AF-M315E Propulsion System Advances & Improvements

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ABSTRACT

Even as for the GR-1 awaits its first on-orbit demonstration on the planned 2017 launch of NASA's Green Propulsion Infusion Mission (GPIM) program, ongoing efforts continue to advance the technical state-of-the-art through improvements in the performance, life capability, and affordability of both Aerojet Rocketdyne' s 1-N-class GR-1 and 20-N-class GR-22 green monopropellant thrusters. Hot-fire testing of a design upgrade of the GR-22 thruster successfully demonstrated resolution of a life-limiting thermo-structural issue encountered during prototype testing on the GPIM program, yielding both an approximately 2× increase in demonstrating life capability, as well as fundamental insights relating to how ionic liquid thrusters operate, thruster scaling, and operational factors affecting catalyst bed life. Further, a number of producibility improvements, related to both materials and processes and promising up to 50% unit cost reduction, have been identified through a comprehensive Design for Manufacturing and Assembly (DFMA) assessment activity recently completed at Aerojet Rocketdyne. Focused specifically on the GR-1 but applicable to the common-core architecture of both thrusters, ongoing laboratory (heavyweight) thruster testing being conducted under a Space Act Agreement at NASA Glenn Research Center has already validated a number of these proposed manufacturability upgrades, additionally achieving a >40% increase in thruster life. In parallel with technical advancements relevant to conventional large spacecraft, a joint effort between NASA and Aerojet Rocketdyne is underway to prepare 1-U CubeSat AF-M315E propulsion module for first flight demonstration in 2018.

I. Nomenclature

AFRL = Air Force Research Laboratory
EELV = Evolved Expendable Launch Vehicle
ESPA = EELV Secondary Payload Adapter
GPIM = Green Propellant Infusion Mission
GRAIL = Gravity Recovery and Interior Laboratory
HAN = Hydroxylammonium Nitrate
I_{sp} = Specific Impulse
ρI_{sp} = Density-Specific Impulse
MRO = Mars Reconnaissance Orbiter
MSL = Mars Science Laboratory
NASA = National Aeronautics and Space Administration
SCAPE = Self-Contained Atmospheric Protection Ensemble

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II. Introduction

The long-sought benefits of a low toxicity, high performance green monopropellant AF-M315E[1,2,3,4,5,6]. propulsion system, offering a 50% greater ρI_{sp} than hydrazine, have become reality. Aerojet Rocketdyne has developed a fully functional propulsion system, incorporating a complete set of AF-M315E-compatible components ready for deployment on a wide range of missions. With all assembly and integration of the flight green propulsion system payload and host Ball Aerospace BCP 100 ESPA-class spacecraft bus now complete, final launch preparations for its first flight demonstration on NASA's Green Propulsion Infusion Mission (GPIM) are in work, comprising principally fine-tuning and validation of the flight software and operations handbook at Ball Aerospace, as well as development of propellant handling and loading logistics at Kennedy Space Center.

Corresponding to one each of two mission-predominant thrust levels (together comprising >80% of present monopropellant thruster market share), recent AF-M315E development work focused on 1-N (GR-1) and 20-N (GR-22) class flight thrusters. However, only the 1-N GR-1 thruster is included in the on-orbit demonstration mission phase of the GPIM program although that program completed mission life demonstrations for both thrusters. Leveraging work done on the GPIM program, upgrades to the GR-22 have been implemented and verification testing of has been successfully completed on Aerojet Rocketdyne internal funding demonstrating a 2× improvement in life capability. Additionally, to further facilitate near-term industry infusion of AF-M315E green technology, Aerojet Rocketdyne has identified a series of manufacturability improvements to be first applied on a next generation version of the GR-1 thruster promising up to 50% cost reduction. Preliminary testing conducted by NASA Glenn Research Center in collaboration under a Space Act Agreement, has already demonstrated important validation of some of the proposed design revisions in laboratory (heavyweight) thrusters, as well as ~40% increases in thruster total impulse life capability compared to the baseline GR-1 design flying on GPIM.

III. AF-M315E Advanced Green Monopropellant

The GR-1 and GR-22 thrusters employ a high-performance green propellant invented at the AFRL in 1998 known as AF-M315E, a true ionic liquid derived of hydroxylammonium nitrate (HAN), water, and an also highly hygroscope fuel (vs. other propellant formulations that actually include non-ionic, and in some cases toxic, volatiles such as methanol) [7]. Delivering approximately 50% higher ρI_{sp} than hydrazine (5% higher I_{sp} combined with a 46% higher density, AF-M315E offers comparable performance to traditional storable bipropellants for low ΔV missions while employing roughly half the number of components, thereby retaining the well-established increased reliability and reduced cost of traditional monopropellants. Many design issues and failure modes associated with long-duration interplanetary missions (e.g. control of mixture ratio, of propellant vapor diffusion and reaction, oxidizer flow decay) do not apply to an equally capable AF-M315E system.

AF-M315E (shown as routinely handled in Fig. 1 derives its low-toxicity-hazard characteristics and high mixture stability (even to very low temperatures) from the high solubility and negligible vapor pressure of all solution constituents, such that indefinite exposure to the open environment poses no safety issue. As such, AF-M315E simplifies the safe design and development of propulsion systems compared to conventional toxic propellants such as hydrazine. Since leakage of AF-M315E has been verified as a critical rather than catastrophic failure with range safety personnel per AFSPCMAN 91-710, only single-fault-tolerance is required for safety in handling flight systems. This alone accounts for significant savings, as redundant components are eliminated, yielding simpler architectures. Further, simpler and much less expensive design and verification criteria govern flight-qualification of fracture-critical hardware (e.g., propellant tanks) for non-hazardous propellants such as AF-M315E compared to hydrazine. The aggregate potential impact of these and increased performance-related cost savings is highly mission-dependent, but has been evaluated to tens of millions of dollars for large space missions such as Juno, MSL, and Europa; and to several million for more modest missions such as GRAIL and MRO[8].

Figure 1. AF-M315E propellant can be safely handled in open containers without need of respiratory protective equipment.

With its ultra-low minimum storage temperature, AF-M315E yields an additional advantage mitigating operational concerns related to long-duration system thermal management. Whereas hydrazine space tanks and lines must be heated at all times to prevent freezing, AF-M315E cannot freeze (it undergoes glass transition at -80 ºC). Thus, during long coast periods an AF-M315E propulsion system may be allowed to fall to very low temperatures and later reheated for operation without risk of line rupture by phase-change-induced expansion. This can be particularly beneficial with respect to the often limited power budgets of smallsats, as well as interplanetary spacecraft and planetary ascent vehicles, which missions can call for years of propellant storage in cold environments. For <1 AU interplanetary exploration missions, solar power is naturally more limited than for Earth-orbiting satellites; e.g., equivalent solar power generation designs in Mars (e.g., MRO), Vesta (e.g., Dawn), and Jupiter (e.g., JUNO) orbits produce roughly 43%, 16%, and 3.7% of the electrical power they yield in Earth orbit, respectively. Tests also have demonstrated AF-M315E to have a significantly reduced sensitivity to adiabatic compression than hydrazine and other green propellants.

The cost savings green propellants promise through simplified range operations are quantifiable. The average contractual cost to load a NASA mission with conventional propellants is $135,000[8]. The cost for loading with AF-M315E will be a small fraction of this, and the associated schedule significantly expedited. Per current conventions, propellant loading operations require one shift for setup in SCAPE, a second shift waiting for propellant test confirmations, a third shift or more for actual loading, and a final additional shift to break down the setup, during which all remaining launch processing staff must wait at costs exceeding $100k/day for a typical Class B NASA mission. Thus elimination of the interruption of launch processing associated toxic propellant loading can save more than $100k per launch and two shifts of schedule. Naturally, it follows that simplified range operations would equally benefit commercial users through lower launch costs. An early Aerojet Rocketdyne study evaluating replacement of hydrazine with a HAN-based advanced monopropellant for the Centaur reaction control system on the Atlas launch vehicle concluded ground support costs of fueling could be reduced by two-thirds[9].

IV. Green Advanced Monopropellant Thrusters

Representing the culmination of over two decades of research and development, the GR-1 and GR-22 advanced monopropellant thrusters (Fig. 2) combine a breakthrough high temperature catalyst with stability-enhancing design techniques to enable duty-cycle-unlimited operation on state-of-the-art green ionic liquid propellants while delivering substantially improved performance and reduced handling costs compared to conventional toxic monopropellants. Though bearing general resemblance to the series-assembled valve, injector, catalyst chamber, and nozzle of standard catalytic hydrazine thrusters of similar thrust class, the common core architecture of both designs incorporates a number of optimizations specific to the increased thermal management requirements of high-performance (and higher flame temperature) advanced monopropellants. Most immediately distinctive are the thrusters' two-piece extended stand-off structures. This increased thermal isolation is accomplished with no added length in either case, while heat dissipation during and following extended thruster firings, this innovative design approach confines the need for high-temperature refractory alloys to the catalyst bed preheating to the nominal 315 ºC start temperature, and thereby associated power, are minimized. Key thruster functional characteristics and demonstrated performance are summarized in Table 1.

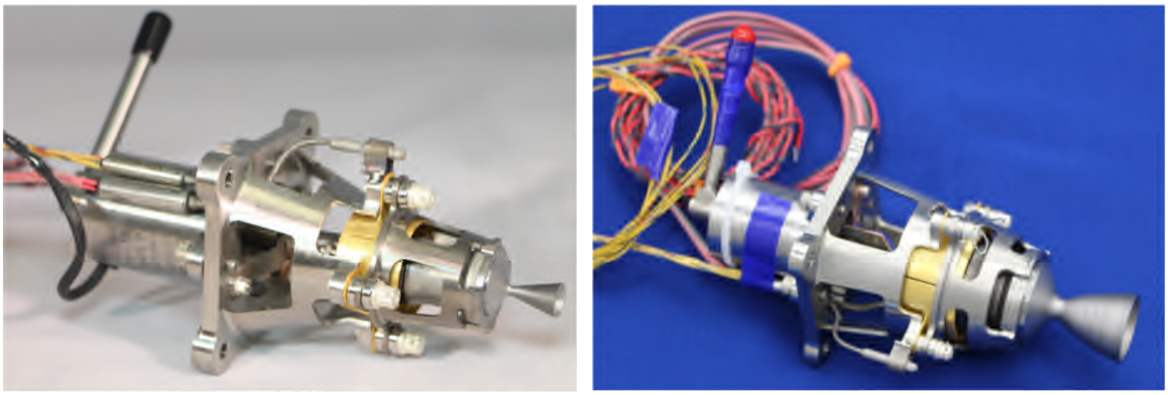

Figure 2. Prototype Aerojet GR-1 (left) and GR-22 (right) thrusters.

Table 1. GPIM thruster functional characteristics and demonstrated performance summary

	GR-1	GR-22
Nozzle Expansion Ratio:	100:1	100:1
Valve Power @ 28VDC, 10 ºC (W):	8.3	15.9
Feed Pressure (bar):	37.9-6.9	37.9-6.9
Thrust (N):	1.42-0.26	26.9-5.7
Maximum Steady-State I_{sp} (s):	231	248
Total Pulses:	11,107	944
Estimated Max Propellant Throughput Capability* (kg):	12	7

Both thrusters employ notably smaller, single-seat valves with higher net reliability than the two-seat scheme generally favored for comparable hydrazine thrusters. This results from an inadvertent benefit inherent to specific properties of ionic liquid propellants. Being typically more viscous than hydrazine, AF-M315E propellant is intrinsically far less prone to leakage, such that the added cost and doubled risk of a thruster becoming inoperable in the event of either of two redundant stages failing closed is not justified. Moreover, having essentially no vapor pressure, true ionic liquids will not self-pressurize or evaporate through small fissures such as a flaw in a valve seat. In the very unlikely event that thruster valve leakage should occur, isolation of the downstream feed system by closing an upstream system latch valve will fully prevent any loss of propellant. Likewise for launch range operations, the innate safety of ionic liquid propellants, accounting for both their low vapor toxicity and inability to activate un-preheated thrusters or react with external system and immediate work environment materials (unlike hydrazine), obviates conventional rationale for the use of dual-seat thruster valves. Thus, single seat valves provide higher mission assurance at lower mass, power (partially offsetting added preheat power requirements), and cost. Further, the resulting compactness of the GR-1 and GR-22 designs facilitates integration within the close packaging of small spacecraft where the high ρI_{sp} offered by ionic liquid propellants is most advantageous. Single seat valves have actually been used on many hydrazine-propelled spacecraft, and particularly NASA missions such as Cassini, Deep Impact, New Horizons, and Voyager (still successfully operating since its launch in 1977). Note, however, that unlike these examples, range safety has not required the addition of a secondary upstream latch valve to compensate for the loss of redundant leak inhibits on the thrusters for the GPIM demonstration, owed the inherent safety characteristics of the propellant.

As previously published[10], between June 5 and October 8, 2014, GR-1 and GR-22 prototypes were subjected to a three sequential test phases under the GPIM program:

Phase 1: Extended Acceptance Test Procedure Hot-fire – Basic functional and stability verification as planned for flight unit acceptance testing, followed by performance mapping over a broad range of duty cycles.

Phase 2: Vibration Testing – Conducted on three spacecraft reference coordinate axis.

Phase 3: Protoflight Hot-Fire Test – Extended performance characterization, followed by a life accumulation segment comprising alternating pulse-mode health-check and 20-min steady-state burns.

The GR-1 prototype was tested through approximately 3× planned demonstration mission life, corresponding to 4.47 kg total propellant throughput out of an estimated life capability of 12 kg (based on prior testing of functionally-equivalent heavyweight test units). Testing of the GR-22 prototype proceeded through Phases 1 and 2 without incident, but was terminated at approximately 3 kg accumulated propellant throughput (out of an estimated 15 kg total life capability) when a crack was detected in the thrust chamber. Both thrusters exhibited close-to-predicted thrust, I_{sp}, and start-up response characteristics, as well as high pulse-to-pulse repeatability.

A. GR-22 Recent Developments

Post-test inspection of the test article and refined thermal analysis conclusively revealed the cracking of the GR-22 chamber body observed during prototype testing to be the result of low-cycle thermal fatigue induced by steep temperature gradients in the vicinity of injectant impingement points against the chamber wall. In response, Aerojet Rocketdyne initiated an internal development effort to implement a combination of corrective design upgrades. A comprehensive verification hot-fire test plan for the updated design was developed in conformance with three primary test objectives, summarized as follows:

Objective 1: Verify successful mitigation of low-cycle thermal fatigue susceptibility – In order to accomplish highest confidence verification of robustness of the upgraded thruster design against the structural failure mode that precipitated early termination on the GPIM prototype test program, the same test plan was executed up to the point where the prior failure occurred to verify that the upgraded design can successfully complete the duty cycle sequence that precipitated prior thruster failure without adverse result

Objective 2: Verify duty-cycle-unlimited operability – The broad range of duty cycles successfully executed by the GR-1 and GR-22 during prototype testing on the GPIM program provided high confidence of duty-cycle unlimited operability for both thrusters with respect to thrust stability, thermal performance, and structural integrity. For the GR-22 corrective design effort, unlimited duty-cycle operability, as similarly verified, was retained as a key functional requirement necessary to ensure broad utility of the product line.

Objective 3: Determine life capability of current GR-22 design – The chamber structural failure encountered during GPIM prototype testing preempted achievement of the program's 7 kg propellant minimum throughput goal for the GR-22 thruster; thus this objective was carried forward among the success criteria established for the corrective design and test effort.

1. *Test Results*

Oct. 21-22, 2015 hot-fire testing of the upgraded GR-22 prototype 1010 pulses interspaced with twenty steady-state burns met all primary objectives. All tested pulse modes of operation, summarized by operating pressure, commanded pulse width, and duty cycle in Table 2, completed without indication of chamber pressure or other instability. Importantly, the thruster completed all tested modes of operation without indication of thermal-fatigue-induced damage to the thrust chamber. The thruster accumulated approximately 7.5 kg of propellant throughput before reaching the end-of-life criterion (defined as the point where chamber pressure roughness consistently exceeded ±50%. While moderately exceeding the >7 kg GPIM program-derived objective, that the achieved throughput life represents a substantial reduction compared to that demonstrated by earlier tested functionally-equivalent heavyweight test units provides important insights into the mechanisms that drive aging of the catalyst over thruster life.

Table 2. Pulse-mode thruster operated feed pressure (psia) vs. commanded pulse width and duty cycle.

	Duty Cycle										
Pulse Width (sec)	1%	2%	3%	4%	5%	9%	25%	50%	70%	80%	90%
0.016										425	
0.02	100			425							
0.05	100	100									
0.08		100	100								
0.1	100	100			425						
0.5						Multiple	425	425	425		
0.7											
0.9											425

The apparent key differentiator between the life achieved by the revised flight thruster and its heavyweight predecessors is perhaps best elucidated by examining the rate of onset of roughness (defined as two times chamber pressure standard deviation, σ) over the course of accumulated throughput, as plotted in Fig. 4. Because computed roughness is generally significantly higher for pulsed vs. steady-state operation, data corresponding to each operating mode are differentiated in the figure to facilitate interpretation. The data clearly show that for the first 2.5 kg of throughput, comprising a variety of short-to-medium-length (<30 sec) pulse-mode and steady-state test sequences, chamber pressure roughness remained very low, generally >1% and > 10% for steady-state and pulse modes of operation, respectively. Thereafter, however, rapid onset of roughness is observed – notably during a single extended test segment of 600 half-second pulses at 50% duty cycle. Providing strong indication that operation at this duty cycle substantially accelerates catalyst attrition, chamber pressure roughness is seen thereafter to progress through various periods of partial attenuation and resurgence until ultimately reaching the consistently >50% end-of-life condition even in extended steady-state operation at approximately 7.5 kg. It follows that significantly greater life may be expected where operations do not emphasize this duty cycle.

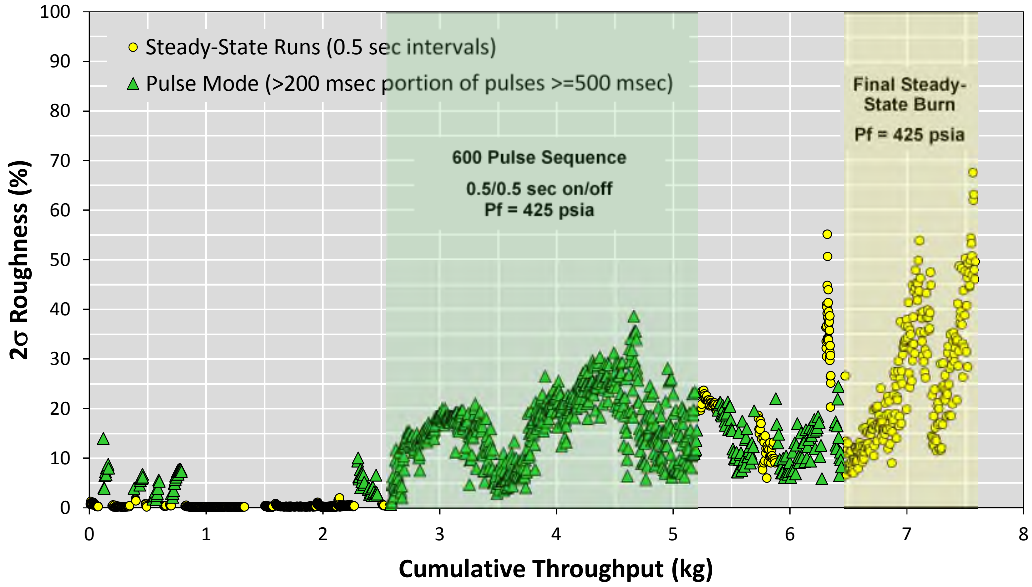

Figure 4. Roughness vs. cumulative propellant throughput.

The greater attrition of the 0.5/0.5 sec on/off duty cycle on the thruster catalyst bed is further illustrated in Fig. 3, where plots of recovery pressure traces taken by a pitot probe directed into the thruster provide a direct comparison of chamber pressure roughness just before (shown in orange) and following (shown in blue) the 600-pulse sequence. Traces corresponding to operation at high and low feed pressures are shown (High: Sequences 17 and 32, Low: Sequences 27 and 37, representing beginning-of-life and end-of-life operating points for a typical high blow-down ratio mission). The before vs. after difference in thruster performance is striking, and, equally informatively, not observed in testing of the lower-thrust-density GR-1. Hence a key insight relevant to ongoing efforts to scale AF-M315E to higher thrust classes has been gained. The test result also reinforces conclusions drawn as the result of Aerojet Rocketdyne's investigation regarding the root cause of the chamber structural failure encountered during GPIM program testing of the predecessor prototype at the very same duty cycle, as it is now clear that the increased rate of void growth within the catalyst bed would have been accompanied by commensurate augmentation of propellant impingement against, and thermally-induced strain in, the thrust chamber wall.

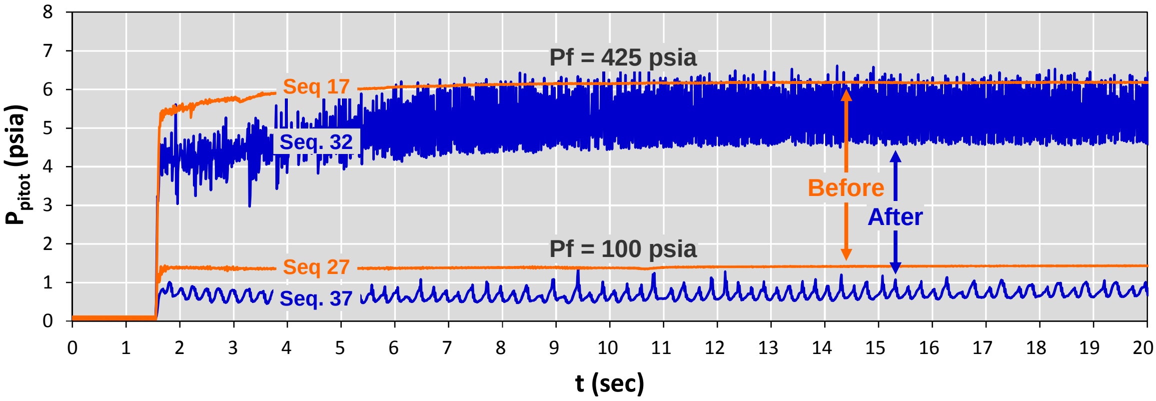

Figure 3. Steady-state pitot probe traces before and after 600-Pulse 0.5/0.5 Sec on/off sequence (31).

2. *Next Steps*

With the GR-22 corrective design effort having demonstrated complete resolution of the low-cycle thermal fatigue issue of its predecessor, ongoing efforts will focus on three areas of development necessary to achieve broad mission utility. Firstly, significant augmentation of the thruster's throughput life capability is essential.

Auspiciously, it is anticipated that substantial life enhancements demonstrated even as recently as since completion of the revised GR-22 test effort on the GR-1 1-N thruster (discussed below) can be leveraged to achieve similar gains for the GR-22. Secondly, further test data analysis reveals the need for improved thermal isolation of the thruster control valve to address increases in heat soak-back from the thrust chamber observed to set in as chamber pressure roughness grows over thruster life. Thirdly, feedback consistently received from candidate industry users underscore reduced cost as critical to achieving market competitiveness with Aerojet Rocketdyne's well-established conventional hydrazine product offerings. Here again, promising producibility improvements currently being implemented on the GR-1 thruster auger commensurate collateral benefits for the GR-22.

B. GR-1 Recent Developments

At 27 kN-sec demonstrated total impulse life, the GR-1 thruster design represents a mission-ready green technology statistically capable of meeting the operational requirements of approximately 50% of applications typically performed by conventional hydrazine. However, high unit production cost, principally driven by the thruster's refractory metal construction necessary to withstand the high flame temperature of the AF-M315E propellant, remains an appreciable obstacle to full realization of the benefits offered by high-performance green propulsion. In response, Aerojet Rocketdyne recently undertook a comprehensive design-for-manufacture activity whereby were identified a series of both design and process improvements yielding a combined potential of as much as a 50% cost reduction compared to the original GR-1 point-of-departure baseline. In particular, aspects of the present construction approach accounting for the greatest opportunity comprise:

- Options to improve the manufacturability of the catalyst bed heater.
- Design and manufacture alternatives for the refractory metal thrust chamber.
- Modification of the refractory thrust chamber support structure to facilitate fabrication from lower cost raw materials stock while requiring less machining.
- Simplification of the injector integration approach.
- Replacement of complex heat shields with parts made from cut-foil
- Catalyst materials and manufacturing process development

Under a Space Act Agreement, a series of screening tests of heavyweight development test articles are being conducted by NASA Glenn Research Center to assess various configuration options potentially affecting thruster stability margin and life capability in addition to manufacturability. Drawing on the same methodology earlier employed to carry out efficient evaluation of candidate thruster material system and design options in the original GR-1 development effort, these tests combine an initial broad series of stability assessments to verify duty cycle independent operability with an expedited life-accumulation segment comprising steady-state operation at full thrust with pulse-mode health-check sequences interspersed at five-minute intervals until the 50% end-of-life criterion is reached. In so doing, down-selection between competing design alternatives can be accomplished much more quickly and cost effectively than were a more flight-like duty cycle implemented for each configuration of interest. Enhancing the information that can be learned from a single two-week test series, the test article allows for variation of certain design parameters cyclically throughout testing, such that the performance of multiple sub-variants of a single configuration can effectively be characterized simultaneously over the life of a single catalyst bed.

In addition to functional verification of proposed cost-saving revisions to the thruster core architecture, results obtained from the first configurationally test article have already yielded invaluable insights potentially providing a path to substantially increased life capability compared to the GPIM thruster design. Notably, the sub-variants tested were essentially indistinguishable at the beginning of life, demonstrating <5% roughness. However, whereas roughness growth of up to 35% has been demonstrated to date by various tested sub-variant configurations, roughness for the best performing sub-variant, presented in Fig. 5, as remained below 20% for the same amount of accumulated total propellant throughput. Thus, while all tested cases have already exceeded the total impulse capability of the GPIM design by >40% with more to go, the data suggest additional optimization of the design may offer an avenue for greater life extension still. Sample chamber pressure traces taken at various points throughout the test and normalized by average steady-state value are provided for further illustration in Fig. 6.

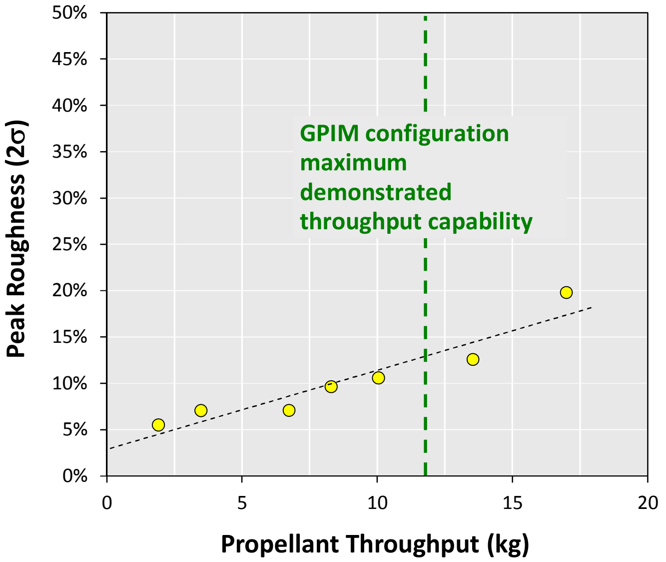

Figure 5. Roughness vs. accumulated propellant throughput for best-performing sub-variant configuration.

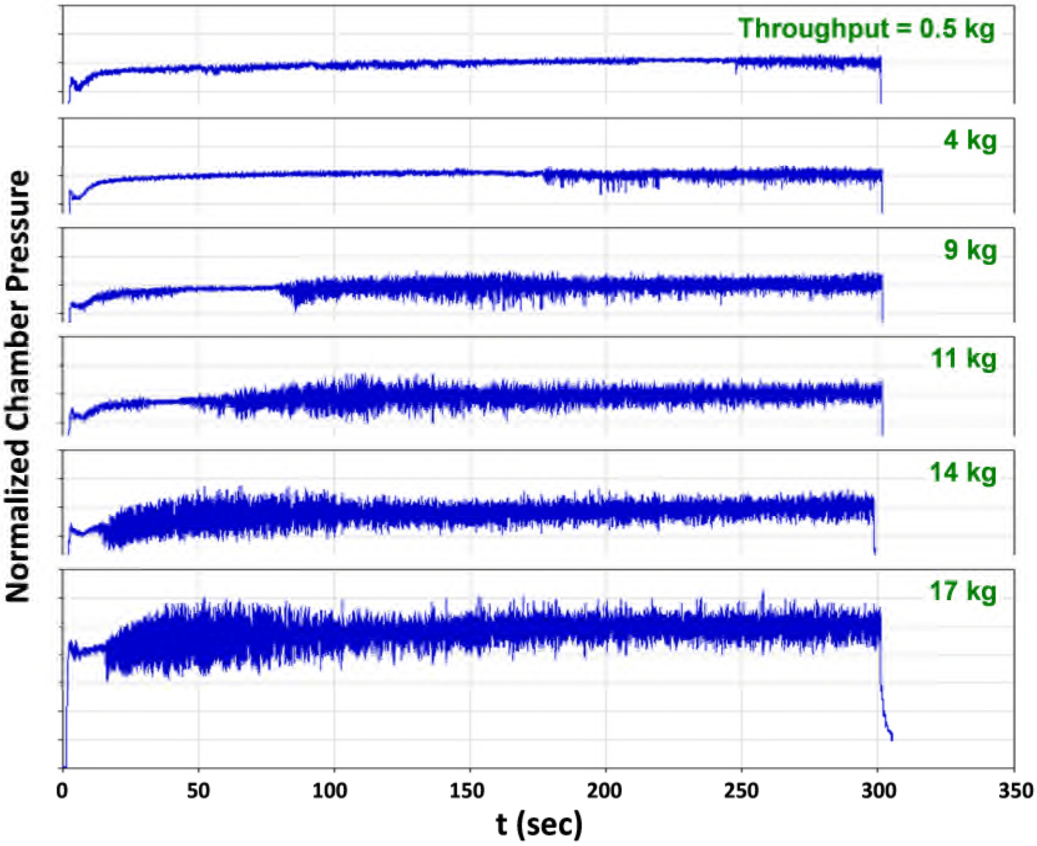

Figure 6. Normalized chamber pressure traces at various levels of cumulative propellant throughput for best-performing sub-variant configuration.

At present testing has been temporarily suspended to accommodate routine facility maintenance at the NASA Glenn test site. Completion of hot-fire testing through end-of-life of the first test article is scheduled to resume in August 2016, to be followed by similar testing of up to two additional configurations. While invaluable for cost-effective screening of material and design alternatives, the expedited life test approach likely well under-predicts the total impulse likely achievable under more flight-like operating conditions. In particular demonstrated increases in life associated with throttling to lower thrust density portend appreciable increases in total delivered impulse may be realized through operation over the typical blow-down operating scheme employed by most monopropellant propulsion systems. Following implementation of the enhanced design principles being developed under the present laboratory thruster test activity, a more flight-like life test program is planned for 2017 qualification testing of the resulting upgraded flight thruster design, also to be conducted at NASA GRC.

C. Advancing AF-M315E CubeSat Technology

Even as final preparations are in work for the first flight demonstration of AF-M315E high-performance green monopropellant technology on NASA's Green Propellant Infusion Mission program, in 2017, key strides are being made in the development of even more capable next generation AF-M315E thrusters. Recently completed testing has verified successful resolution of life-limiting low-thermal-cycle fatigue issues encountered during development of the GR-22 thruster on the GPIM program, such that infusion of AF-M315E into 22-N thrust class applications now principally awaits the completion of needed enhancements in affordability and thruster total impulse life capability to close the gap with heritage hydrazine counterparts. Such enhancements are potentially near-term to what extent can be leveraged advances currently being made toward same objectives for the similar 1-N GR-1 thruster. At the beginning of 2016 Aerojet Rocketdyne initiated a two-year planned effort aimed at reducing cost of the GR-1 by 50% by implementing a series of identified design revisions for improved manufacturability. Laboratory thruster hot-fire testing currently ongoing at NASA Glenn Research Center under a Space Act Agreement has already validated a number of candidate configuration options of interest while demonstrating >40% increased thruster total impulse life. Efforts are also underway to mature CubeSat AF-M315E green propulsion technology for a flight demonstration readiness in 2018.

V. Conclusion

Even as final preparations are in work for the first flight demonstration of AF-M315E high-performance green monopropellant technology on NASA's Green Propellant Infusion Mission program, in 2017, key strides are being made in the development of even more capable next generation AF-M315E thrusters. Recently completed testing has verified successful resolution of life-limiting low-thermal-cycle fatigue issues encountered during development of the GR-22 thruster on the GPIM program, such that infusion of AF-M315E into 22-N thrust class applications now principally awaits the completion of needed enhancements in affordability and thruster total impulse life capability to close the gap with heritage hydrazine counterparts. Such enhancements are potentially near-term to what extent can be leveraged advances currently being made toward same objectives for the similar 1-N GR-1 thruster. At the beginning of 2016 Aerojet Rocketdyne initiated two-year planned effort aimed at reducing cost of the GR-1 by 50% by implementing a series of identified design revisions for improved manufacturability. Laboratory thruster hot-fire testing currently ongoing at NASA Glenn Research Center under a Space Act Agreement has already validated a number of candidate configuration options of interest while demonstrating >40% increased thruster total impulse life. Efforts are also underway to mature CubeSat AF-M315E green propulsion technology for a flight demonstration readiness in 2018.

VI. Acknowledgments

The authors gratefully wish to thank NASA Glenn Research Center for outstanding diligence in the performance of laboratory thruster testing; the NASA Space Technology Mission Directorate for contribution of GPIM program surplus hardware ad catalyst for use in test articles, as well as funding provided for CubeSat green propulsion development as part of the "Tipping Point" initiative; and the AFRL for provided propellant and invaluable technical expertise.

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