LOX/Methane In-Space Propulsion Systems Technology Status and Gaps

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Background

- **Human exploration architecture studies have identified liquid oxygen (LOX)/Methane (LCH4) 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 that have demonstrated practical components and sub-systems needed to field future methane space transportation elements**

- **These advanced development efforts have formed a foundation of LOX/LCH4 propulsion knowledge that has significantly reduced the development risks of future methane based in-space transportation**

LOx/Methane Propellants Advantages and Disadvantages

- **As a bipropellant propulsion system, LOX/LCH4 has some favorable characteristics for long life and reusability, which are critical to lunar and Mars missions**
  - **Non-toxic, non-corrosive, self-venting, and simple to purge**
  - **No extensive decontamination process required as with toxic propellants**
  - **High vapor pressure provides for excellent vacuum ignition characteristics**
  - **Performance is better than current earth storable propellants for human scale spacecraft**

- **Provides the capability for future Mars exploration missions to use propellants that are produced in-situ on Mars**

- **Liquid Methane is thermally similar to O_2 as a cryogenic propellant, 90,111 K (LO2, LCH4 respectively) instead of the 23 K of LH_2**
  - **Allows for common components and thus providing cost savings as compared to liquid hydrogen (LH_2)**
  - **Due to liquid methane having a 6x higher density than hydrogen, it can be stored in much smaller volumes**

- **Cryogenic storage aspect of these propellants needs to be addressed**
  - **Passive techniques using shielding and orientations to deep space**
  - **Refrigeration may be required to maintain both oxygen and methane in liquid forms**

Needs for Beyond Earth Orbit Human Exploration

- **Some architecture studies have identified the potential for commonality between interplanetary and descent/ascent propulsion solutions using LOX/LCH4**

- **Meeting these functions (interplanetary, descent, and ascent propulsion) will require many or all of the following subsystems, components, and capabilities:**
  - **Reaction Control Propulsion: ~ 100 to 880 N (25 lbf – 200 lbf) class**
  - **Pressure fed engine: ~ 25 KN (6000 lbf) class**
  - **Pump fed engine system~ 100 KN (25,000 lbf) class**
  - **Long Duration Cryogenic Fluid Management and Distribution**
    - **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 boil-off and component leakage**

Defined Performance Needs, Goals, Solution Space

Lox/Methane Propulsion System Technology	Performance needs for a Deep space based lander or other vehicles (service	Goals	Technology Solutions
Integrated System	High Reliability - several usages of the same vehicle, Low cost, HIgh delta-v, long life reusable, High mass fraction, quality and origin of methane	1. Reliability > 0.995 2. Life > 10 operating cycles 3. Mass Fraction > 0.85 (Prop dry+structure)	1. Design for re-usability
Pressurization System	High density light weight storage	50% reduction in volume and mass over ambient temperature storage	1. Ghe cold storage with heat exchanger 2. partial autogenous systems
Pressure vessel	Lightweight	1. PV/W > [Tank Pressure*volume/Tank Mass]	1. Metallic (aluminum lithium) 2. Composite Overwrap 3. All Composite
Thermal Management	low boiloff, thermodynamical management of propellants during launcher phase from Earth ground	1. deep space Zero boil-off (0 W/m2) storage at EML1 2. lunar surface surface heat leak 0.25 Watts/m2	1. Passive 2. active
Liquid Acquistion in zero/low g	zero-g start, refueling capability, slosh damping, and anti vortex	1. 2% residuals	1. Screens channel 2. Vanes 3. Sponges
Feedsystem	Redundancy management, propellant distribution	1. Lightweight 2. Low Pressure drop 3. low heat leak	1. Cryogenic Feedsystem for LOx/LCH4 main engine and RCS
Reaction Control Engines	Provide Min. Impulse Bit, Thrust, and high cycle life	1. Min Ibit TBD 2. Thrust Range 3. Cycle Life > TBD	
Main Engines	Throttle capability including idle mode, High Isp, High reliability, Thrust / Weight ratio	1. > 4:1 throttle depending on T/W 2. Isp > 355 sec 3. Thrust >30 KN 4. Helium free design	1. Pump-fed, 2. Pressure-fed Ablative 3. Pressure-fed regen

STATUS OF TECHNOLOGY

Italy - Agenzia Spaziale Italiana (ASI)

- **Tested MIRA Demonstrator, a 100-kN (10-tonne) thrust class, expander cycle LOx/LCH4 engine, for the a new upper stage of Vega, in cooperation with Roscosmos**
  - **Successfully tested at the complete engine level**
    - **More than 11 tests performed up to full operating condition**
    - **Accumulating more than 600 s of firing.**
  - **Development and testing of liquid methane fuel turbo-pump bearings**
- **With JAXA, ASI is investigating the methane thermal behavior, characterizing bearings working in liquid methane, and designing a regenerative thrust chamber in the 100-kN (10-tonne) class which is to be tested in Italy**
- **Designing small methane thrusters to be applied as a potential reaction control system of the launcher stage**
- **The Italian Aerospace Research Center, CIRA, is developing the 'Hyprob' research program, specifically dedicated to combustion phenomena studies and breadboard testing, up to the design of a medium scale**
  - **30-kN (3-tonne thrust class) regenerative thrust chamber**
  - **Program developing test facilities at both laboratory level and thrust chamber assembly (up to 100-kN (10-tonne class)**

FIGURE 8 MIRA THRUST CHAMBER

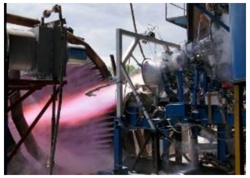


FIGURE 9 MIRA ENGINE DEMONSTRATOR TESTED MAY 2014

FIGURE 7 MIRA CH4 TURBINE MANIFOLD PRODUCED BY DMLS TECHNIQUES

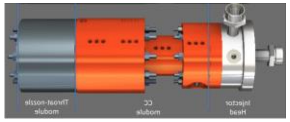
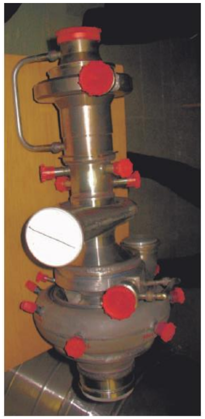


FIGURE 6 SINGLE INJECTOR RESEARCH THRUST CHAMBER

France
CNES *(Centre national d'études spatiales)*

- **Engine tests on KVD1 Russian engine during a French – Russian cooperation**

- **Research & Development activities are being performed in parallel with several designs, manufacturing and testing at subsystem level (combustion tests and simulation capabilities including high-frequency -HF- instability analysis, pump and inducer performances, for example)**

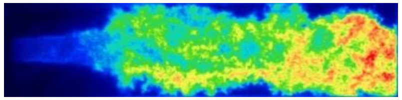


- **French capabilities are currently being developed for cryogenic propellant management**

- **Current main objective for CNES with French industry support is to prepare a LOX/LCH4 low cost, gas-generator engine demonstration at 1000-kN (100 t) thrust level before 2023**
  - **10-kN scale – bleed expander cycle**
  - **Capability of current LOx/LH2 engines to operate with LOX/LCH4 is also being addressed**

Germany
DLR *(Deutsches* Zentrum *für Luft- und Raumfahrt)*

- **Investigated flame visualization in optically accessible chambers OH* and CH* visualization for sub and super-critical pressures**



- **Investigated injector behavior**
  - **Flame stabilization of coaxial and porous injectors was investigated**
  - **Combustion efficiency investigations are planned**
- **Investigated combustion stability with a single coax injector**
- **Ignition of LOX/CH_4 multi-injector configurations**
  - **Chemical igniters (LOX/H_2 flame)**
  - **Laser ignition**
- **High-altitude ignition of LOX/GCH_4**
  - **Laser ignition of a full-scale 200-400 N RCS chamber was performed to determine the minimal ignition energy and demonstrate the feasibility of laser ignition.**
  - **Pre-ignition flow conditions in the chamber were visualized**
- **LOX/Methane pre-burner applications**
  - **Film cooling and Regenerative cooling with methane**

JAXA (*Japanese Aerospace Exploration Agency)*

- **100-kN class LNG rocket engine, named LE-8, developed by (JAXA) and IHI Aerospace Co., Ltd. (IA)**
  - **Completed more than 2000 seconds of its firing tests**
- **30 KN LNG engine for the purpose of obtaining performance data with a high altitude test stand (HATS)**
  - **Five firing tests with a total of 122 seconds at altitude conditions**
- **The LE-8 and the 30-kN class engines consist of an ablative chamber and a liquid-liquid impinging type injector – simpler engine and reduced cost**
- **LNG engine with regenerative cooling chamber was designed and demonstrated in a sea level test facility**
  - **Equivalent I_{sp} reached to approximately 350 sec**
- **To achieve higher performance, JAXA is carrying out a research activity on LNG engines focusing on a regenerative cooling type engine**

	LE-8 engine	30 kN-class engine	IHI in-house engine
Thrust(Vacuum)(kN)	107	30	98.0
Isp(Vacuum)(sec)	314	335	354
Combustion chamber pressure(Pc)(MPa)	1.2	1.2	5.2
Mixture ratio(Thrust chamber)	3.2	3.0	3.5
Chamber cooling	Ablative	Ablative	Regenerative
Nozzle expansion ratio	42	49	150



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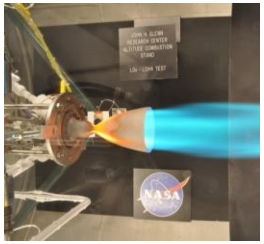
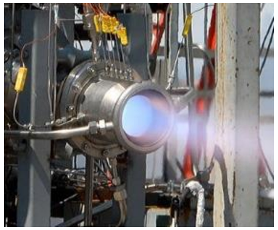
Recent activities (10 years)

- **CFM:**
  - **1.2 m diameter spherical tank was used to demonstrate insulation**
  - **Zero-boil-off (ZBO) system for LO2 was demonstrated using a flight-like cryocooler**
  - **Radio Frequency Mass Gauge (RFMG) for mass gauging in micro-gravity**
  - **Cryogenic feed systems for multiple RCS engines and main engine in a vacuum**
- **Engines:**
  - **RCS engines at thrust levels of 88 N (25 lbf), 444 N (100 lbf), and 3.8 kN (870 lbf)**
  - **24.5 kN (5.5 klbf) ablative engine for lunar ascent - 2% of target 355 s Isp @ 150:1**
  - **Throttling 24 kN (5 klbf) and 8.8 kN (2 klbf) with ablative/film-cooling**
- **System:**
  - **Integrated feed system, RCS, main engine at altitude**
  - **Flight testing of an integrated LOx/Methane system on terrestrial lander**



Current Activities

- **CFM - Evolvable Cryogenics project is developing**
  - **RFMG for cryogenic subsystem of the Robotic Refueling Mission 3**
  - **Zero Boil-off Transfer (ZBOT) payload for the ISS Microgravity Science Glovebox**
  - **Sub-scale Laboratory Investigation of Cooling Enhancements (SLICE) - welded vs. bolted design for skirt designs**
- **Engines:**
  - **Currently, small-scale pressure fed (17 kN (4 klbf)) and large-scale pump fed (111 kN (25 klbf)) engine components are being built using Advanced Manufacturing**



Other Activities

- **SpaceX – Raptor Development (738 Klbf, full flow staged combustion)**
- **Blue Origin – BE-4 (550 Klbf oxygen rich staged combustion)**
- **Air Force Research Lab**
  - **Third Generation Reusable Booster (3GRB)**
- **Other smaller companies – Masten, TGV, Wask, Exquadrum, Sierra Nevada, etc.**
- **Universities – UTEP, Purdue, etc.**

GAPS

GAPS

- **Develop a throttle-able regenerative-cooled pump-fed and/or pressure-fed engines to address gap for throttling (5:1 – 10:1), 360-365 sec, and for regenerative-cooled engines in the 25 – 100 kN range**
- **Develop 100 to 880-N RCS thrusters with integrated cryogenic feed systems to address gap for thruster size/cost and then to evaluate GNC impulse bit and thrust requirements**
- **Develop long duration reliable cryogenic refrigeration systems capable of maintaining zero-boil-off and performing liquefaction of in-situ produced propellants (several hundred watts at ~90 K)**
- **Develop composite cryogenic tanks with focus on spherical geometry to addresses gap in propellant tank technology**

GAPS

- **Develop high performance pressurization systems that improve storage density and reduce mass to address gap for use with cryogenic propellants**
- **Develop low-leakage, long-duration cryogenic valves and leak detection**
- **Develop automated fluid couplings**
- **Conduct extended duration thermal vacuum testing of integrated system to address gap of integrated system testing in thermal vacuum environment**
- **Fly a zero-g cryogenic liquid acquisition experiment in space, such as on the ISS or in a cis-lunar location to address gap of lack of demonstration of LOX/LCH4 in these conditions**
- **Fly a test vehicle in space as a technology infusion mission to demonstrate integrated LOX/LCH4 propulsion systems to address gap of no in-space flight experience**

Overall References

Dig into references within references

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Summary and Conclusions

- **LOX/LCH4 is an enabler for future exploration with in-situ propellant production**

- **Offers improved performance, improved reusability and elimination of toxicity issues for surface operations, and fluid commonality**

- **Foundational R&D activities 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**