Pulse Train	120	150	850
Long Pulse Train	120	150	850
Short Pulse Train	120	20	4,980
Short Pulse Train	120	20	4,980
20 ms baseline	120	20	980
20 ms baseline	120	20	980

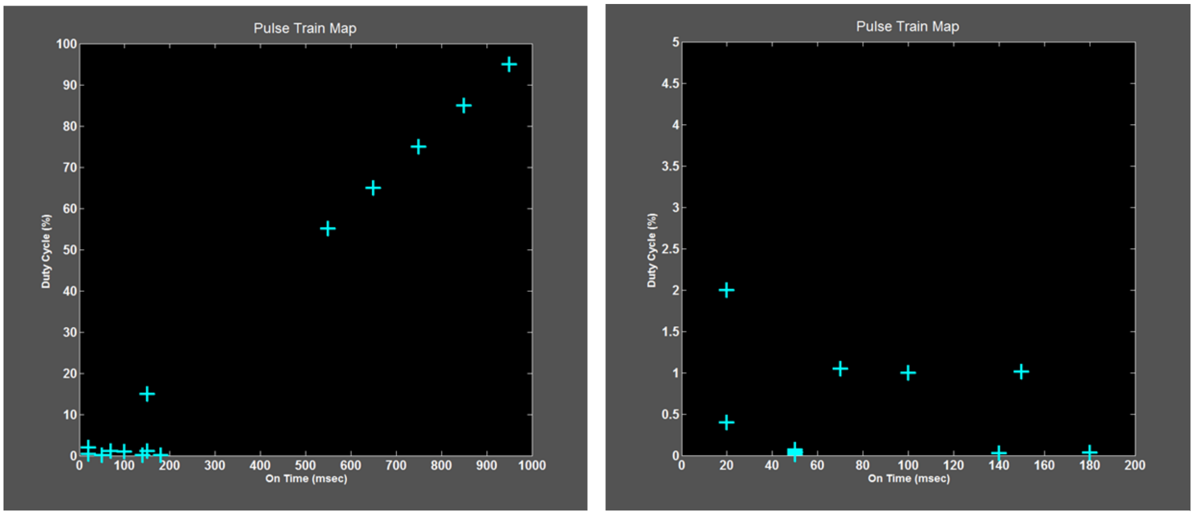


Figure 2. Pulse Train Map for the Life Test (left). Magnified Pulse Train Map in the region of 200 ms on-time and 5% DC (right).

V. Test Facility and Data Acquisition

The test facility is a JPL heritage facility used for thruster testing in the 1970's for the Voyager project. The facility was updated for the SMAP Life Test with a new hydrazine feed system (Fig. 3) and the integration of a LabVIEW data acquisition system. The LabVIEW data acquisition system gathers the primary measurements of thruster inlet pressure (Pf), thruster chamber pressure (Pc), and flow rate ($\dot{m}$). Temperatures were recorded at 7 locations on the thruster: two at the valve, one at the flange, two at the catalyst bed and two at the throat. The vacuum chamber used for testing held a very stable vacuum level of 5 milliTorr. The thruster feed pressure was measured with a commercial off the shelf pressure gauge. The chamber pressure was measured with a fast response Kistler transducer, type 6041 with a charge amplifier. The flow rate was measured with an Endress Hauser Proline Promass 83A that has a mass flow range of 0- 44 kg/hr.

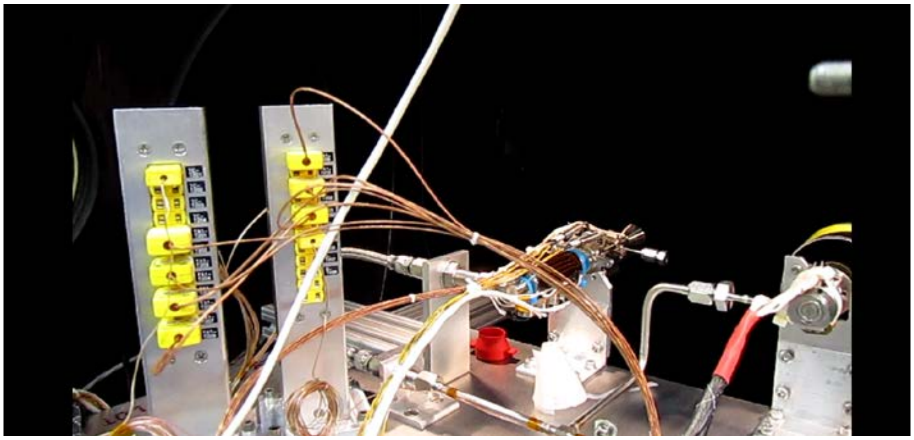
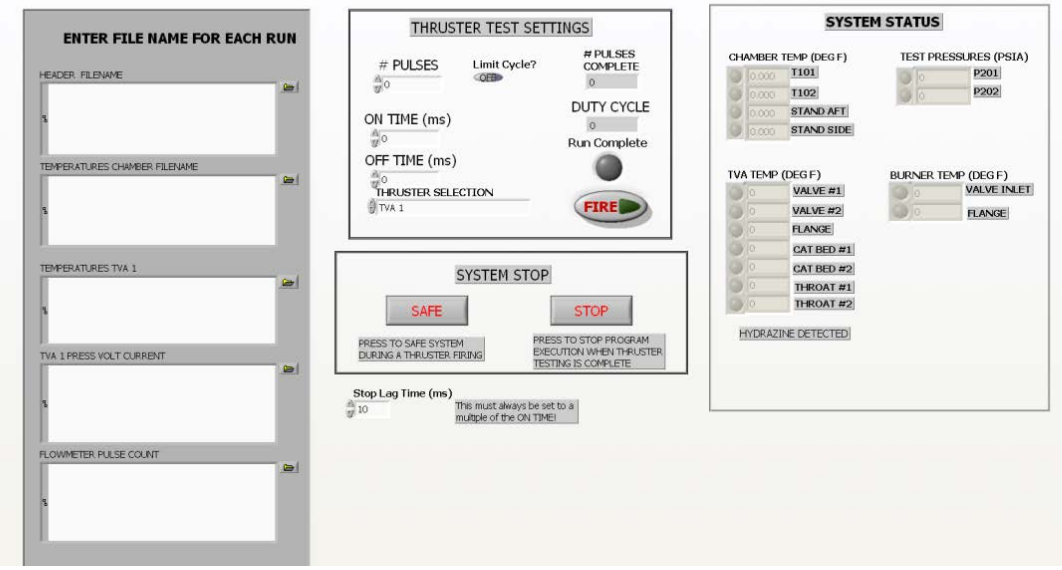


Figure 3. Life Test MONARC 5 pictured in the center. Thermocouples are connected for data transmission to LabVIEW. Thruster chamber pressure transducer is not connected.

The LabVIEW data acquisition program was an in-house JPL program that controlled the hydrazine feed system, the thruster and recorded the test data. The hot-fire control panel is pictured below in Figure 4. It provides user input for test sequence data and real time pressure and temperature data during testing with visual alarms. The LabVIEW program operated without issue during the Life Test.



PULSES 0
Limit Cycle? OFF
PULSES COMPLETE 0
ON TIME (ms) 0
DUTY CYCLE 0
OFF TIME (ms) 0
Run Complete
THRUSTER SELECTION TVA 1

PRESS TO SAFE SYSTEM DURING A THRUSTER FIRING
PRESS TO STOP PROGRAM EXECUTION WHEN THRUSTER TESTING IS COMPLETE

Stop Lag Time (ms) 10
This must always be set to a multiple of the ON TIME!

0.000 T101
0.000 T102
0.000 STAND AFT
0.000 STAND SIDE

0 P201
0 P202

0 VALVE #1
0 VALVE #2
0 FLANGE
0 CAT BED #1
0 CAT BED #2
0 THROAT #1
0 THROAT #2

0 VALVE INLET
0 FLANGE

Figure 4. LabVIEW control panel for hot-fire.

VI. Data Analysis and Results

Data analysis was accomplished via a JPL in-house Matlab code. This software approach allowed for the analysis of a very large data set, as over 446 test sequences were executed over 57 days. It also provided excellent quick look data at the completion of each test sequence. Lastly, each pulse could be reviewed independently allowing for the comparison of individual pulses for a single test sequence or across test sequences. This was ideal for analyzing cold start data.

Overall, thruster performance was acceptable. The test objectives were all met except for the total cumulative impulse which fell slightly short of the 31,010 lbf-s by 8% (Table 3). This was likely due to the overall thrust degradation during margin testing. The total impulse was calculated using the MOOG-ISP thrust coefficient performance calculation for the Life Test thruster. The total cumulative impulse and throughput were a result of a total thruster on time of 31,632 seconds.

Table 3. Life Test objectives and results

Test Objectives	Results
Demonstrate at least 36,000 off-pulses	37,308
Demonstrate at least 24,000 on-pulses	25,629
Demonstrate total cumulative impulse of at least 31,010 lbf-s	28,553 lbf-s
Demonstrate 15 cold starts	15 cold starts completed nominal results
Demonstrate 132.3 lbm throughput	132.5 lbm
Demonstrate 445 hot starts	446
Demonstrate 7,145 limit cycle pulses (DC of 0% to 5%)	7,230

A. Steady State Data

The health check steady state data is provided in the Figures 5 to 9. From Table 4, it is noted that the thrust degradation at 355 psia is 6% and at 225 psia is 10% and at 120 psia it is 15%. A 6% degradation in thrust at 355 psia is acceptable as this is at 200% margin on the nominal mission. The degradation of less than 1% was noted between Health Check #1 and Health Check #2. This is well within the desired range of 5%. Total steady state on time was 28,530 seconds.

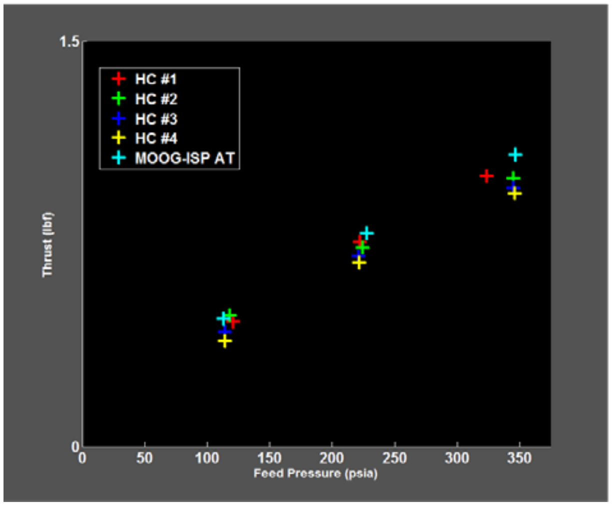


Figure 5. Thrust vs. Feed Pressure for the Health Checks #1 to #4 compared to the MOOG-ISP AT data (steady state, 100% DC).

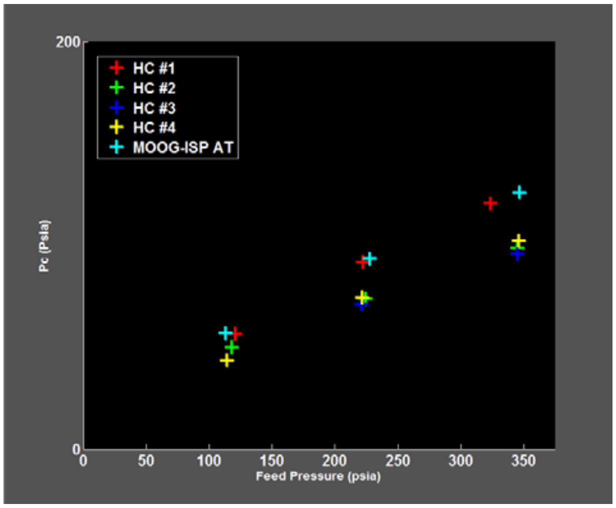


Figure 6. Chamber Pressure vs. Feed pressure for the Health Checks #1 to #4 compared to the MOOG-ISP AT data (steady state, 100% DC).

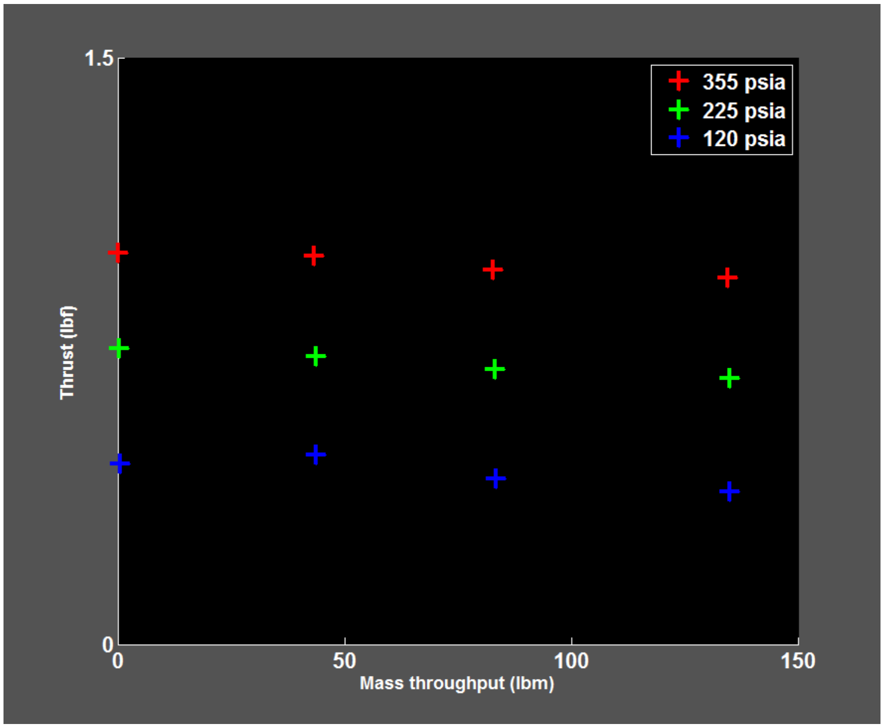


Figure 7. Thrust vs. Mass Throughput. Each interval represents one of the four health checks. (steady state, 100% DC).

Table 4. Thrust degradation measured at each health check as a function of mass throughput. (steady state, 100% DC)

Feed Pressure (psia)	Mass Throughput (lbm)	Thrust (lbf)	Degradation (%)
324	0	1.001	0
345	43.2	0.9925	-0.85
345	82.82	0.9581	-4.29
346	131.6	0.9375	-6.34
222	0.3181	0.7564	0.00
225	43.69	0.7349	-2.84
221	83.19	0.7032	-7.03
222	131.9	0.6788	-10.26
121	0.5538	0.4609	0.00
118	43.85	0.4841	5.03
114	83.34	0.4232	-8.18
114	132	0.389	-15.60

The range of specific impulse for all four health checks ranged from 191.47 seconds to 236.57 seconds. Likewise the chamber pressure roughness remained under 5% for the health check steady state testing.

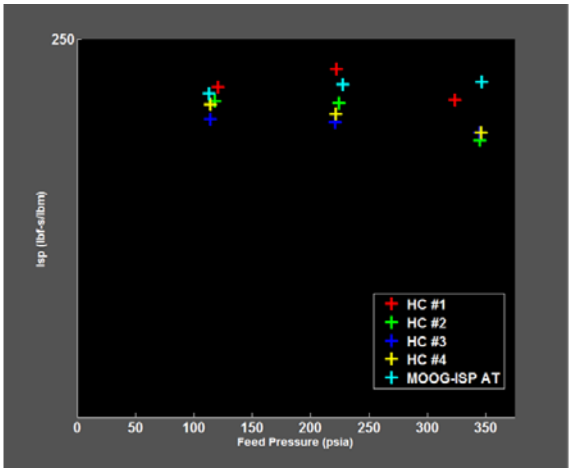


Figure 8. Isp vs. Feed Pressure for the Health Checks #1 to #4 compared to the MOOG-ISP AT data (steady state, 100% DC).

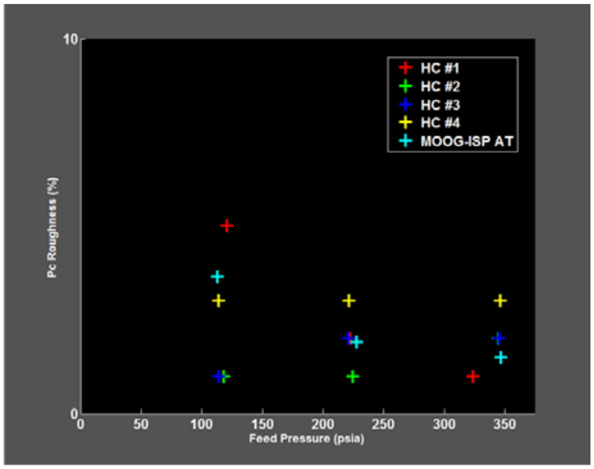


Figure 9. Chamber Pressure Roughness vs. Feed Pressure for the Health Checks #1 to #4 compared to the MOOG-ISP AT data (steady state, 100% DC).

B. Pulse Performance

The thruster pulse performance was acceptable. The Isp, time to 90% thrust (T90), and Impulse Bit compare well with MOOG-ISP acceptance Test data (Figures 10 to 13). The thruster did begin to show signs of degradation during Health Check #2, completed after the nominal mission sequences. Even though the thruster showed signs of degradation through subsequent health checks, the Isp and the Impulse Bit were still acceptable. The Isp values of near 250 for on-pulses and limit cycles are in error. The flow meter provided poor mass flow data for pulsed behavior and significant work was done during the analysis to bring the mass flow values to reasonable values, based on the Health Check #1 data, for the remainder of the test matrix.

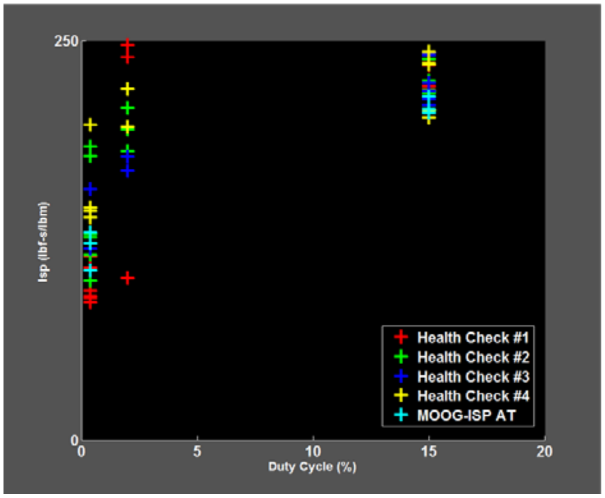


Figure 10. Isp vs. Duty Cycle for the Health Checks #1 to #4 compared to the MOOG-ISP AT data

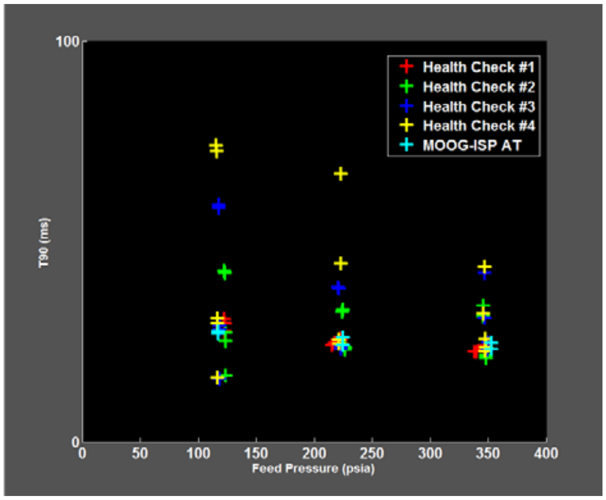


Figure 11. T90 vs. Feed Pressure for the Health Checks #1 to #4 compared to the MOOG-ISP AT data

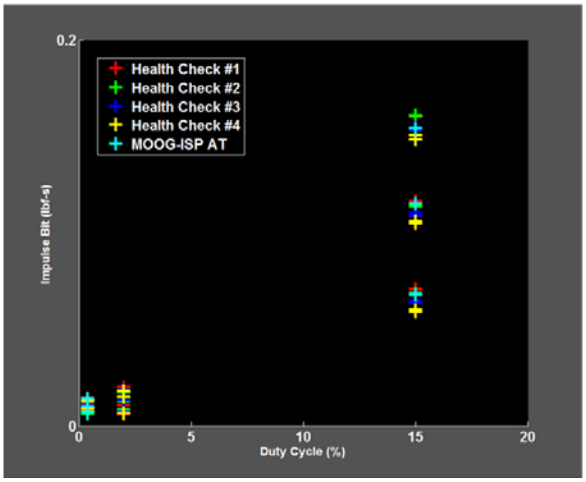


Figure 12. Impulse Bit vs. Duty Cycle for the Health Checks #1 to #4 compared to the MOOG-ISP AT data

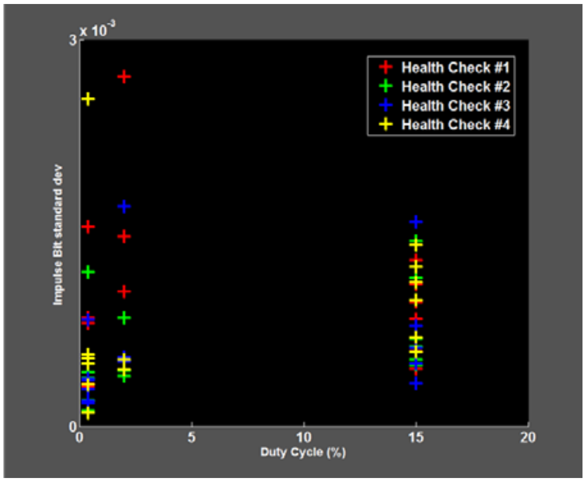


Figure 13. Impulse Bit Standard Deviation vs. Duty Cycle for the Health Checks #1 to #4 compared to the MOOG-ISP AT data

The health check sequence for 95% duty cycle showed that at Health Check #2 there were signs of thruster degradation. This sequence was not included in the first health check. But was reconsidered for future Health Checks as this sequence provided insight into thruster health regarding a high duty cycle off-pulse sequence. The results of the 95% health check duty cycle are provided in Table 5.

Table 5. The thruster performance for health check sequences with a pulse on-time of 950 ms and off-time of 50 ms.

	Inlet pressure (psia)	Impulse bit (lbf-s)	Isp (s)	T 90 (ms)
MOOG ISP AT Data	350	1.018	235	22
Health Check #1	-	-	-	-
Health Check #2	344	0.8567	207	42.4
Health Check #3	344	0.8034	186	64.2
Health Check #4	345	0.7928	219	83.8

The limit cycle pulsing performed below the predicted 150 lbf-s/lbm for very low duty cycles ($1x10^{-6}$ %) (Figures 14 and 15). In the nominal mission (Life 1) Isp was in the range of 47-150 lbf-s/lbm and Impulse Bit in the range of 0.01 to 0.12. The excursions in Isp and Impulse Bit are due to the inaccuracy of the flow meter for small pulse widths.

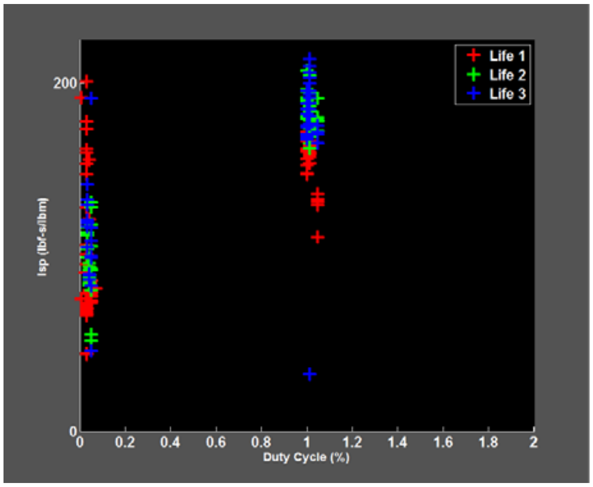


Figure 14. Isp vs. Duty Cycle for limit cycle testing during the Life Test.

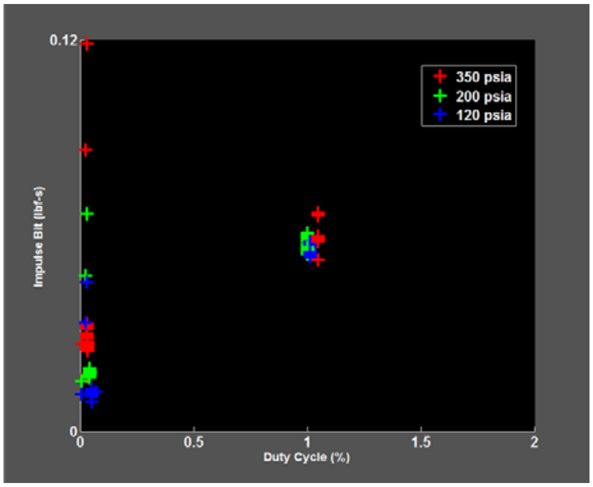


Figure 15. Impulse Bit vs. Duty Cycle for limit cycle testing during the Life Test.

C. Cold Start Data

A total of 9 cold starts were conducted during the nominal life portion of the test. This equated to three cold starts at each of the respective test inlet pressures of 350 psia, 200 psia and 120 psia. Another three cold starts were conducted in the first margin portion of testing. This equated to one cold start at each of the respective inlet pressures. Finally an additional three cold starts were conducted during the second margin portion of testing. Again there was one cold start at each of the test inlet pressures.

The cold start data shows that the thruster behaves very well when subjected to a room temperature catalyst bed start. The spiking at the start of the pulse decreased as life was put on the thruster due to the catalyst bed reactivity decreasing with life. The catalyst bed recovered quickly from a cold start and returned to nominal chamber pressures early in the 120 pulse train. Also, all data was within the pressure transducer limit of 210 psia. In other words, there were no pressure spikes that were cause for concern. Figure 16 depicts the 1st and 120th (last) pulse chamber pressure and thrust in the train at 350 psia inlet pressure for the first cold start in the nominal mission portion of the test.

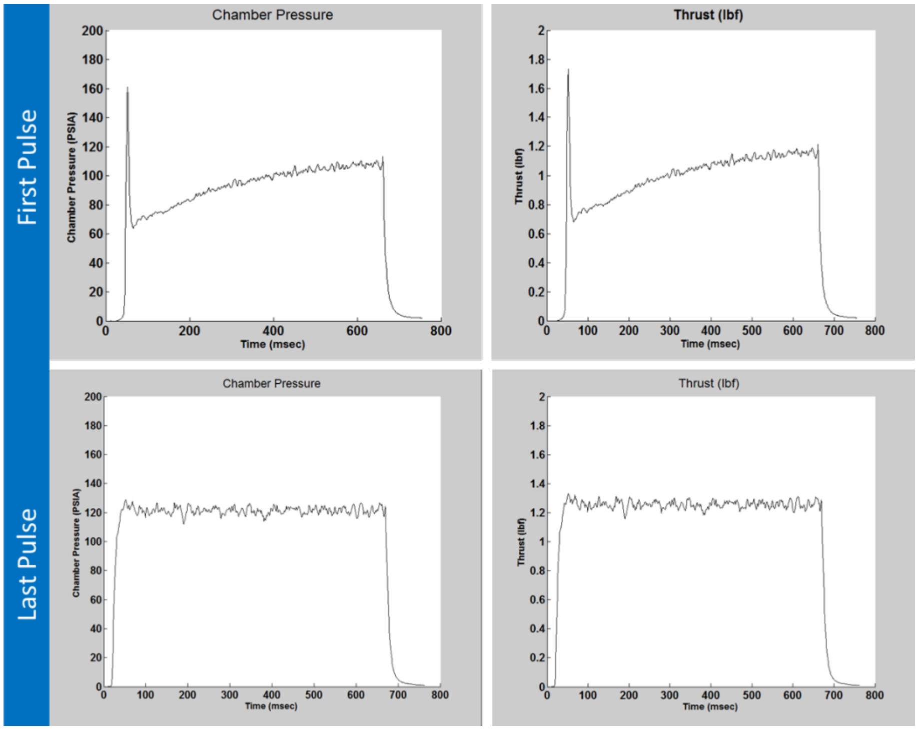


Figure 16. The first Cold Start conducted at 350 psia and a catalyst bed temperature of 82 deg F (27 deg C) for the first pulse and reaches an acceptable 1387 deg F (752 deg C) during the last pulse.

A summary of all the cold start sequence data is provided in Table 6 below. Note that overall, the variance in impulse bit for the last five pulses of the sequence is negligible for cold start in the first life and show degradation of less than 9% over the full test matrix.

Table 6. Summary of the cold start test sequence performance.

Inlet Pressure (psia)	Catalyst Bed Temperature (degF)	Impulse Bit (lbf-s)
337	82.3	0.8196
339	79.09	0.8222
336	82.07	0.8174
197	75.85	0.5267
194	76.66	0.5199
197	77.76	0.5250
122	78.04	0.3491
115	73.34	0.3333
116	72.19	0.3358
350	70.71	0.7880
193	73.72	0.3994
119	68.51	0.3219
342	69.77	0.7550
192	70.35	0.4806
119	73.38	0.3143

VII. Conclusion

At test completion, the thruster successfully met all but the cumulative impulse test objectives. A total of 37,308 pulses were demonstrated, well in excess of the 36,000 required. The thruster demonstrated excellent performance for cold starts throughout the life test. Overall it was noted that the effect of cold starts for this thruster are negligible for the SMAP mission requirements. The Isp over the range of duty cycles was in good agreement with the expected performance except for limit cycles. Here the Isp was lower than anticipated at 80 s. This however, is not a major mission driver as there is sufficient propellant margin to address the Isp shortfall. The thruster successfully delivered over 28,571 lbf-sec of impulse with a total propellant throughput of over 132.5 lbm. Overall, the thruster had degraded within the range anticipated, with off-pulsing duty cycles causing greater degradation than steady state. This was noted over the four thruster health monitoring tests. Thruster degradation was already noticeable on the first Health Check conducted after the nominal mission life cycle. Over, the test regime the total degradation of steady state thrust was 6% for an inlet pressure of 355 psia. The Life Test shows that the MONARC 5 thrusters with Heraeus catalyst meet the propulsion requirements of the SMAP project

Appendix

A. SMAP Life Test Matrix

	Hot-Fire Test Sequence	Inlet Pres (psia)	On Time (msec)	Off Time (msec)	Pulse Count/Train
Health and Repeatability Check 1	Steady State	355	60000		1
	Long Pulse Train	355	150	850	30
	Long Pulse Train	355	150	850	30
	Short Pulse Train	355	20	4980	30
	Short Pulse Train	355	20	4980	30
	20 msec baseline	355	20	980	100
	Steady State	225	60000		1
	Long Pulse Train	225	150	850	30
	Long Pulse Train	225	150	850	30
	Short Pulse Train	225	20	4980	30
	Short Pulse Train	225	20	4980	30
	20 msec baseline	225	20	980	100
	Steady State	120	60000		1
	Long Pulse Train	120	150	850	30
	Long Pulse Train	120	150	850	30
	Short Pulse Train	120	20	4980	30
	Short Pulse Train	120	20	4980	30
	20 msec baseline	120	20	980	100
Thruster ACS	Characterization Test	350	50	579050	10
	Characterization Test	350	140	578960	10
Thruster ACS	Characterization Test	350	180	578920	10
Cold Start begins test day	Cold Start Detumble	350	650	350	120
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Cold Start begins test day	Cold Start Detumble	350	650	350	120
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Cold Start begins test day	Cold Start Detumble	350	650	350	120
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
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Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70
Thruster ACS	Thruster ACS Mode	350	50	156950	70

	Hot-Fire Test Sequence	Inlet Pres (psia)	On Time (msec)	Off Time (msec)	Pulse Count/Train
Delta Velocity Off-Pulsing	Delta Velocity	120	550	450	270
Delta Velocity Off-Pulsing	Delta Velocity	120	550	450	270
Delta Velocity Off-Pulsing	Delta Velocity	120	550	450	270
	Delta Velocity	120	650	350	270
	Delta Velocity	120	650	350	270
	Delta Velocity	120	650	350	270
	Delta Velocity	120	750	250	270
	Delta Velocity	120	750	250	270
	Delta Velocity	120	750	250	270
	Delta Velocity	120	850	150	270
	Delta Velocity	120	850	150	270
	Delta Velocity	120	850	150	270
	Delta Velocity	120	950	50	270
	Delta Velocity	120	950	50	270
	Delta Velocity	120	950	50	270
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Delta Velocity	120	460000		1
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
	Roll Control	120	150	14650	18
Thruster ACS	Characterization Test	120	50	579050	10
	Characterization Test	120	140	578960	10
	Characterization Test	120	180	578920	10
Thruster ACS	Thruster ACS Mode	120	50	100000	30
Thruster ACS	Thruster ACS Mode	120	50	70000	30
Thruster ACS	Thruster ACS Mode	120	50	99950	20
Thruster ACS	Thruster ACS Mode	120	50	99950	20
Thruster ACS	Thruster ACS Mode	120	50	99950	40
Cold Start begins test day	Cold Start Detumble	120	650	350	120
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Cold Start begins test day	Cold Start Detumble	120	650	350	120
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Cold Start begins test day	Cold Start Detumble	120	650	350	120
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70
Thruster ACS	Thruster ACS Mode	120	50	99950	70

	Hot-Fire Test Sequence	Inlet Pres (psia)	On Time (msec)	Off Time (msec)	Pulse Count/Train
Health and Repeatability Check 2	Steady State	355	60000		1
	Off Pulse	355	950	50	30
	Long Pulse Train	355	150	850	30
	Long Pulse Train	355	150	850	30
	Short Pulse Train	355	20	4980	30
	Short Pulse Train	355	20	4980	30
	20 msec baseline	355	20	980	100
	Steady State	225	60000		1
	Long Pulse Train	225	150	850	30
	Long Pulse Train	225	150	850	30
	Short Pulse Train	225	20	4980	30
	Short Pulse Train	225	20	4980	30
	20 msec baseline	225	20	980	100
	Steady State	120	60000		1
	Long Pulse Train	120	150	850	30
	Long Pulse Train	120	150	850	30
	Short Pulse Train	120	20	4980	30
	Short Pulse Train	120	20	4980	30
	20 msec baseline	120	20	980	100
	20 msec baseline	120	20	980	100

Acknowledgments

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