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GPIM AF-M315E Propulsion System

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The NASA Space Technology mission Directorate's (STMD) Green Propellant Infusion Mission (GPIM) Technology Demonstration Mission (TDM) will demonstrate an operational AF-M315E green propellant propulsion system. Aerojet-Rocketdyne is responsible for the development of the propulsion system payload. This paper statuses the propulsion system module development, including thruster design, system design and system component materials compatibility testing. Major system components of the propulsion system module include: propellant tank, latch valve, service valve and thruster valve. All system components, except the thruster valve, are flight proven (TRL 9) for hydrazine propellant; Status is given on modifications of these components to ensure that all internal wetted surfaces are compatible with the AF-M315E propellant.

The culmination of this program will be high-performance, green AF-M315E propulsion system technology at TRL 7+, with components demonstrated to TRL 9, ready for direct infusion to a wide range of applications for the space user community.

Nomenclature

EM	=	Engineering model
ESPA	=	EELV secondary payload adapter
GPIM	=	Green Propellant Infusion Mission
HAN	=	Hydroxyl ammonium nitrate
I_{sp}	=	Specific Impulse
IHPRPT	=	Integrated High Payoff Rocket Propulsion Technology
SCAPE	=	Self-Contained Atmospheric Protection Ensemble
TRL	=	Technology Readiness Level

I. Introduction

For four decades, monopropellant hydrazine systems have been the dominant propulsion technology for low-total-impulse applications; however, expensive storage, handling, and disposal procedures are required to address the propellant toxicity and flammability hazards, which, though well established, continue to hinder efforts to reduce mission integration costs and schedule. While traditional green alternatives such as cold gas and electric propulsion may reduce schedule and cost impacts, their limited specific impulse and thrust respectively preclude their application to missions requiring high total impulse and/or thrust. As such, the last decade has seen a growing awareness that the development of a low-toxicity alternative offering performance better than hydrazine would yield substantial crosscutting benefits to NASA and all space users. Toward this objective, the NASA Space Technology Mission Directorate (STMD) has initiated the Green Propellant Infusion Mission (GPIM) program with the objective of completing the first on-orbit demonstration of a complete AF-M315E high-performance (+50% density–I_{sp} compared to traditional hydrazine) green propellant propulsion system by the end of 2015. Hosted on a Ball Aerospace BCP-100 ESPA-class spacecraft bus, the GPIM Technology Demonstration Mission (TDM) will employ an Aerojet-developed advanced monopropellant payload module as the sole means of on-board propulsion,

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performing a comprehensive battery of performance characterization and capabilities assessment maneuvers using both 1N and 22N thrusters[1,2,3,4,5]. The 1N and 22N thrust classes representing the largest segments of the monopropellant thruster market, see Figure 1). Although current planning calls for the on-orbit segment of the TDM to be completed within three months, the specific intent of the GPIM program is to advance AF-M315E technology to a readiness level suitable for immediate infusion in both short-duration and extended near-future applications. The propulsion system under development incorporates principally heritage hydrazine system components selected for the long-duration compatibility of their materials of construction with the new propellant.

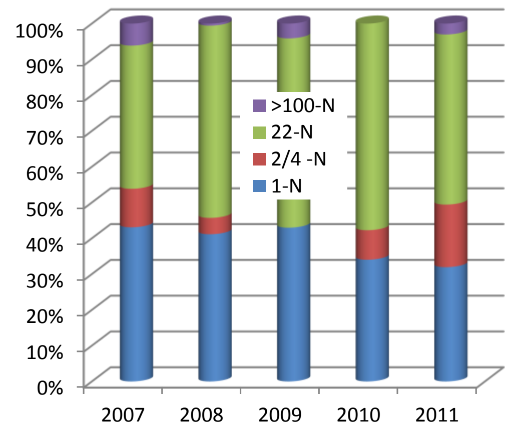

Figure 1 Market share by thrust level, 2007-2011

Aerojet Rocketdyne's commitment to green propulsion has spanned two decades and a wide range of propellant options. Initial experience was gained with HAN/glycine and HAN/methanol formulations[6]. Shifting focus to AFRL-developed AF-M315E ionic liquid advanced monopropellant in 2001, Aerojet Rocketdyne's green thruster technologies had matured to TRL5 by 2011, meeting the IHPRPT Phase II objective of 50% increased density-Isp over conventional hydrazine equivalents. Unique among a number of hydrazine alternatives that have emerged in recent years, AF-M315E is sufficiently green to enable safe handling in open containers for unlimited durations, whereas the properties and/or handling hazards (such as super-atmospheric vapor pressure or necessary stabilizers which may evaporate) of other current low-toxicity candidates preclude this. The summation of numerous development efforts and programs over many years, 2011 saw the first successful demonstration of more than 11.5 hrs firing life by an AF-M315E thruster employing a breakthrough patent-pending high-temperature catalyst (operated at near full thrust throughout), heralding readiness for infusion into a wide range of NASA, DoD, and commercial missions.

II. Payoff to NASA, Commercial and DoD Missions

NASA science missions place a special premium on performance, cost, robustness, and thermal requirements, all of which are enhanced by the use of GPIM's AF-M315E propulsion technology. AF-M315E offers higher performance than hydrazine, yields 12% higher I_{sp} (257 vs. 235 sec), and is 45% more dense (1.47 vs. 1.00 g/cc), affecting both reduced propellant and tank mass. A recent study showed significant benefits could be realized by using a high-performance, long-life hydrazine replacement for all of the three principal mission recommendations of the New Worlds, New Horizons in Astronomy and Astrophysics Decadal Survey (WFIRST, LISA, and IXO).[7] The study found that an AF-M315E system would reduce the propellant mass of WFIRST by >160 kg, about 10%, with a corresponding reduction in system dry mass (due to reduced tankage) of >30%. Other case studies in the report illustrate similar percent-wise benefits for missions in lower energy HEO and LEO orbits. Aerojet Rocketdyne estimates that an AF-M315E-based descent stage on the Mars Science Laboratory would have enabled 58 kg increased landed mass for the 930-kg rover compared to the hydrazine system that was flown. In addition to reduced test and loading costs owed to its low toxicity, AF-M315E simplifies the safe design and development of propulsion systems compared to hydrazine. Since leakage of AF-M315E is rated as a critical rather than catastrophic failure, 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].

With its lower minimum temperature threshold, AF-M315E yields an additional advantage of 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 has a glass transition). 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 to planetary spacecraft and planetary ascent vehicles, which 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; 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 has a significantly reduced sensitivity to adiabatic compression than hydrazine.

AF-M315E also offers comparable performance (density–I_{sp}) 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.

The cost savings of green propellants associated with 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 Centaur RCS on an Atlas launch vehicle concluded ground support costs of fueling could be reduced by two-thirds[9].

III. GPIM Propulsion System

Under development as a self-contained module to allow independent assembly at Aerojet Rocketdyne for subsequent integration into the bus, the GPIM demonstration payload, illustrated in Figure 3 and shown in schematic in Figure 2, will deliver 50% more impulse than a comparably-packaged hydrazine system. Designed to attach to the Ball Aerospace BCP-100 bus via its standard payload interface plate (PIP), the GPIM demonstration payload comprises a simple, single-string, blow-down AF-M315E advanced green monopropellant propulsion system employing four 1N attitude-control thrusters and a single 22N primary divert thruster. The propellant feed manifold's principal components, consisting of a standard diaphragm propellant tank, latch valve, and service valves, represent all flight-proven (TRL 9 with hydrazine propellant) designs selected specifically for the long-term compatibility of their materials of construction with AF-M315E. Redundant pressure transducers monitor gas-side propellant tank pressure (and hence propellant consumption). Thrusters are mounted on the upper deck of a box-like payload primary structure. The 22N primary divert thruster is mounted on the spacecraft centerline with the thrust axis pointed through the PIP-mounted propellant tank and spacecraft centers of mass. The four 1N thrusters are

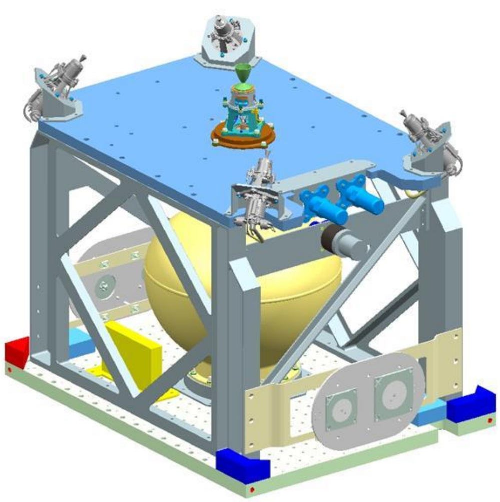

Figure 3 AF-M315E Propulsion System

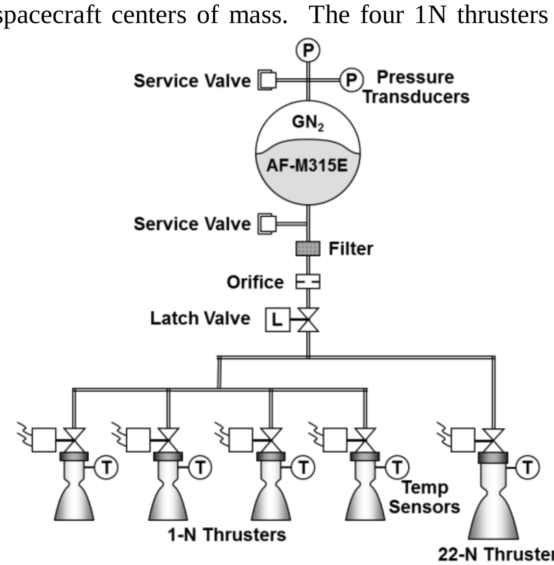

Figure 2 Propulsion System Schematic

canted on brackets at the corners of the upper deck to maximize the moment arm to the spacecraft center of mass, and thereby control authority and resolution of impulse measurement by the bus attitude and orbit determination and control (AODC) sensors. The remaining propulsion system components are consolidated on a component panel attached to the underside of the upper deck, except for the two service valves, which mount to a separate bracket positioned for easy access during fueling and range operations.

Design considerations for the AF-M315E propulsion system are mostly similar to a traditional hydrazine system, with a few special considerations. Principally, all system components must be compatible with AF-M315E, and therefore system component selections must strongly take compatibility into account, especially for longer duration missions. As the general schematic layout is identical to single string blow-down hydrazine systems commonly employed on small spacecraft, many of the same general design guidelines apply. The AF-M315E system however, is far less hazardous than a traditional hydrazine system when considering range safety requirements. The propellant is far less prone to leakage (due to higher viscosity), is non-toxic if leaked, and the thrusters cannot inadvertently fire without having first preheated catalyst beds. Initial discussions with KSC range safety personnel have consequently indicated the likely eventual acceptance of a reduced hazard severity classification of “critical” and possibly even “marginal” per MIL-STD-882E (Standard Practice for System Safety). In contrast, hydrazine external leakage is ranked a “catastrophic” hazard rating. Per Range Safety AFSPCMAN 91-710 requirements, a classification of “critical” or less only requires a two-seal inhibits to external leakage; hence no additional latch valves other isolation device are required in the feed system despite the fact that the advanced monopropellant thrusters employ only single-seat valves (for reasons that will be explained in Section IV). This approach reduces the complexity, power, and mass of the thruster valve, while simplifying electrical interfaces, all without sacrificing mission reliability.

Other differentiating design considerations arise principally from differences in the thermal characteristics of AF-M315E vs. conventional thrusters. Due to the advanced monopropellant thrusters’ elevated minimum start temperature, catalyst bed preheat power requirements are higher compared to a conventional hydrazine system. This increase is partially offset, however, by the reduced power needs of the thrusters’ single seat valves, as well as much lower power required for system thermal management during non-operating periods enabled by the propellant’s demonstrated storage stability very low temperatures (although current CONOPS for the GPIM mission call for the propellant to be maintained within nominal system operating range). Radiation and conduction from the advanced monopropellant thrusters’ high temperature chambers also impart a moderate increase in the thermal load to the system mounting interface.

IV. AF-M315E Green Advanced Monopropellant Thrusters

The Aerojet Rocketdyne 1N (GR-1) and 22N (GR-22) advanced monopropellant thrusters to be employed on GPIM represent the culmination of over two decades of research, spanning the development of enabling high-temperature test and data acquisition techniques applied to testing of a number of candidate propellants, extensive evaluation and test of numerous material systems for structural components and catalysts, and thruster performance characterization ranging from less than one up to 670 N (150 lbf) thrust in both sea-level and vacuum environments. Throughout a large portion of over two decades of research, inherently high reaction temperatures associated with ionic liquid propellants, coupled with poorly understood ionic-liquid thruster stability dynamics, constrained both thruster life and operational duty cycle capabilities. The last several years, however, have yielded significant breakthroughs related to both materials and a fundamental understanding of the governing mechanics of ionic liquid thrusters necessary to design and fabricate robust, practical (duty-cycle-unlimited) thrusters with sufficient life capability to meet real mission needs. A key, albeit by no means exclusive, contributor to the rapid acceleration in maturation of AF-M315E thruster technology seen in recent times has been the advent of Aerojet’s patent-pending LCH-240 high-temperature long-life catalyst, demonstrating sufficient endurance within the propellant’s decomposition/combustion environment to extend thruster life over 15× compared to the prior state-of-the-art.

The GR-1 and GR-22 advanced monopropellant thrusters implement a common design strategy whereby the use of refractory alloys (to accommodate the flame temperature of the AF-M315E propellant) is confined to the thrust chamber, nozzle and an upper thermal isolation structure, such that much of the thruster can be fabricated with conventional alloys in common use on hydrazine thrusters today. Trade studies indicate this hybrid approach yields significant respective cost and power savings compared to evaluated alternatives entailing either all-refractory or bulkier, heavily-insulated conventional alloy construction. The resulting flight thruster designs, shown side-by-side for comparison in Figure 4, comprise a series-assembled valve, injector, catalyst-containing chamber, and nozzle bearing general resemblance to conventional catalytic hydrazine thrusters of corresponding thrust classes, with two readily notable differences.

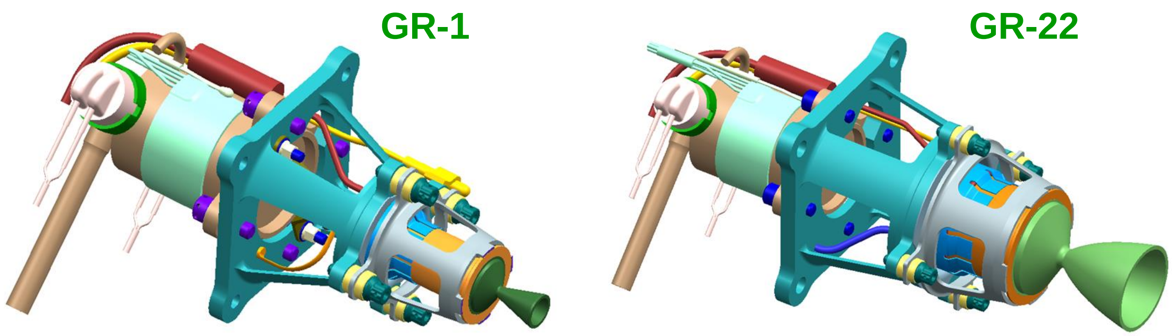

Figure 4 Aerojet GR 1 and GR 22 Thrusters

Most immediately apparent are the extended two-piece stand-off structures employed by both designs. These provide additional thermal isolation serving the dual roles of preventing overheating of the spacecraft interface by heat soak-back from the chambers during and following extended thruster firings, as well as limiting heat loss from the catalyst bed during thruster preheating, thereby minimizing power necessary to preheat the catalyst bed to the nominal start temperature. The stand-off structure employs a bolted mechanical joint as the primary interface between refractory and lower-temperature-capable conventional alloys, wherein a series of thermal spacers provide an efficient means to achieve the high temperature step-down necessary to implement a compact, highly thermally isolating, assembly. In accordance with engineering best practices, the GR-1 and GR-22 thruster designs incorporate redundancy on all fracture-critical structural elements, including both portions of the mounting structure and thermal stand-off and their conjoining fasteners (as well as at the control valve-to-thruster, and thruster-to-spacecraft mechanical interfaces). As dynamic load specifications imposed for both thrusters comprise up-to-date composite spectra developed by Aerojet to ensure broad utility of new/upgraded hydrazine thrusters designs, the GR-1 and GR-22 will be readily infusible into most applications likely to employ conventional monopropellants.

The GR-1 and GR-22 thrusters also 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 the ionic liquid propellant. Being more viscous than hydrazine, AF-M315E is intrinsically far less prone to leakage, such that the doubled risk of a thruster becoming inoperable in the event of either of two valve stages becoming inoperable is not justified. Moreover, having essentially no vapor pressure, AF-M315E will not self-pressurize or evaporate through small fissures such as a flaw in a valve seat, such that, in the very unlikely event that thruster valve leakage should occur, isolation of the downstream feed system by closing the upstream system latch valve would fully prevent any loss of propellant. Likewise for launch range operations, the innate safety of the propellant, accounting for its low vapor toxicity, and inability to activate un-preheated thrusters or react with external system and immediate work environment materials (unlike hydrazine), obviates the 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 solution for the GPIM and future missions. Further, the added compactness of the GR-1 and GR-22 designs realized through the selection of single-seat valves has proven substantially facilitating in the close packaging of the GPIM demonstration system module, portending similar benefits to future ESPA-class spacecraft. Note that single seat valves have been used on many hydrazine-propelled spacecraft, and particularly prior NASA missions such as Cassini, Deep Impact, New Horizons, and Voyager (still successfully operating since its launch in 1977).

Technically, it is possible to complete the GPIM demonstration's planned three-month on-orbit life using conventional hydrazine thruster valves. Nevertheless, with a view to maximizing immediate infusability of the technology into both short-duration and extended missions, AF-M315E-specific material compatibility requirements (which differ from hydrazine) have been addressed in the selection of control valves for the GR-1 and GR-22 thrusters. Unlike for the upstream GPIM propellant feed system, where it was possible to simply select flight-heritage hydrazine components readily usable with AF-M315E with little or no modification, no such option exists for these new thrusters. In particular, as a mild acid, AF-M315E demonstrates long-term compatibility with a limited set of metals, none of which are ferromagnetic. Thus, the GR-1 and GR-22 thrusters employ largely new valve designs incorporating AF-M315E compatible wetted surfaces. The valves still derive considerable design and manufacturing process heritage from flight-proven products. Indeed, the GR-1 and GR-22 valve designs leverage existing process capabilities developed specifically for other applications necessitating isolation of valve ferromagnetics from working fluids.

The ongoing GPIM flight thruster development effort is structured in three overlapping phases. The first will execute early (June 2013) sea-level testing of heavyweight hardware derived from parallel preliminary flight thruster design activities. This testing will first perform duty cycle mapping of (principally the 22-N) thruster over a comprehensive range to verify broad functional stability, thereafter to anchor thruster life models as operated at duty cycles and simulated feed pressure blow-down ratio closely approximating projected mission performance requirements. Extensive thermal instrumentation will also yield detailed data to be used to anchor thermal models and optimize flight-thruster designs. Guided by test results, flight thruster designs will be completed in Phase 2. Engineering models (EM) of both the 1N and 22N thrusters will be fabricated and incorporated into a breadboard feed system functionally equivalent to the GPIM flight propulsion module for high-altitude protoflight testing. In Phase 3, flight designs will be finalized and flight (one each) qualification units fabricated. All thrusters will undergo standardized acceptance testing, comprising shock, vibration, and a check-out hot-fire. Qualification units will thereafter be subjected to qualification-level shock and vibration loads, followed by a mission-representative life test. On orbit, the thrusters will perform a series of maneuvers designed to both fully characterize thrust, Ibit, specific impulse, and thermal performance over a variety of duty cycles intended to encompass the full needs of near-future space applications.

Thruster Performance

Designed as functional alternatives to Aerojet Rocketdyne's 1N class MR-103G and 22N class MR-106L, thrust vs. feed pressure characteristics for the GR-1 and GR-22 are presented in Figure 5, with key operating metrics summarized in Table 1.

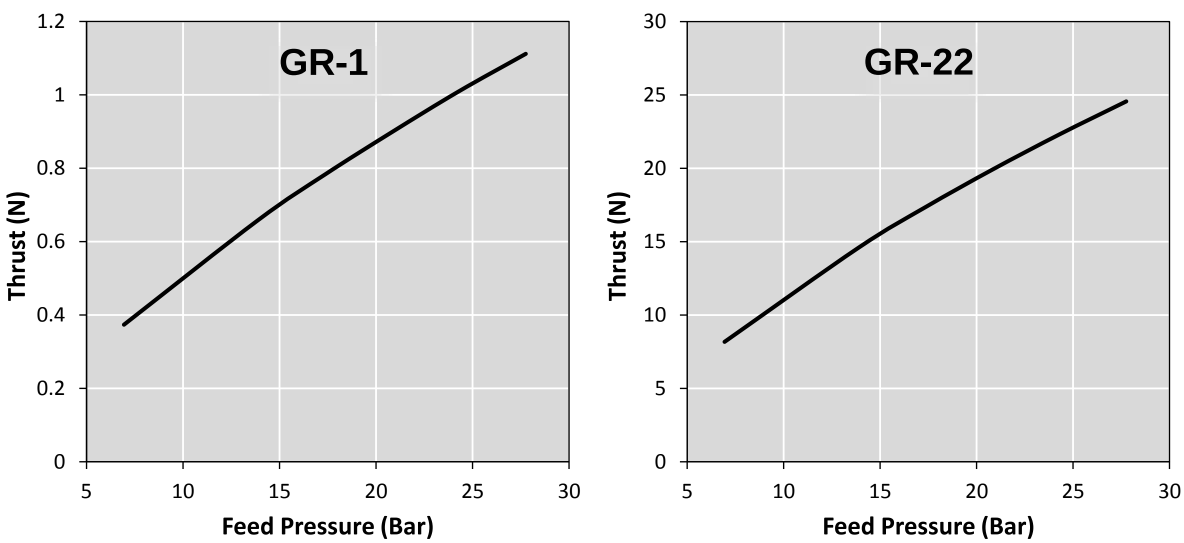

Figure 5 Aerojet Rocketdyne GR-1 and GR-22 Thrust vs. Feed Pressure

Table 1 Thruster Predicted Performance Summary

	GR-1	GR-22
Thrust (N)	0.4 - 1.1	8 - 25
Feed Pressure (bar)	6.8 - 27.6	6.8 - 27.6
Nozzle Expansion Ratio	100:1	50:1
Valve Power (W)	12	28
Preheat Power (W)	10	30
Specific Impulse (s)	235	250
Total Impulse (N-s)	23,000	74,000
Minimum Impulse Bit (mN-s)	8.0	116

V. Materials Compatibility Testing

AF-M315E propellant is acidic which can result in leaching of some common aerospace materials with long term propellant exposure. In addition, this fuel can act as both a reducing agent or as an oxidizing agent, so establishing metal passivation is more difficult than for pure reducing (hydrazine) or pure oxidizing (nitrogen tetroxide) propellants. Laboratory studies of this propellant inevitably show that for some test materials, it leaches metal ions. Nonetheless, safe, long-term storage of AF-M315E propellant in metallic and non-metallic tanks has been demonstrated[10]. For service components – valves, filters, elastomers, and lubricants – there is a small, but growing set of materials where laboratory testing indicates sufficient compatibility for at least 3-5 year missions[11].

A major effort of the GPIM program is to mature and qualify all AF-M315E propulsion system components for this mission, and for infusion on future space missions. An extensive materials compatibility test campaign is currently underway to confirm that all materials in system components that are wetted with the AF-M315E propellant are fully compatible, or material replacement of known incompatibles. The thruster valve requires the most extensive modifications to ensure it is AF-M315E compatible. All wetted surfaces for the thruster valve, service valve, latch valve and propellant filter will be manufactured from materials which are fully compatible with this propellant. The service valves being updated requires minor changes to all the sealing subcomponents. The latch valve is being evaluated to determine if any modifications to its materials is required. The system filter is the only system component that does not require any changes since its propellant wetted surfaces are already compatible.

Preliminary tests at elevated temperature revealed that the propellant tank elastomeric material met AMS-R-83412A specification requirements for compatibility. A longer term exposure test is currently being performed to determine any decrease in material functional properties and metal leaching profile over time. Latch valve components in test are: poppet seal, spring, and torque tube. For the service valve, the ball seal material, and back-up-ring are in test. The thruster valve seal elastomer material, is likewise in evaluation. In the very near future, common component materials, O-ring material and lubricants will be tested.

VI. Technology Maturation Status

As can be seen in the propulsion system schematic of Section III, AF-M315E-based advanced monopropellant systems are functionally equivalent to hydrazine systems, comprising the same number and type of components, but are distinct in that the different propellants have different material compatibilities. Historically AF-M315E and similar propellants have suggested only short duration compatibility with many common aerospace materials[12]. However, more recent accelerated aging tests performed under contract on Aerojet's Post-Boost program indicate AF-M315E to have similarly good long-term compatibility with a wider range of common aerospace materials, such that a large portion of existing flight-proven components are suitable for use with AF-M315E, although some elastomers (e.g. valve seats) may still require substitution (Component TRL status and required modifications are tabulated in Table 2). The available data provide high confidence that appropriately-selected flight-proven hydrazine components represent a low-risk option for the proposed TDM, and likely for future missions of at least five years and potentially longer. Feed systems similar to that planned for the proposed TDM are currently regularly flown in monopropellant and bipropellant applications where contamination by conventional propellants from propellant lines and components represents an unacceptable mission risk, such as A2100 and the Solar Dynamics Observatory spacecraft recently completed at NASA GSFC.

Liquid propellants similar to AF-M315E have been studied for over twenty years. Aerojet Rocketdyne has been a partner in this work and has participated in many material compatibility and propellant characterization studies. Aerojet Rocketdyne's assessment of propellant compatibility is based on long-standing experience of hydrazine compatibility testing. The topic of material compatibility immediately branches into two sub-topics: 1) the effect of the material on the propellant and 2) the effect of the propellant on the material.

- **Propellant Tank**

The propellant tank maturation approach is designed to maximize future mission infusion potential by emphasizing proven components and processes, while focusing only upon those areas required to achieve the GPIM goals to minimize cost and schedule risk. The program has shown that the shell material of the selected tank has long-term compatibility with AF-M315E. Recent compatibility testing of the bladder material has like-wise shown acceptable performance for multi-year missions, and hence made a wide variety of existing tanks applicable for the GPIM demonstration and future missions. This revelation is a major benefit for the infusion of the technology as it enables the use of simpler and lower cost elastomeric diaphragm tanks instead of more complex propellant management device (PMD) style tanks or metal diaphragm tanks. A PMD tank approach is possible for longer duration missions, however it would require an updated design, analysis and delta-qualification of the PMD for use with AF-M315E. Even with hydrazine, a PMD design usually has to be re-analyzed for each mission application, whereas a positive expulsion diaphragm provides a more robust and less sensitive propellant expulsion approach.

No delta-qualification of the tank is expected for the GPIM mission, as a qualification-by-similarity and analysis approach should be sufficient to meet mission goals. However, close attention will be paid to the fracture behavior of the tank material with AF-M315E and must be confirmed to comply with the fracture mechanics requirements of AFSPCMAN 91-710 for safe operation of a pressure vessel containing a non-hazardous fluid.

The application of the new propellant in the qualified design reduces the technical readiness of this tank from TRL9 when operating with hydrazine, to ~TRL6 with AF-M315E. The TRL 6 rating is based on the facts that (a) the tank is already qualified with a positive expulsion diaphragm that has shown acceptable compatibility for missions up to several years, and (b) the tank is already qualified for leak-before-burst at a higher proof pressure than required for this demonstration, and (c) the tank shell material has been shown to have long-term compatibility with AF-M315E.

Table 2 Propulsion System Component Summary

Component	Design Adaptation	TRL w/ AFM-315E	TRL w/ Hydrazine
Thruster Valve	Change wetted surface material	5	9 (similar N_2H_4 valve)
Latch Valve	No Change	6	9
System Transducer	No Change	N/A (gas side)	9
Filter	No Change	6	9 (similar N_2H_4 filter)
Service Valves	Change sealing ball material	5	9 (similar N_2H_4 valve)

- **Components**

Table 2 summarizes component selections, respective mission readiness, and modifications required for the TDM green propulsion system. Existing hydrazine system components (TRL9, but evaluated at TRL6 for use with AF-M315E) comprise a nearly complete compatible set, with several components requiring straightforward modifications. The thruster valve will require the interior wetted surfaces to be lined with fully tested compatible material.

For the GPIM mission, the pressure transducers are remaining on the nitrogen pressurant side of the propellant feed system. With the use of a diaphragm tank as a fuel barrier, no changes in the original pressure transducer were required for the GPIM mission. Future component development can be completed at relatively low risk to provide an AF-M315E compatible material version of the pressure transducer for more flexibility in pressure monitoring for future systems. The filter is based off of an existing flight proven design and requires no changes. Similarly, an existing latch valve was deemed acceptable for use on the GPIM program (although longer duration missions would likely need to replace the small valve springs). Lastly, an existing hydrazine flight-qualified service valve will be used commonly throughout the system, except that seal ball comprising one of the three redundant seals will be replaced with more acceptable material, and has already demonstrated compatible for this purpose on the AFRL funded LEAP-DP program.

VII. Propulsion System Payload Module Development Schedule

The overall propulsion effort can principally be divided into two major efforts, development of the thrusters and manufacturing of the propulsion system, Figure 6. Immediate system tasks included assessment of which system components to employ, and understanding of the scope of modifications needed to TRL9 hydrazine components for use with AF-M315E propellant. A complimentary effort was also initiated at the beginning to test the compatibility of all unknown materials with this green propellant. The flight system design effort has two phases, 1) system design up through PDR and 2) final system design up to CDR. The thruster development is divided into three phases: 1) Lab model 22N thruster development, 2) Engineering model (EM) thruster design and then 3) the final flight design activity. Flight thruster designs are expected to be only minor modifications to the EM model based on lessons learned from the EM system bench testing. Testing is also principally divided into three tasks: 1) initial lab model testing of the 22N thruster, 2) EM system bench level testing which includes assessment of both the 1N and 22N EM thruster designs as well as performance evaluation of the complete propulsion system with EM level components and 3) acceptance and qualification testing. Propulsion system delivery to Ball Aerospace Corporation is in November 2014.

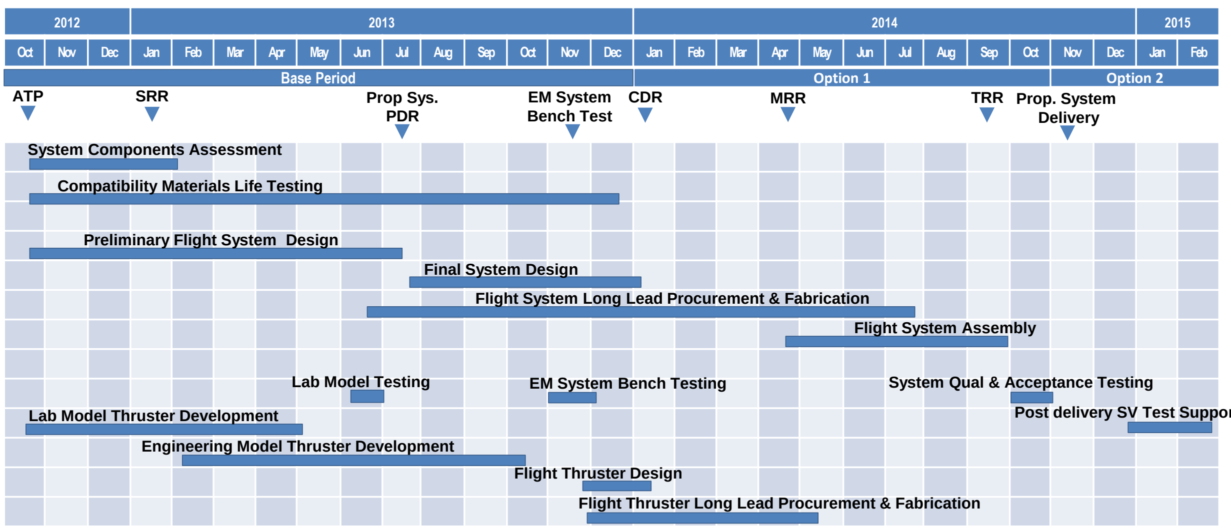

Figure 6 Propulsion System Schedule

VIII. Conclusion

The culmination of this program will be high-performance, green AF-M315E propulsion system technology at TRL 7+ that is ready for direct infusion to a wide range of applications for the space user community.

The combined benefits of low toxicity, easy open-container handling, and high performance of AF-M315E offer a strong alternative to hydrazine for dramatically reducing the cost of access to space for the small vehicles being developed by NASA, DoD and the commercial sector.

AF-M315E propulsion systems will enable spacecraft designers to accommodate significantly more propulsive performance than hydrazine, especially where volume is limited. Some differences in design considerations are needed over hydrazine systems, but in general the approaches are very similar. The GPIM demonstration program will show that these considerations are manageable, especially when compared to the significant benefits of AF-M315E propulsion systems.

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