

Foundational Methane Propulsion Related Technology Efforts, and Challenges for Applications to Human Exploration Beyond Earth Orbit

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ABSTRACT:

Current interest in human exploration beyond earth orbit is driving requirements for high performance, long duration space transportation capabilities. Continued advancement in photovoltaic power systems and investments in high performance electric propulsion promise to enable solar electric options for cargo delivery and pre-deployment of operational architecture elements. However, higher thrust options are required for human in-space transportation as well as planetary descent and ascent functions.

While high thrust requirements for interplanetary transportation may be provided by chemical or nuclear thermal propulsion systems, planetary descent and ascent systems are limited to chemical solutions due to their higher thrust to weight and potential planetary protection concerns. Liquid hydrogen fueled systems provide high specific impulse, but pose challenges due to low propellant density and the thermal issues of long term propellant storage. Liquid methane fueled propulsion is a promising compromise with lower specific impulse, higher bulk propellant density and compatibility with proposed in-situ propellant production concepts. Additionally, some architecture

studies have identified the potential for commonality between interplanetary and descent/ascent propulsion solutions using liquid methane (LCH₄) and liquid oxygen (LOX) propellants. These commonalities may lead to reduced overall development costs and more affordable exploration architectures.

With this increased interest, it is critical to understand the current state of LOX/LCH₄ propulsion technology and the remaining challenges to its application to beyond earth orbit human exploration. This paper provides a survey of NASA's past and current methane propulsion related technology efforts, assesses the accomplishments to date, and examines the remaining risks associated with full scale development.

1. INTRODUCTION:

Human, beyond-earth-orbit, exploration architecture studies have identified LOX/LCH₄ as a strong candidate for both interplanetary and descent/ascent propulsion solutions. While methane fuel has yet to be implemented in such in-space flight systems, significant research efforts have been conducted for over 50 years, ranging from fundamental combustion and mixing efforts to rocket chamber and system-level demonstrations. In addition, over the past 15 years, NASA and its partners have built upon these early research activities, conducting many advanced

development efforts that have demonstrated the practical components and sub-systems needed to field future methane space transportation elements (e.g. thrusters, main engines, and propellant storage and distribution systems). Relevant advanced development efforts began with a push to field non-toxic Orbital Maneuvering System (OMS) and Reaction Control Systems (RCS) for NASA's Space Shuttle System. Early Non-Toxic RCS efforts did not utilize methane fuel. However, these demonstrations are applicable from the common challenges of cryogenic propellants for on demand systems. Likewise some earlier pump-fed throttleable lander engine efforts used liquid hydrogen (LH₂) fuel, but are applicable from a cryogenic propellant and throttle control/stability perspective.

These related efforts and a significant number of direct methane propulsion demonstration activities have formed a foundation of LOX/LCH₄ (and related) propulsion knowledge that has significantly reduced the development risks of future methane based space transportation elements for human exploration beyond earth orbit.

While LOX/LCH₄ propulsion has been identified as a potential solution for multiple transportation functions, some architecture efforts have identified the potential for commonality between interplanetary and descent/ascent propulsion solutions using LOX/LCH₄ propellants (common approaches could reduce development costs). These architecture efforts have generally indicated needs for the following propulsion subsystem and components capabilities:

- RCS Propulsion: ~ 25-lb_f – 100-lb_f class
- Pressure-fed main engine: ~ 6000-lb_f class
- Pump-fed (throttleable) main engine: ~ 25,000-lb_f class
- Long Duration Cryogenic Fluid Management and Distribution (CFM&D), including:
 - High performance pressurization systems
 - Thermal management with high performance multilayer insulation and 90K class cryocooler systems integrated with CFM&D
 - Management of propellant losses due to boiloff and component leakage

The following sections will review/summarize recent NASA, LOX/LCH₄ advanced development efforts, consider remaining risks to develop future flight systems, and make some general recommendations for a path forward.

2. LOX/LCH₄ IGNITERS

Relative to more conventional, hypergolic storable solutions, one of the largest risks associated with LOX/LCH₄ propulsion is reliable ignition. In the 2005 – 2010 timeframe, the NASA Propulsion and Cryogenics Advanced Development Project (PCAD) conducted numerous in-house experimental efforts to examine the issue [1, 2]. The work was completed at both Reaction Control Engine (RCE) and larger main engine scales. The majority of the work was conducted with spark torch igniters. However, there were also successful demonstrations of microwave torch ignition, and a combination spark torch/glow plug igniter.

Overall there were no significant issues identified that would prohibit the reliable ignition over a range of conditions with LOX/LCH₄. One of the last ignition specific activities completed was the demonstration of 30,000 ignition cycles on a spark torch ignition system at vacuum conditions. Completion of this activity did not identify any issues with the hardware or designs for long duration applications. The work did, however, identify issues with spark plug durability and the reliability of power exciter units. Figs. 1 through 4 present examples of the igniters that were demonstrated and evaluated.



Figure 1. Main Engine Class Spark Torch Igniter (Firing)



Figure 2. RCE Class spark torch igniter (Firing)



Figure 3. Dual, Diverse Ignition Torch (Firing)

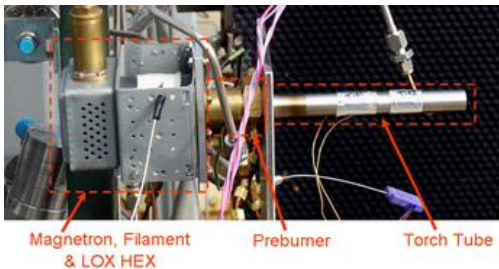


Figure 4. Microwave Ignition Torch

Many of the remaining ignition associated risks are related to specific requirements and duty cycles that will be imposed on future systems and conduct of final spaceflight qualification. One general area that still requires investigation is ignition in the cold thermal environment of space where both the hardware and propellants have been exposed for a significant period of time prior to required operation.

3. REACTION CONTROL SYSTEM THRUSTERS

During NASAs 2nd Generation Reusable Launch Vehicle/Next Gen Launch Technology Program – Auxiliary Propulsion Project (2000-2004), advanced development efforts focused on non-toxic

alternatives to more conventional hypergolic storable OMS/RCS were initiated. The primary focus was reduction in ground processing costs due to simplified operations. These efforts are applicable to LOX/LCH₄ propulsion due to the common challenges related to cryogenic propellants, and because some of the hardware was later transitioned to perform the early PCAD LOX/LCH₄ RCS demonstrations.

Two non-toxic RCS efforts were conducted. Aerojet developed and demonstrated a dual thrust (25-lb_f and 870-lb_f) LOX/Ethanol RCE [3]. This thruster was successfully demonstrated at both thrust levels in pulsed and steady state modes.

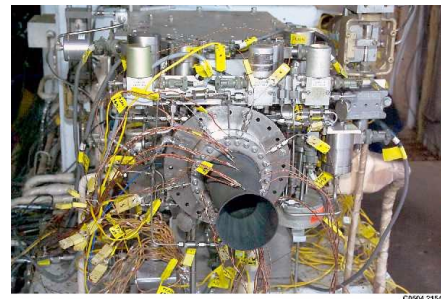


Figure 5. Aerojet Non-Toxic LOX/Ethanol RCE



Figure 6. TRW Non-Toxic LOX/LH₂ RCE

TRW conducted two non-toxic RCS demonstration efforts. One demonstrated a dual thrust (25-lb_f and 870-lb_f) LOX/Ethanol RCE, while the second effort focused on a 1000-lb_f LOX/LH₂ RCS Thruster [4]. Both designs were successfully demonstrated in hot fire tests.

Later NASA shifted focus from reusable launch technologies to advanced chemical propulsion for space exploration. The PCAD project focused the top three risks identified for RCE technology: 1) Ignition reliability; 2) Performance (vacuum specific

impulse (Isp)); and 3) Pulse width repeatability. To address the risks, PCAD undertook a combination of in-house and contract activities.

In 2006, the PCAD project awarded RCE contracts to Aerojet and Northrop Grumman (previous TRW propulsion group). Each contract focused on the development and delivery of a 100-lb_f thrust pre-prototype engine subsystem. The key performance requirements were: 1) 317-second vacuum Isp; 2) 4-lb_fsec minimum impulse bit (Ibit); 3) 80-ms electrical pulse width (EPW); 4) 25,000 valve cycles and 5) ignition and operation over a range of inlet conditions including liquid and gaseous propellants. The two suppliers pursued different engine concepts in response to these requirements.

The Aerojet concept was based on the earlier LOX/Ethanol engine development and other internally funded activities. Initial testing was performed with 870-lb_f engines that were originally designed to operate on LOX/Ethanol propellants and were modified to accommodate LOX/LCH₄. NASA successfully tested these modified units at altitude with the results influencing the 100-lb_f engine design.



Figure 7. Aerojet 100-lb_f LOX/LCH₄ RCE

The Aerojet 100-lb_f RCE consisted of compact integral exciter/spark plug system, a dual coil direct-acting solenoid valve for oxidizer and fuel, an integral igniter and injector, and a columbium chamber/nozzle with an expansion area ratio of 80:1 (See Fig. 7).

Propellant flow to both the main chamber and igniter were controlled by a single set of dual coil valves. Over 55,000 cycles were demonstrated at cryogenic temperatures, exceeding the specified 25,000 cycle life. A series injector concepts were tested at sea

level to examine engine performance, and the design used a spark torch igniter. Ultimately, all key performance criteria were demonstrated using an impinging injector design. Aerojet conducted over 1300 engine pulse tests at a variety of duty cycles and accumulated more than 1900 seconds of operating time during sea-level, engine development testing. Aerojet met the 317-sec Isp requirement, calculated based on estimated nozzle losses and exceeded the 80-msec EPW requirement by demonstrating 40-msec EPW. Aerojet provided 5 engines to NASA that were subsequently tested in a multiple engine configurations on the Auxiliary Propulsion System Test Bed (APSTB) and 2 units for testing at the thruster level in NASA's Altitude Combustion Stand (ACS).

NASA conducted sea-level and altitude performance testing, including a total of 60 altitude hot-fire tests with the Aerojet 100-lb_f LOX/LCH₄ engine over a wide range of propellant inlet conditions (pressure and temperature), to simulate operation in a variety of space environments. Testing was conducted using a 45:1 area ratio columbium radiation cooled nozzle.

The main goal of the testing was to develop Isp performance curves as a function of mixture ratio. The engine demonstrated that meeting the required 317-sec performance is feasible for the 80:1 nozzle based on the results with a 45:1 nozzle.

The Northrop Grumman concept was primarily based on previous work on hypergolic propellant engines. The combustion chamber and a portion of the nozzle were regeneratively cooled with both oxygen and methane. The full engine area ratio (120:1) was completed with a columbium radiation-cooled nozzle extension. Propellant flow to both the main chamber and igniter was controlled by a single set of independent single coil fuel and oxidizer valves. Ignition was accomplished with the use of a spark torch igniter. A series of hardware configurations were tested, starting with workhorse hardware, to develop the engine cooling circuit. Northrop Grumman developed a single pre-prototype unit that was tested in vacuum conditions at their Capistrano test facility (See Fig. 8).

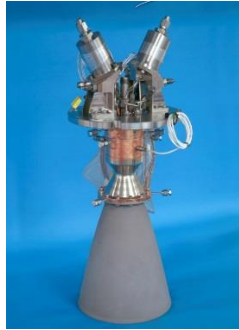


Figure 8. Northrop Grumman Pre-Prototype 100-lbf RCE

Test results indicated that the engine concept was able to meet the performance goals, including exceeding the Isp requirement. The measured Isp was approximately 331 sec, which exceeded the demonstration requirement of 317 sec.

4. MAIN ENGINE INJECTOR PARAMETRICS

In parallel to the contracted efforts, NASA conducted in-house development of larger scale LOX/LCH₄ injectors [5]. Tests were conducted on both 2-inch diameter and 6-inch diameter chambers at NASA.



Figure 9. Impinging Injector Tests

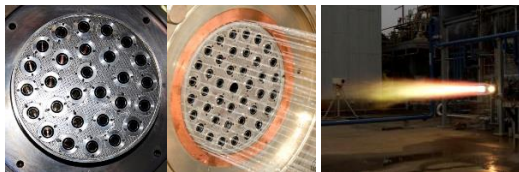


Figure 10. Coaxial and Swirl Coaxial Injector Tests

This effort investigated performance and stability characteristics of impinging, coaxial and swirl coaxial

injectors with multiple combustion chamber lengths. Testing demonstrated C* efficiencies over 98%. A water cooled combustion chamber was used to collect heat transfer data. Different length chambers were used to obtain performance level correlations to chamber length.

The chambers were also instrumented to collect combustion stability data (both for direct injector design evaluation, and anchoring analytical models).

5. PRESSURE-FED MAIN ENGINE EFFORTS

In 2006 NASA funded ATK and KT Engineering (KTE) to conduct LOX/LCH₄ main engine workhorse demonstration efforts. Each contract was focused on the development and delivery of a 7,500-lbf thrust pre-prototype engine. The key performance targets for the activity were: 1) 7,500-lbf thrust, 355-sec vacuum Isp; 2) 90% rated thrust within 0.5 seconds; 3) total of 24 restarts; and 5) operation over a range of inlet conditions from gas to liquid for start. The companies design solutions varied significantly with one pursuing a regenerative cooling approach and the other implementing an ablative design. ATK teamed with XCOR to develop a pressure-fed engine concept that was regeneratively cooled by the methane fuel. Sea-level testing was conducted with both water and methane cooled combustion chambers at XCOR facilities in Mojave, CA [6].



Figure 11. ATK/XCOR Engine Testing at Mojave, CA.

KT Engineering pursued an ablative combustion chamber design. A number of sea-level tests were conducted at NASA on this workhorse design as well. Unfortunately, shifting technology demonstration requirements (toward Lunar Lander applications) resulted in the ATK/XCOR, and KT Engineering contract options not being exercised.

In response to the evolving technology demonstration requirements, NASA funded Aerojet to develop a vacuum workhorse engine demonstrator [7]. This effort focused on demonstrating the following requirements 1) 5,500-lb_f thrust, 355-sec vacuum Isp; 2) 90% rated thrust within 0.5 seconds; 3) total of 24 restarts; and 5) operation over a range of inlet conditions from gas to liquid for start. The Aerojet design included an ablative chamber and liquid oxygen/liquid methane injection system. The overall activity was broken into two phases. The first phase involved Aerojet fabrication and sea-level testing of multiple injector designs. In the second phase, NASA took delivery of the engines and conducted altitude performance testing. Testing at NASA proceeded with the first injector produced under the Aerojet contract. While sea-level performance was lower than desired, altitude testing was conducted to correlate the sea-level and altitude results and to validate *nozzle performance analysis*.



Figure 12. Aerojet 5500-lb_f LOX/LCH₄ Main Engine Demonstration Testing

Testing was conducted with an 8-inch long ablative combustion chamber and a radiation cooled columbium Space Shuttle OMS engine nozzle extension, which provided an area ratio of 129:1. Design area ratio for the prototype engine design was 150:1. A total of 187 seconds of run time was accumulated on the engine including seven 20-second tests and one 40-second test. The injector, chamber and nozzle were all in good physical condition after the testing. The average vacuum Isp calculated for the test program was 344 sec and the maximum was 345 sec. Extrapolating to an area ratio

of 150:1, a specific impulse of approximately 348 sec could be achieved, which was within 2% of the performance goal.

More recent in-house efforts at NASA are currently pursuing additively manufactured (3D printed) regenerative cooled LOX/LCH₄ engine concepts [5]. Demonstration hardware includes a 3D printed Inconel injector, with a separate porous faceplate. The injector also includes variable fuel film cooling and a center igniter port. The regeneratively cooled chamber includes fully printed coolant channels, eliminating the need for a separate liner/jacket joint. The chamber design also includes printed thermocouple ports along one coolant channel (Fig. 13). Work is also underway to evaluate a GRCop-84 (Copper) printed unit.



Figure 13. Additively Manufactured LOX/LCH₄ Pressure-Fed Main Engine

Initial hot fire testing has verified injector stability, and has successfully demonstrated the 3D printed concept (Fig. 13). Testing also provided detailed regenerative cooling data for a 2-phase thermal model (critical for future pressure-fed, regenerative engine development).

6. PUMP FED MAIN ENGINE EFFORTS

The NASA Propulsion Cryogenics & Advanced Development (PCAD) Project also conducted both contracted and in-house efforts related to deeply throttleable pump-fed main engines. These efforts (conducted between 2005 and 2010) were focused on demonstrating technologies for lunar lander descent stage applications, and all efforts utilized LOX/LH₂ propellant combinations. Future Mars transfer stage and Mars lander/ascent vehicle applications require LOX/Methane propellant combinations. However, the PCAD efforts are relevant due to lessons learned related to deep throttle injector stability, pump performance and system response of cryogenic engine systems.

PCAD funded Pratt and Whitney Rocketdyne to demonstrate the Common Extensible Cryogenic Engine (CECE) [1]. This demonstrator utilized a modified RL10 engine. Design changes included injector modifications, valve modifications, and system trim adjustments.



Figure 14. Pratt and Whitney Rocketdyne Common Extensible Cryogenic Engine (CECE)

The CECE effort successfully demonstrated stable throttling (> 10:1), and met overall performance goals (448 sec at 100% Power, 436 sec at low power). Testing also demonstrated reliable ignition over 20 engine starts.

While the CECE effort utilized a fixed injector (with increased pressure drop, enabling deep throttling), variable geometry injector concepts were also investigated. Variable injector geometry concepts maintain stability margins at low power levels, without large increases in injector pressure drop at high power levels, resulting in higher overall system performance. PCAD funded Northrop Grumman's efforts to develop a throttling LOX/LH₂ pintle injector [1]. The throttling pintle injector (Fig. 15) is continuously adjustable throughout the throttle range, and was successfully demonstrated in injector/chamber sea-level testing at NASA.



Figure 15. Northrop Grumman Throttling LOX/LH₂ Pintle injector

A second variable geometry injector was designed in-house at NASA [1]. This two-stage injector utilized separate injector manifolds to enable a transition between two fixed injector geometries. Unlike the Northrop Grumman pintle design, the two stage injector is not continuously variable, but is able to shift between a lower flow resistance, high power geometry and more resistive low power geometry. Like the pintle the two stage design also enables greater system-level performance by reducing injector pressure drop at high power. The two-stage injector was also successfully demonstrated throughout its throttle range, in injector/chamber, sea-level testing at NASA (Fig. 16).

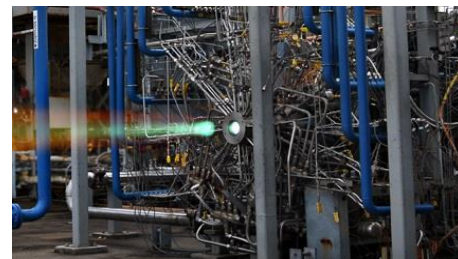


Figure 16. Two Stage Throttleable Injector Testing

More recent in-house pump-fed engine efforts (2012 – Current) at NASA have focused on an Additive Manufacturing Demonstration (AMD) Engine [8]. This effort demonstrated the ability to utilize additive manufacturing to greatly reduce development time and production costs of a 30-Klb_f-class LOX/LH₂ engine. This activity produced the majority of the engine system components (including rotating turbomachinery parts) through additive/3D printing techniques. The projects' Integrated AMD breadboard system testing demonstrated multiple components simultaneously, in relevant environments for relatively low costs

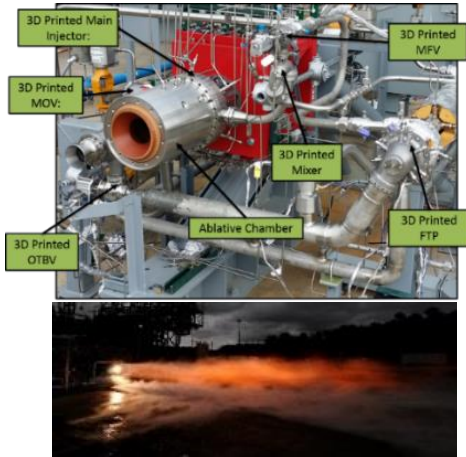


Figure 17. Additive Manufacturing Demonstration (AMD) Engine at NASA

Due to the technology pull from future Mars exploration missions, the AMD test bed concept is being transitioned to demonstrate LOX/LCH₄ engine components and systems operation. In March, 2016 the NASA team successfully demonstrated an additively manufactured LOX/LCH₄ Turbo-Pump

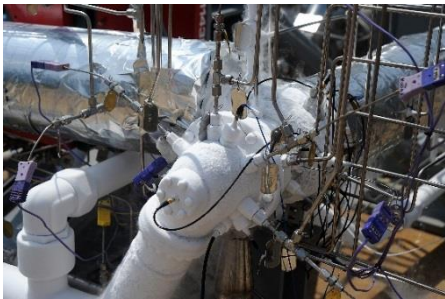


Figure 18. Additively Manufactured LOX/LCH₄ Turbo-pump Testing



Figure 19. Additively Manufactured LOX/LCH₄ Turbo-pump Testing

Early LOX/LCH₄ turbo-pump level demonstrations sent the entire fuel flow to an external burn stack for

disposal (Fig. 19). However, development of other LOX/LCH₄ engine system components are underway, and system-level test-bed demonstrations are planned for the near future.

7. CRYOGENIC FLUID MANAGEMENT AND DISTRIBUTION

Since the primary application for cryogenic propulsion systems has been launch vehicle boosters and upper stages, LOX/LCH₄ propulsion systems for missions beyond earth orbit must overcome challenges that traditional cryogenic propulsion systems have not yet encountered. For example, while pre-launch thermal loads and ascent heating have dominated the design requirements for traditional cryogenic propulsion systems, farther-reaching missions employing cryogenics must also withstand post-ascent thermal loads during venting and equilibration of multi-layer insulation (MLI) and deal with subsequent effects that will impact system performance, such as radiative heating from planetary bodies, solar heating, and microgravity fluid behavior and its impacts on thermal stratification, heat transfer, and pressures within the propellant tanks. Tank mounting schemes and tank penetrations will also play a much more dominant role in system performance, as total heat leak into cryogenic tanks becomes far more impactful for longer mission durations.

7.1. Passive CFM capabilities

Previous NASA work has shown that cooling LOX and LCH₄ below their boiling points prior to launch and fielding a passive cryogenic fluid management (CFM) system could be sufficient for missions to polar regions on the surface of the moon. This mission would require an insulation system designed for the pre-launch, ascent, and vacuum environments, low-conductivity tank mounting, and directional sun shielding. A thermodynamic vent system (TVS) would provide mixing and recirculation to counteract thermal stratification and control pressure rise within the tanks. NASA modeling tools indicated that an LOX/LCH₄ system integrating these features could enable a polar-region lunar surface dwell time as long as 240 days without active refrigeration [2]. NASA has demonstrated 13-day storage of LCH₄ with helium pressurization using passive CFM techniques in the Multipurpose

Hydrogen Test Bed (MHTB) in 2006 (Fig. 20a) [9]. Also, NASA's Methane Lunar Surface Thermal Control (MLSTC) Test (Fig. 20b) validated control predictions for the tanks of a lunar ascent vehicle concept [2].



Figure 20. a. Multipurpose Hydrogen Test Bed (MHTB) tank (left) and b. Methane Lunar Surface Thermal Control (MLSTC) tank (center) and c. LOX zero-boiloff test (right).

7.2. Active CFM (Cryocoolers)

Longer-duration missions such as near-earth loiters or missions to Mars would, however, heighten the Need for active refrigeration and would increase demand for on-board electrical power. Therefore, in recent years, NASA has invested in 90 K flight-weight cryocooler technology to address this need and has taken delivery of an operational prototype 90 K reverse Brayton prototype developed by Creare. This unit has also been used to demonstrate Initial subscale testing with LOX indicated its robust capability for maintaining LOX storage with zero boil-off (see Fig. 20c) [10]. Further work remains to assess cryocooler performance in an integrated LCH₄ system, and to reduce active CFM risks for a full-scale LOX/LCH₄ flight system.

7.3. Composite Struts

All foreseeable cryogenic missions will rely heavily on thermal isolation of the propellant tanks. NASA's recent work with the now-cancelled Cryogenic Propellant Storage and Transfer (CPST) project included analysis, design, manufacturing, and test of low-conductivity light-weight composite tank struts for cryogenic propellant tanks. Load testing (both compression and tension) under liquid-hydrogen-to-ambient thermal gradient conditions showed very positive results for this strut design, indicating robust mechanical properties and significant reductions in

overall heat leak into the tank. While CPST focused on liquid hydrogen stored at 20 K, the strut concept is directly relevant to LOX/LCH₄ systems, whose warmer storage temperatures are less challenging than the hydrogen application in which the strut has already succeeded.



Figure 21. NASA's CPST Composite Strut Design, as installed.

7.4. Propellant Quantity Gauging

Since most existing cryogenic propulsion systems have found use in launch environments or atmospheric flight environments, historical cryogenic propellant quantity gauging methods have benefitted from propellant settling, which avoids the complexities associated with microgravity fluid behavior. As a result, relatively robust technologies exist for gauging oxygen and methane under settled conditions. These technologies include discrete sensor "rakes", capacitance probes, and derivatives of these basic concepts. Settling, of course, assumes that either a cryogenic reaction control system (RCS) incorporates functional LADs to allow RCS start-up from unsettled conditions in order to settle propellants or the spacecraft initially relies on a more bulky gas-fed system or a conventional storable-liquid system.

Some more advanced missions, of course, may be less tolerant of the impacts of settling propellants whenever a propellant quantity measurement is needed. Hence, NASA has continued to invest in gauging methods for *unsettled* cryogenic propellants. Previous work within the Exploration Technology Development Program CFM Project (CFMP) investigated the application of pressure-volume-temperature (PVT) methods, which are routinely used in storable-propellant systems, for application in cryogenic systems. This methodology

proved feasible [2], although intuitively with greater uncertainties than are typical for storable applications. Seeking greater accuracy for cryogenic gauging in microgravity, NASA has continued to invest in the promising Radio-Frequency Mass Gauge (RFMG) concept, through the CFMP, CPST, and Evolvable Cryogenics (eCRYO) projects. This concept uses the propellant's dielectric properties and the electromagnetic Eigenmodes (natural resonant frequencies) of the tank and propellant. This approach involves injecting a radio frequency signal into the tank and pattern-matching the reflected power spectrum to a database of simulated Eigenmode frequencies to determine propellant mass. This concept has been validated for oxygen and methane under settled conditions during ground testing and for a simulant fluid under unsettled conditions during parabolic aircraft flights [2]. At present, NASA's investment continues, as eCRYO is developing an RFMG for demonstration aboard the International Space Station (ISS) as part of Robotic Refueling Mission 3. This continued progress (as well as ongoing low-level investments in alternate backup concepts) bodes well for the availability of unsettled propellant gauging capabilities within the foreseeable future.

7.5. Liquid Acquisition Devices

To enable the full range of missions without the burden of separate propulsion systems for cryogenic propellant settling, NASA has also continued to invest in the development of cryogenic liquid acquisition devices (LADs) which exploit surface tension properties to separate liquid from gas and to assure expulsion of gas-free liquid from the propellant tanks in microgravity. One notable achievement within the CFMP included measurement of bubble point pressures (i.e. the differential pressure across the LAD screen at which gas pressure overcomes surface tension on the wetted screen surface) for both LOX and LCH₄. CFMP also investigated heat entrapment effects and helium evolution effects and commissioned an independent LAD concept development through a competitive procurement. Subsequent work under the LH₂-focused CPST project conquered weld and manufacturing challenges and produced prototype LAD designs that were successfully manufactured and tested under gravity conditions. CPST also

developed and matured thermal and fluid physics modeling tools for the design of future cryogenic LADs. Remaining risks for LOX/LCH₄ LADs can be retired with ground testing and detailed modeling of flight-representative LADs, followed by demonstration in a microgravity environment before fully relying on LAD performance in a high-risk mission. Hence, initial missions may need to rely operationally on propellant settling while carrying LADs as a flight demonstration objective.

8. INTEGRATED SYSTEMS DEMONSTRATION

As shown above, much work has been completed in the development and maturation of technologies required for an in-space LOX/LCH₄ propulsion system capable of performing basic functions. More recent efforts at NASA have sought to evaluate these technologies within a system framework with the goal of identifying system interactions, investigating integrated system timelines, and evaluating integrated system performance. Even within an environment of fluctuating budgets and shifting priorities, NASA has continued to take steps toward this goal of demonstrating the integration of CFM technologies and integrated operations within storage tanks and feed lines, although without yet accomplishing the goal of a *fully integrated system-level* ground test incorporating all requisite technologies.

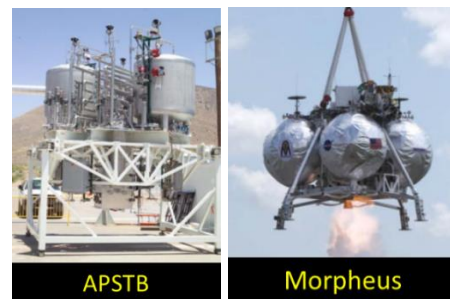


Figure 22. a. NASA's Auxiliary Propulsion System Test Bed (left) and b. NASA's Morpheus Flight Test Vehicle (right)

NASA's partially integrated system demonstrations include work performed within several projects, including PCAD, the CFM project, Morpheus, CPST, and the ongoing eCRYO project. The PCAD project demonstrated LOX/LCH₄ conditioning and distribution with an integrated flight-weight feed system

and thrusters in the APSTB (Fig. 22a) [11]. This test demonstrated use of a thermodynamic vent to chill the propellant manifold. By demonstrating feed line thermal performance that met or exceeded thruster inlet condition requirements, this test showed that distributed feed lines can be successfully designed to deliver gas-free liquid cryogenic propellants to thruster inlets in a spacecraft or vehicle application.

Although not focused on long-duration cryogenic storage, the well-publicized Morpheus vehicle flight tests (Fig. 22b) have successfully provided short-duration atmospheric flight demonstrations, investigating control algorithms and response times of an LOX/LCH₄ propulsion system during time-critical ascent and descent operations [12].

Finally, the hydrogen-focused CPST project successfully performed vibroacoustic tests of a cryogenic tank with integrated foam and MLI insulation (Fig. 23a) and later demonstrated (more difficult) LH₂ storage in the Engineering Development Unit (EDU) tank (Fig. 23b) incorporating an integrated passive CFM approach as well as the composite struts, prototype LADs, and RFMG described in the preceding section.

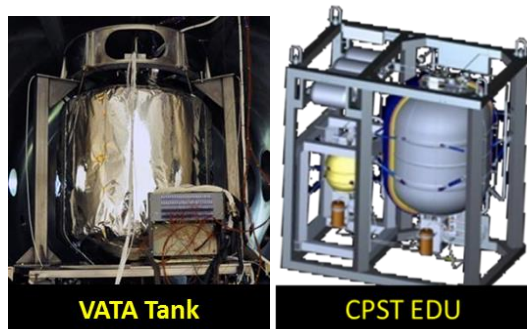


Figure 23. a. The CPST Vibroacoustic Test Article (VATA) with integrated foam and MLI (left) and b. The CPST Engineering Development Unit (EDU) in its eventual, fully outfitted configuration (right)

Considered in total, these partial system-level demonstrations combine to increase confidence that the infusion of LOX/LCH₄ technologies into initial mission capabilities is nearly within reach, with only a short list of challenges remaining.

9. CHALLENGES FOR FUTURE HUMAN EXPLORATION

Considering the advanced development efforts conducted by NASA (and industry partners) over the last 15 years, the overall development risk for LOX/LCH₄ in-space propulsion has been significantly reduced. While these efforts have provided a strong foundation for the pursuit of an initial flight capability, some challenges still exist, requiring additional investigations/risk reduction testing. These remaining challenges include the following:

- Integrated Storage testing with 90-Kelvin cryocoolers
- Reaction control thruster design maturation
- Design maturation for regeneratively cooled main engines
- Design of low-leakage, long-duration cryogenic valves

More advanced in-space capabilities (landers, ascent stages, depots, etc.) require additional technology maturation for:

- Pump-fed LOX/LCH₄ engines with deep throttle capability
- Leak detection
- Zero-G mass gauging technology maturation
- Automated fluid couplings for space cryogenic systems
- Zero-G demonstration of cryogenic liquid acquisition devices

Due to currently evolving architecture requirements a flexible test-bed approach to risk reduction testing is recommended. A system-level ground test bed capable of parametric adjustment of operating and test conditions could evolve as the architecture requirements solidify, and could ultimately lead to a potential risk reduction flight demonstration.

10. SUMMARY AND CONCLUSIONS

Building on years of foundational R&D activities NASA has conducted multiple LOX Methane advanced development efforts and hardware demonstrations over the last 15 years. While, over the years, these efforts were focused on different ultimate applications (e.g. non-toxic propulsion for

RLVs, crew module and lunar lander propulsion, human space exploration) these efforts combine to significantly reduce development risks associated with future methane propulsion systems for human exploration. Building on these foundational risk reduction efforts, we are well positioned to pursue an initial operational capability. A system-level ground test bed capable of parametric operating and test conditions is a logical next step. This test bed would evolve as the architecture requirements solidify, and would ultimately lead to a potential risk reduction flight demonstration.

While development risks still exist (requiring some advanced development efforts), the majority are related to engineering challenges rather than the development of entirely new technologies.

Sufficient investments have been made to enable a path toward an initial LOX/LCH₄ propulsion capability.

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