Survey of Constellation-Era LOX/Methane Development Activities and Future Development Needs

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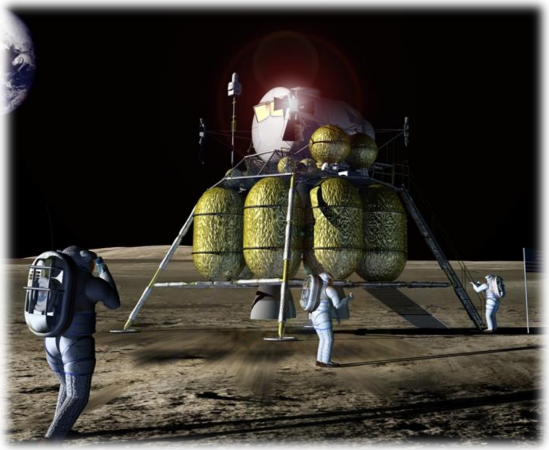
Constellation Program

- NASA formed the Constellation Program in 2005 to achieve the objectives of maintaining American presence in low-Earth orbit, returning to the moon for purposes of establishing an outpost, and laying the foundation to explore Mars and beyond in the first half of the 21st century
- The Exploration Technology Development Program (ETDP) was formulated to address the technology needs to address Constellation architecture decisions
- The Propellants and Cryogenic Advanced Development (PCAD) project was tasked with risk mitigation of specific propulsion related technologies to support ETDP



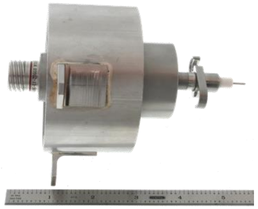
Propellants and Advanced Cryogenics Development (PCAD)

- Propulsion systems were identified as critical technologies owing to the high "gear-ratio" of lunar & Mars landers
  - Cryogenic propellants offer performance advantage over storables (NTO/MMH)
    - Mass savings translate to greater payload capacity
  - In-situ production of propellant an attractive feature; methane and oxygen identified as possible Martian in-situ propellants
- New technologies were required to meet more difficult missions
  - High performance LOX/LH_2 deep throttle descent engines
  - High performance LOX/LCH_4 ascent main and reaction control system (RCS) engines
- The PCAD project sought to provide those technologies through
  - Reliable ignition & pulse RCS
  - Fast start
  - High efficiency engines
  - Stable deep throttling

Methane Ignition Risk Reduction

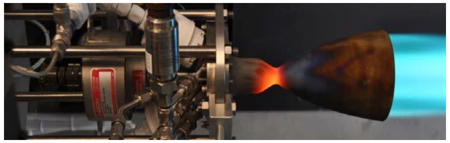
- Methane was historically seen as difficult to ignite compared to other cryogens
  - It has a longer ignition delay and higher ignition energy requirement as compared to other cryogenic fuels traditionally used in propulsion (e.g. hydrogen)
- Methane ignition was seen as a primary risk reduction area
  - Identify minimum ignition energy required
  - Identify life-limiting phenomena in igniter
  - Demonstrate reliable ignition over range of conditions and pulse cycles
- PCAD accomplished several goals with ignition risk reduction
  - 30,000+ pulses of methane spark igniter
  - Ignition studies with multiple igniter types
  - Ignition margin in RCE tests
  - RCE ignition over range of propellant temperatures

Augmented Spark Impinging (ASI) Igniter developed by MSFC



Unison compact-style igniter developed for AME and RCE engines

Microwave Igniter tested at MSFC



100-lb Aerojet RCE with Unison compact exciter installed at GRC

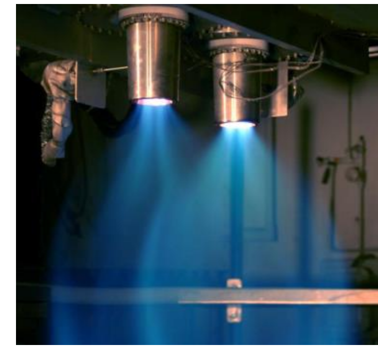
Ascent Main Engine class igniter during vacuum test at GRC

WASK spark-torch igniter during pulse durability testing at GRC

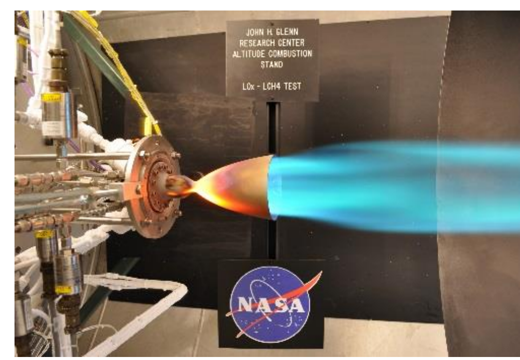
Reaction Control Engine Development

- Focused on 100-1000-lbf class engines
- Top 3 risks areas were
  - Reliable ignition
  - Vacuum performance
  - Repeatable pulse width
- For 100-lb RCE, goals were
  - MIB of 4 lb_f-s
  - Vacuum I_{sp} of >317 s
  - 80 ms electric pulse widths (EPW)
  - 25,000 valve cycles
  - Operation over range of temperature inlet conditions
    (160 °R LOX/170 °R CH4 to 224 °R LOX & CH4)
- Two 100-lb engine concepts were developed and tested

100-lbf Northrop Grumman LOX/LCH_4 RCE



870-lbf Aerojet LOX/LCH_4 RCE Tests at WSTF



Aerojet LOX/LCH_4 RCE testing at GRC

Ascent & Descent Engine Development

- Three key risk identified for Methane Ascent Engines
  - Reliable ignition
  - Fast start (90% thrust in 0.5 s)
  - Performance (Vac. I_{sp} > 355 s)
- Analysis efforts to compare sea-level test data to altitude conditions
- Engine tests were aimed at achieving 355 s Vac. I_{sp}
  - AME (5500-lbf) tests were within 2% of I_{sp} target
- Descent engine testing focused on 10:1 throttle with LOX/LH2


MSFC designed Swirl-Coaxial Injector


PWR CECE Descent Engine altitude tests at PWR


Northrop Grumman Pintle Injector during water tests


ATK/XCOR workhorse engine test at XCOR

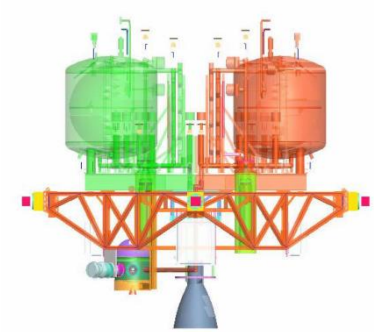

5500-lbf Aerojet LOX/LCH_4 AME testing at WSTF


KTE engine test at MSFC


Armadillo Aerospace dual-bell nozzle test at WSTF

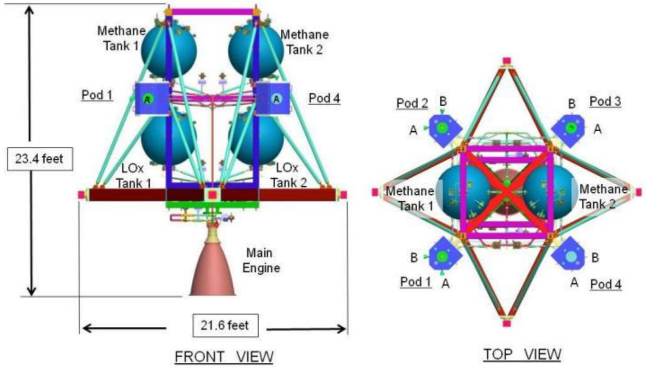
Integrated Propulsion System Testbed (IPSTB)

- Auxiliary Propulsion Systems Test Bed (APSTB) was precursor to IPSTB
  - APSTB was used to support PCAD RS-18, AME, RCE testing at WSTF-TS401
  - Modified to support concurrent testing of RS-18, AME and RCE thrusters
  - Originally designed for the Space Shuttle systems development, the rig was significantly oversized for PCAD needs
- IPSTB was designed to study, characterize, and model the integrated operation of LOX/LCH_4 components in an end to end propulsion system
  - Designed with smaller propellant tanks and with the flexibility to change component locations or vary feedline lengths



APSTB shown with RCE thruster bell jar and RS-18 mounted.

APSTB being installed into WSTF-TS401



IPSTB Structural Overview

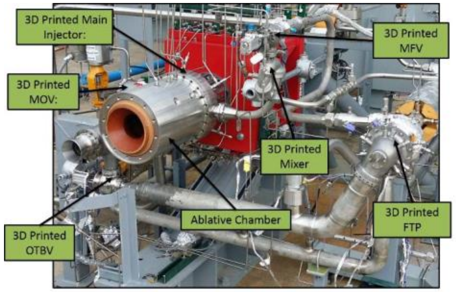
Summary of PCAD Accomplishments

- PCAD successfully provided risk reduction activities with respect to LOX/LCH4 engine technology
  - Demonstrated reliable ignition of LOX/LCH4 over a range of propellant conditions
  - Demonstrated 30,000+ ignition pulses of methane igniter hardware
  - Demonstrated RCE can be developed to pre-prototype level to meet mission requirements
- Additionally, PCAD also demonstrated stable throttling down to 10:1 power for a LOX/LH_2 descent scale main engine
- PCAD was heading towards integrated test bed modeling and test efforts
- An extensive set of literature is available to detail the numerous PCAD efforts

Activities Since PCAD (2011+)

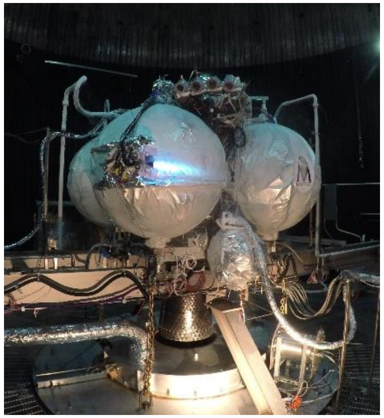
- Additive Manufacturing Demonstration (AMD) Engine at MSFC (2012 –Current)
- Morpheus Testing (2011-current)
  - Test-bed article for exploring lander system technologies
    - Tethered flights at JSC
    - Free flights at KSC with ALHAT system
    - Vacuum tests in GRC B-2

Cold He heat-exchanger on Morpheus



MSFC AMD Engine/Breadboard System test article

Morpheus Engine tests at SSC E-3



Morpheus Test Article integrated system tests in GRC B-2

Morpheus Test Article during free flight at KSC

Activities Since PCAD (2011+)

Additive Manufactured (AM) Thruster Hardware – Hot-fire Testing @ MSFC

Funding: Lander Technologies/CATALYST, LCUSP (Low Cost Upper Stage Propulsion)

- Uncooled Refractory Chamber
- Inconel LCH_4 cooled Chamber
- GRCop-84 LCH_4 cooled Chamber
- Inconel Swirl Coaxial Main Injectors
- Inconel Impinging Gas Generator Injector
- META4 (Methane Engine Thrust Assy for 4K lb_f) - swirl coaxial injector (LOX/CH_4) + 3D printed GRCop-84 chamber full regen cooling
- Fuel (CH_4) turbopump
- Vacuum testing MSFC ASI igniter & spark exciters at GRC

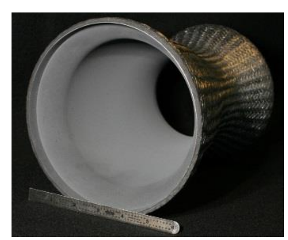

Printed GRCop-84 and printed Inconel Swirl Coax Injector & Chamber

META4 hot-fire testing at MSFC

GG-Injector Water Flow Testing

META4 Chamber

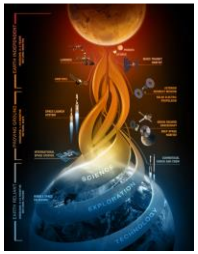
Fuel Turbopump at MSFC



Refractory Chamber

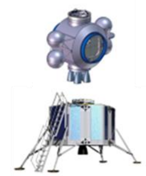
ASI Igniter testing at GRC ACS

Future Needs and Technology Gap Assessment

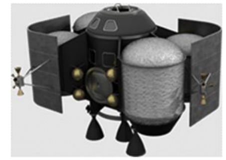


ISECG International Space Exploration Coordination Group

ISECG Looked at Future Needs



Human Lunar Lander



Human Exploration Mars Ascent

Orbital (In Space) Transfer Vehicle

ISECG Identified Tech GAPS Needing Future Work

- Develop a throttle-able regenerative-cooled engines
    - pump-fed and/or pressure-fed engines
    - throttling (5:1 – 10:1), 360-365 sec, 30 – 100 kN range.
- Develop 100 to 220-N RCS thrusters and integrated cryogenic feed systems
- Develop long duration reliable cryogenic refrigeration systems (several hundred watts at ~90 K) for ISRU.
- Develop composite cryogenic tanks with focus on gap for spherical geometry
- Develop high performance pressurization systems that improve storage density and reduce mass
- Conduct extended duration thermal vacuum testing of integrated system
- Fly a zero-g cryogenic liquid acquisition experiment in space
- Fly a test vehicle in space as a technology infusion mission to demonstrate integrated LOx/Methane propulsion systems

Need to address gap of no in-space LOx/Methane flight experience.

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