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

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Agenda

- **Introduction**
  - Background
  - Needs for Beyond Earth Orbit (BEO) human exploration
- **LOX/CH4 Igniters**
- **Reaction Control System (RCS) Thrusters**
  - Large (870 – 1000 lbf) LOX/LH2 and LOX/Ethanol thrusters (TRW & Aerojet)
  - 100 lbf LOX/CH4 thrusters (Aerojet & Northrop Grumman)
- **Main Engine Injector Parametric Testing**
- **Pressure Fed Main Engine Efforts**
  - 7500 lbf LOX/CH4 (XCOR & KT Engineering)
  - 5500 lbf LOX/CH4 (Aerojet)
  - Additively Manufactured 4K Regeneratively Cooled Engine
- **Pump Fed Main Engine Efforts**
  - Common Extensible Cryogenic Engine – LOX/LH2 throttle-able engine
  - 7000 lbf LOX/LH2 (TRW/Northrop Grumman)
  - 7000 lbf LOX/LH2 two stage injector
  - Current efforts with the Additive Manufacturing Demonstration engine
- **Cryogenic Fluid Management (CFM) and Distribution**
- **Integrated Systems Demonstration**
- **Challenges for future Human Exploration**
- **Summary and Conclusions**

Introduction

Background

- Human, beyond earth orbit, exploration architecture studies have identified Methane/Oxygen as a strong candidate for both interplanetary and descent/ascent propulsion solutions.
- Significant research efforts into methane propulsion have been conducted for over 50 years, ranging from fundamental combustion & mixing efforts to rocket chamber and system level demonstrations.
- Over the past 15 years NASA and its partners have built upon these early activities, conducting many advanced development efforts that have demonstrated practical components and sub-systems needed to field future methane space transportation elements (e.g. thrusters, main engines, propellant storage and distribution systems)
- Some early Non-Toxic RCS efforts did not utilize methane fuel. However, these demonstrations are applicable from the common challenges of cryogenic propellants. Likewise some earlier pump fed throttle-able lander engine efforts used liquid hydrogen fuel, but are applicable from a cryogenic propellant and throttle control/stability perspective.
- These advanced development efforts have formed a foundation of LOX/CH4 (and related) propulsion knowledge that has significantly reduced the development risks of future methane based space transportation elements for human exploration beyond earth orbit.

Introduction

Needs for Beyond Earth Orbit (BEO) Human Exploration

- Some architecture studies have identified the potential for commonality between interplanetary and descent/ascent propulsion solutions using liquid methane and liquid oxygen (LOX) propellants (common approaches could reduce development costs)
- Meeting the needs of these functions (interplanetary transportation, planetary descent propulsion, and planetary ascent propulsion), will require many or all of the following subsystems, components and capabilities:
  - Reaction Control Propulsion: ~ 25 lbf – 100 lbf class
  - Pressure fed engine: ~ 6000 lbf class
  - Pump fed engine system~ 25,000 lbf class
  - Long Duration Cryogenic Fluid Management and Distribution (CFM&D)

    Including high performance pressurization systems

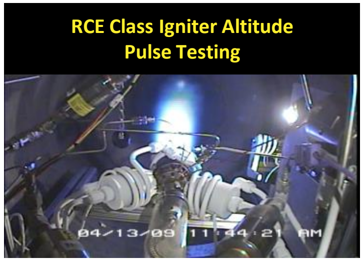
    Including thermal management with high performance Multilayer insulation and 90K class cryo-cooler systems integrated with CFM&D

    Including management of propellant losses due to boiloff, and component leakage

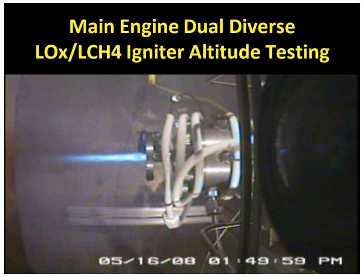
LOX/CH4 Igniters

Propulsion Cryogenics & Advanced Development (PCAD) Project

LOx/LCH$_4$ Torch Ignition


RCE Class Igniter Altitude Pulse Testing

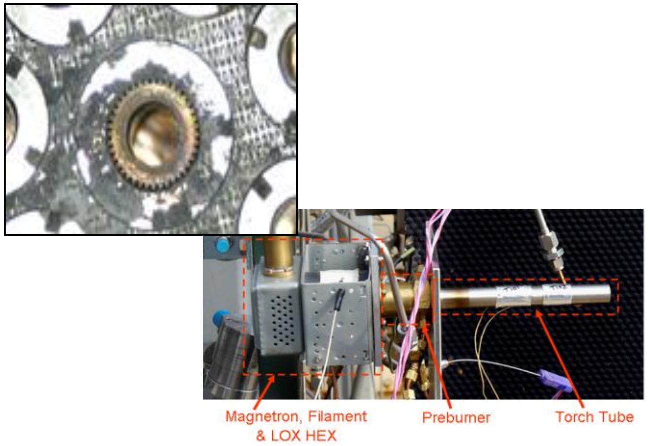

Main Engine Class Igniter Altitude Testing


Main Engine Dual Diverse LOx/LCH4 Igniter Altitude Testing

- Over **30,000** altitude pulse cycles on NASA Reaction Control Engine (RCE) class spark torch igniter
- Over **150** vacuum ignition tests with Aerojet spark torch igniter
- Over **750** tests altitude tests with main engine class spark torch igniter
- Over **100** altitude tests with a glow plug integrated with spark torch igniter for dual diverse redundant ignition
- Over **50** sea level tests with main engine impinging torch igniter

Other Igniters

- NASA MSFCs Augmented Spark Impinging (ASI) Igniter
  - Internal Spark Plug
  - Dual Oxygen flow enhances spark gap plasma
  - Dual fuel flow actively cools torch tube
- Microwave (Plasma) Torch from William Peschel (CA)
  - Similar to torch
  - Plasma generated by internal magnetron



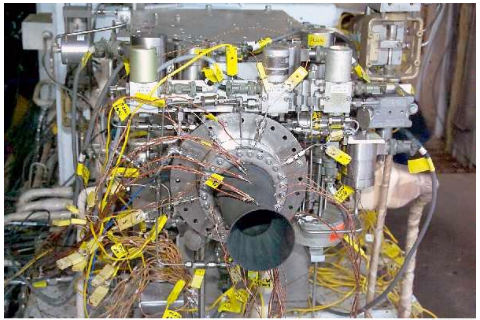
Reaction Control Thrusters

2nd Gen/Next Gen Launch Technology – Auxiliary Propulsion Project (2000-2004)

Technology/Advanced Development effort related to Non-toxic shuttle OMS/RCS upgrades and supporting potential Shuttle replacement concepts. Focus was reduction in operations cost over storable hypergolic systems. Applicable to LOX/CH4 due to cryo challenges

Aerojet LOX/Ethanol RCE Dual Thrust 25lbf/870lbf

Successfully tested in both pulsed and steady state mode



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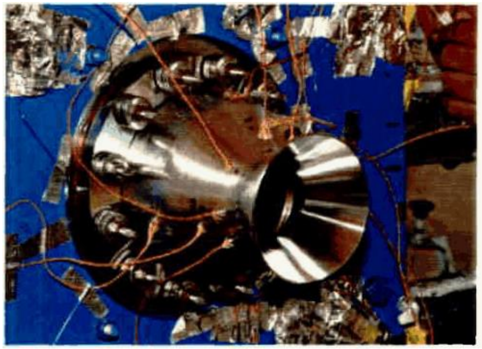
TRW LOX/LH2 RCS Thruster 1000 lbf Thrust

Successfully tested in both pulsed and steady state mode



Reaction Control Thrusters

Propulsion Cryogenics & Advanced Development (PCAD) Project (2005 – 2010)

Activity was directly focused on future exploration applications

Aerojet 100-lbf LOX/LCH$_4$

- Radiative cooled with Columbium chamber/nozzle
- 40 msec Electrical Pulse Width (EPW) / <4 lbf-sec Impulse Bit
- **Isp > 317 sec**
- Gas-Gas Operation Demonstrated

Northrop Grumman 100-lbf LOX/LCH$_4$

- Dual propellant cooled with Columbium nozzle extension
- **Isp ~ 320-330-sec with 150:1 nozzle**.
- Pulsing tests with 80 and 160 msec EPW.

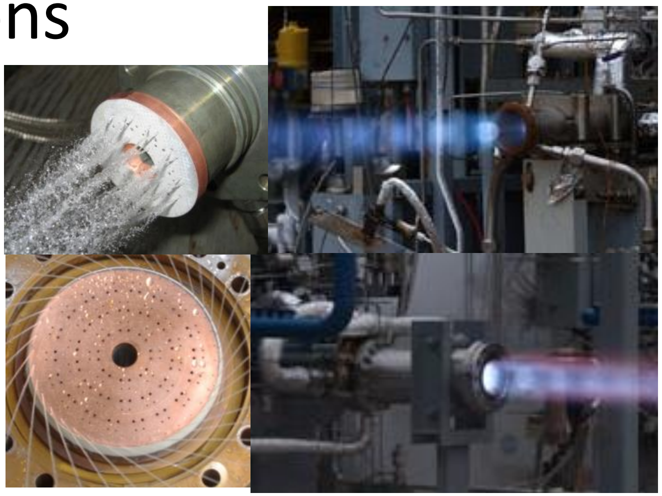
Aerojet 100 lbf LOX/CH4 Thruster

Northrop Grumman 100 lbf LOX/CH4 Thruster

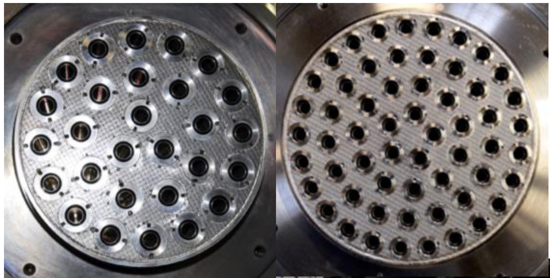
LOX/CH4 Main Engine Injector Parametric Tests

NASA MSFC LOX/CH4 Injector Evaluations

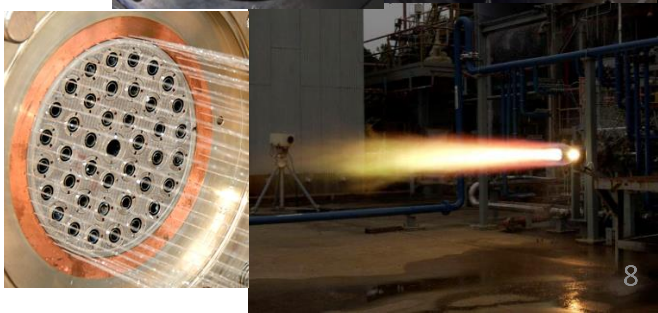
Heat flux profiles collected for a range of operating conditions for all designs



- Impinging Injectors
  - 2 inch design – no film cooling
  - 6 inch design with variable fuel film cooling



- Shear / Swirl Coaxial Injectors
  - No film cooling, side mount ignition
  - Multiple element densities (28, 40, 58)



- 40 Element Swirl Coaxial Injector
  - Variable Film Cooling
  - Center port ignition

Pressure Fed Main Engines

Propulsion Cryogenics & Advanced Development (PCAD) Project (2005 – 2010)

- **Early "workhorse" engines**
  - XCOR / ATK-GASL
    - 7500 lbf Thrust
    - Regeneratively Cooled Chamber
  - KT Engineering
    - 7500 lbf Thrust
    - Ablative Chamber

- **Aerojet "prototype" engine**
  - 5500 lbf thrust
  - Ablative Chamber
  - Reliable ignition – multiple vacuum ignition demonstrations
  - Performance – 355 sec vacuum Isp
  - Fast Start – 90% thrust in 0.5 sec

Injector/Chamber for 2015 Testing with Direct Metal Laser Sintering (DMLS)

Additively Manufactured 4K lbf Regenertively Cooled Engine

- Injector
    - 3D printed Inconel body
    - Separate porous faceplate
    - Variable fuel film cooling
    - Center igniter port
- Regeneratively Cooled Chamber
    - No separate liner/jacket joint – printed coolant channels
    - Printed thermocouple ports along one coolant channel
    - GRCop-84 (Copper) printed unit in work
- Hot Fire Testing
    - Verified injector stability
    - Demonstrated 3D printed concept
    - Provided detailed regen cooling data for 2-phase thermal model

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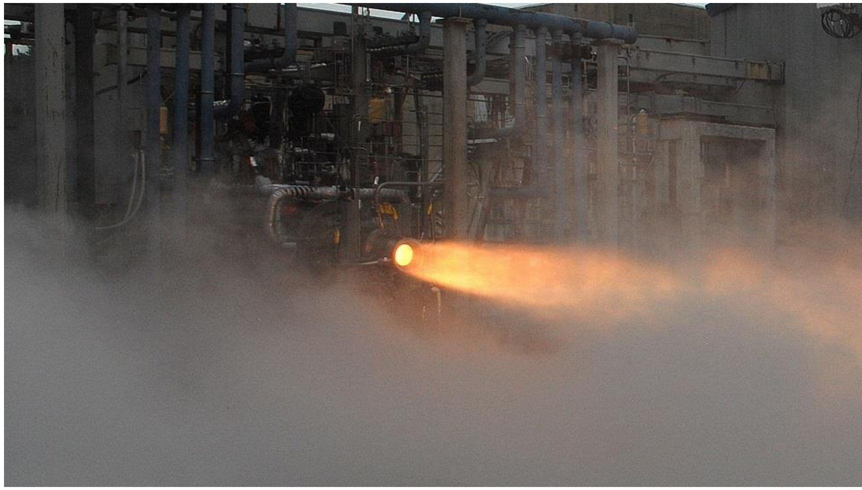
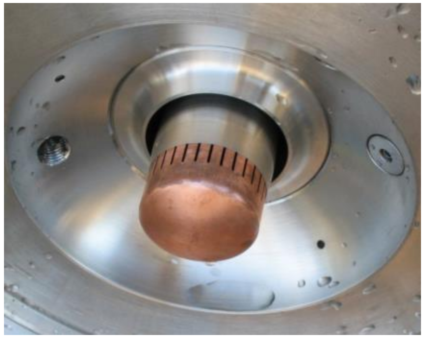


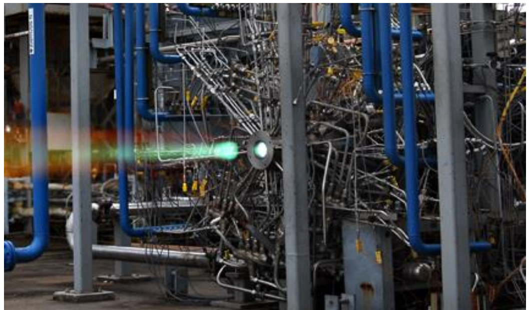
Pump Fed Main Engines

Propulsion Cryogenics & Advanced Development (PCAD) Project (2005 – 2010)

- Pratt and Whitney Rocketdyne CECE Engine (LOX/LH2)
    - Stable Throttling (> 10:1)
    - Performance (448 sec @ 100% Power, 436 sec @ low power)
    - Reliable ignition over 20 starts



- Northrop Grumman Throttling Pintle injector
    - Successful injector/chamber level testing
    - Demonstrated stable throttling

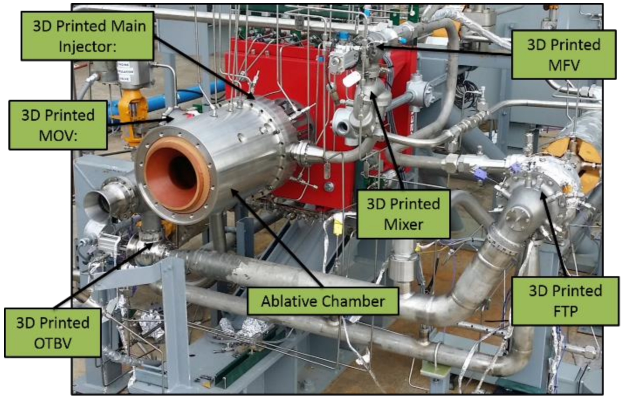


- NASA 2 Stage fixed injector
    - Successful injector/chamber level testing
    - Demonstrated stable throttling

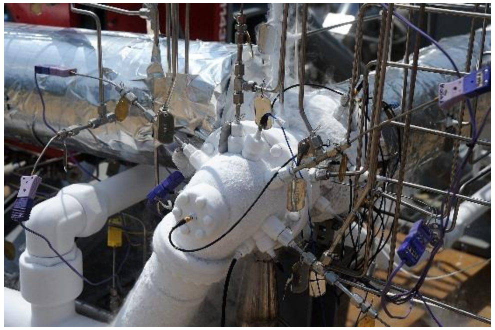
Pump Fed Main Engines

Additive Manufacturing Demonstration (AMD) Engine at MSFC (2012 – Current)

- Integrated AMD Breadboard System Testing (LOX/LH2)
  - Tested multiple components simultaneously for relatively low costs
  - Majority of parts additively manufactured (3D printing) – including rotating machinery (turbo-pump) components



- LOX/CH4 Turbo-Pump demonstration March 2016
  - Moving toward Integrated LOX/CH4 Breadboard Systems Testing



Cryogenic Fluid Management (CFM) and Distribution: Storage Tests

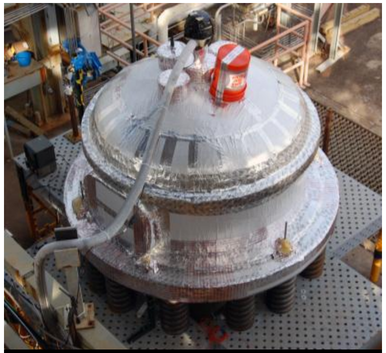
NASA has completed multiple storage tank tests that enable : LOX/CH4

- Completed 13-day storage tests using Methane with helium pressurization using the Multi-Purpose Hydrogen Test Bed (MHTB) test article. (2006)
- Completed Methane Lunar Surface Thermal Control (MLSTC) Test, validating control predictions for lunar ascent tanks. (2011)
- Completed vibro-acoustic testing of a prototype cryogenic spacecraft tank using the Vibro-Acoustic Test Article (VATA) Tank. (2012)
- Developed and tested composite struts to minimize heat leak.
- Completed many other relevant storage and liquid-acquisition tests with LOX, LN2, and LH2.

MHTB Tank

MLSTC Tank

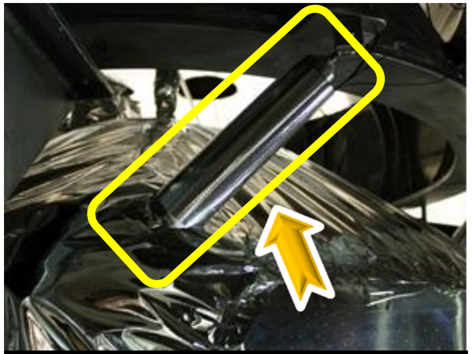
CPST EDU Tank



Cryogenic Test Bed 1

O_2 Zero Boiloff Test

VATA Tank



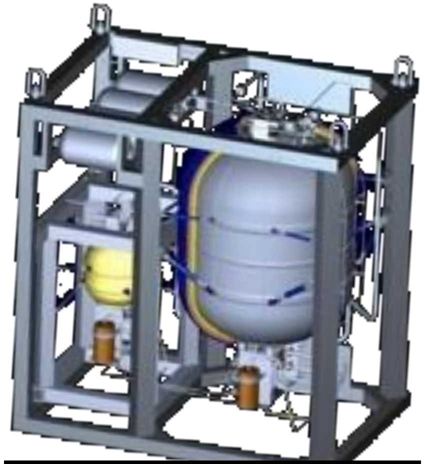
Composite Mounting Strut

Integrated Systems Demonstrations

- NASA demonstrated LOX/CH4 conditioning and distribution with an integrated flight-weight feed system and thrusters in the Auxiliary Propulsion System Test Bed (APSTB). Published 2010.
- NASA's Morpheus has provided short-duration atmospheric flight demonstrations with LOX/CH4.
- Relevant: Cryogenic Propellant Storage and Transfer (CPST) Engineering Development Unit (EDU) ground demonstration with LH_2. Tank system included:
  - Liquid Acquisition Devices
  - Composite Struts
  - 2 Thermodynamic Vent Systems
  - Multi-layer insulation.
  - Radio-Frequency Mass Gauge.

APSTB

Morpheus



CPST EDU

Challenges for BEO Human Exploration

- Initial in-space capability requires some further advanced development and risk reduction testing:
  - 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 technology maturation for:
  - Pump fed LOX/CH4 engines with deep throttle capability
  - Leak detection
  - Zero-G mass gauging technology maturation
  - Automated fluid couplings
  - Zero-G demonstration of cryogenic liquid acquisition devices

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 focused on different ultimate applications these efforts combine to significantly reduce the development risks associated with future methane propulsion systems for human exploration

- Future system level testbed demonstrations (ground) leading to a potential risk reduction flight demonstration is a recommended path forward.

- 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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