The Propulsion and Cryogenics Advanced Development (PCAD) Project in the Exploration Technology Development Program is developing technologies as risk mitigation for Orion and the Lunar Lander. An integrated main and reaction control propulsion system has been identified as a candidate for the Lunar Lander Ascent Module. The propellants used in this integrated system are Liquid Oxygen (LOX) /Liquid Methane (LCH4) propellants. A deep throttle pump fed Liquid Oxygen (LOX) /Liquid Hydrogen (LH2) engine system has been identified for the Lunar Lander Descent Vehicle. The propellant combination and architecture of these propulsion systems are novel and would require risk reduction prior to detailed design and development. The PCAD Project addresses the technology requirements to obtain relevant and necessary test data to further the technology maturity of propulsion hardware utilizing these propellants. This plan and achievements to date will be presented.
Propulsion and Cryogenics Advanced Development (PCAD) Project Propulsion Technologies for the Lunar Lander

Presentation to the Space Technology & Applications International Forum

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**PCAD**

Architectural Benefit

Exploration mission is more ambitious than the Apollo mission
- More people to the surface
- Longer duration stays
Architectural Benefit

Descent Propulsion

• LOx/LH2 is enabling to meet lunar lander weight budget.
• Hypergols would make the lunar lander too heavy to be supported by Ares V

Ascent Propulsion

• Both NTO/MMH and LOx/CH4 under consideration
• Initial Lunar Design Analysis Cycle-1 (LDAC-1) design assumed NTO/MMH integrated Reaction Control System (RCS)/Main Propulsion System (MPS)
• After completion of LDAC-1, Ascent Propulsion System re-designed using LOx/CH4
• LOx/CH4 Ascent Module design completed by Lunar Architecture Team-II (LAT-II) team lead by Eric Hurlbert

LO2-LCH4 Option for Altair Ascent Stage

Benefits (from Cx Prop Study Findings):

- **Improved Performance:**
  - For a minimal ascent stage the savings are 400-800 lbms (from Cx Prop Study Findings)
    - This **mass benefit** translates into a **sizable reduction** in IMLEO (>25,000 lbm based on ESAS LSAM configuration)
    - Lower gross weights translate to **lower launch costs**, increased margins, or decreased program risk for closure (need to quantify)
  - **Cost:** Lowest total estimated LCC alternative option to hypers (+$411M total through 2030)
    - Higher recurring cost based on higher dry mass (worst case analysis)
    - Cost benefit of **higher performance** will reduce LCC (not included in analysis)
  - **Schedule:** Estimated 74 mo. (6.2 year) development schedule compares favorably with 71 mo. estimated for hypers
  - **Reliability:** Mature system reliability equivalent to that of hypers (0.999982 vs 0.999984)
    - Initial lower reliability (0.80 vs 0.95) to be improved through ongoing test program
Lunar Lander Technology Needs

• LOx/LH$_2$ Deep Throttling Pump Feed Engine(s)
• LOx/CH$_4$ Pressure Feed Main Engine
• LOx/CH$_4$ RCS Thrusters
• Cryogenic Propellant Storage and management
  – LOx/LH$_2$
  – LOx/CH$_4$
• Cryo Mass Gauging
  – LOx, LH$_2$, LCH$_4$
• Low Heat Transfer Tank Mountings, and interfaces
• Variable area valve and actuation technology

Lunar Lander Technology Needs

- **LOx/LH₂ Descent Propulsion**
  - 1 – 4 engines
  - 28 – 30 klbf optimal stage thrust
  - 35 – 40 klbs optimal stage thrust (engine out configurations)
  - Throttle range (3.3 to 1) – (8 to 1)
  - LOx/LH₂ Main Engine (Expander Cycle)
    - 9,000 lbf – 28,000 lbf
    - 448 sec Isp (maximize @ 100% RPL)
    - 2 – 4 starts per mission
  - LOx/LH₂ Storage & Fluid Management
    - 14 – 28 days LEO
    - 3 days Transit
    - 2 days LLO

- **LOx/CH₄ Ascent Propulsion**
  - LOX/CH₄ Main Engine (Pressure Feed)
    - 4500 lbf – 6500 lbf
    - 355 sec Isp
    - 1 – 3 starts per mission
  - LOx/CH₄ RCS Thrusters
    - 100 lbf
    - 80 ms pulse length (40 ms growth risk)
    - 300 sec Isp
  - LOx/CH₄ Storage & Fluid Management
    - 14 – 28 days LEO
    - 3 days Transit
    - 2 days LLO
    - 210 days Lunar surface

Propulsion Technical Risk Areas

- Reaction Control Technology
  - Reliable ignition
  - Performance
  - Repeatable pulse width

- Ascent Main Engine
  - Reliable ignition
  - Performance
  - Fast start

- Descent Main Engine
  - Stable throttling
  - Performance
  - Reliable ignition
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Project Structure

Propulsion and Cryogenics Advanced Development
Conduct risk reduction activities to demonstrate that green/non-toxic propellants can be a feasible option for Constellation propulsion systems.

1.0 Project Management
Objective: Manage the overall development of propulsion technologies to increase technology readiness levels and reduce risk.

2.0 Reaction Control System Propulsion
Objective: Reduce the risk of liquid oxygen / liquid methane ignition and demonstrate and validate performance levels for reaction control engines for use on the Lunar Lander descent and ascent stages.

3.0 Main Engines
Objective: Demonstrate and validate performance levels for a Lunar Lander liquid oxygen / liquid methane ascent engine and a deep throttling liquid oxygen / liquid hydrogen descent engine.

4.0 Orion Propulsion
Objective: Demonstrate the key enabling technologies needed for the design of a thruster for oxygen-based non-toxic in-space Orion crew module (CM) propulsion.

5.0 Mars Propulsion Engine Technology
Objective: Demonstrate engine performance levels for engines on the Mars Lander descent and ascent stages (FY12 Start)

6.0 Education and Outreach
Objective: PCAD Project will cooperate with appropriate personnel in any education and outreach activities as requested.
WBS 2.1.1 Exciter Technology (GRC)
- Advanced exciter technology development to reduce weight and volume from current SOA. Both capacitive discharge and inductive designs will be examined.

WBS 2.1.2 Spark Plug Durability (GRC)
- Determine the mechanism of ceramic insulator failure in an igniter system. Provide material solutions to overcome insulator failure.

WBS 2.1.3 Wide Operating Range Ignition (GRC)
- Identify igniter life-limiting phenomena and address wear mechanisms associated with igniter operations. Characterize the repeatability of the ignition pulses over the duration of the test.
- Demonstrate 50,000 ignition pulses using LOx/LCH₄.

WBS 2.1.4 High Area Vacuum Test (WSTF 401)
- The design and testing of high area ratio (150+) workhorse engine to obtain nozzle performance and kinetics data with LOx/LCH₄ in vacuum conditions.

WBS 2.1.5 100-lbf Sea Level Testing (GRC)
- Build a system to provide propellant conditioning for liquid oxygen (LOx) and liquid methane (LCH₄) to test 25-100 lbf rocket engines.
- Tight controls on pressure and temperature to provide a wide range of operating set points not available at other facilities.

WBS 2.1.6 100-lbf Vacuum Testing (GRC)
- Hot-fire testing will be conducted at vacuum conditions to determine the ignition and performance characteristics for a 100-lbf thruster.
- Use propellant conditioning system from sea level testing.
WBS 2.2 – Integrated Testing

- Integrate four 100-lbf RCS into the WSTF (Auxiliary Propulsion System Test Bed) APSTB test bed.
  - Perform integrated engine and feed system testing at altitude.
- Configure APSTB with a main engine simulator
  - Test with multiple RCS engines to determine impacts from main engine operation

870-lbf engine test on APSTB at WSTF 401
Accomplishments – LOx/LCH₄ Ignition

Key Accomplishment:
- Over 150 vacuum ignition tests with Aerojet spark torch igniter in GRC RCL21
- Over 1400 vacuum pulse cycles on in-house RCE class spark torch igniter in GRC RCL21
- Over 750 tests vacuum testing with main engine class spark torch igniter in GRC RCL21
- Aerojet – Vacuum testing of spark torch igniter for 100-lbf RCE thruster
- Northrop Grumman – Vacuum testing of spark torch igniter for 100-lbf RCE thruster
- ATK - Sea level testing spark torch igniter for 7500-lbf thrust main engine
- KTE - Sea level testing spark torch and catalytic igniter for 7500-lbf thrust main engine. Testing also at Purdue University.

Significance:
- Testing has demonstrated that oxygen – methane ignition systems can operate over a wide range of pressure, temperature, and mixture ratio conditions.
- System / sub-system tests are keys to identifying technical challenges for vehicle application.
Accomplishments - RCS Thruster

Key Accomplishment/Deliverable/Milestone:

- GRC successfully completed 156 ignition runs with a modified Aerojet Corporation Igniter.
- Completed Aerojet 870-lbf LOx/LCH4 thruster testing in WSTF Auxiliary Propulsion System Test Bed (APSTB) (April 2007)
- Completed Northrop Grumman 100-lbf thruster Test Series 3 and 4 with workhorse hardware. (May 2007)
- Completed Aerojet 100-lbf thruster Option 1 with pre-prototype engine.
  
  - Fastest known demonstrated pulse width for a cryogenic thruster. The engine has produced a 40 msec EPW (Electrical pulse width 40 msec on 120 msec off-25% Duty Cycle). (June 2007)

Significance:

- Testing has demonstrated that reaction control engines with non-toxic propellants can be ignited over a range of conditions and can meet key performance parameters.
WBS 3.1 – Ascent Main Engine

WBS 3.1.1 Ascent Main Engine Contracts (MSFC/GRC)
- Contract with industry for next-generation of a workhorse engine for engine performance demonstrations.
  - Injector combustion efficiency (target ~98%) and chamber heat transfer

WBS 3.1.2 In-house Combustion Performance (MSFC)
- Evaluate injector concepts with potential of enhancing C* (combustion) efficiency.
  - Characterize C* and heat transfer for either regenerative or ablative combustion chambers in existing 6”-diameter water cooled hardware and ablative chamber

WBS 3.1.3 Main Engine Vacuum Performance (WSTF/MSFC)
- Test workhorse engine hardware in vacuum conditions at WSTF 401 to Characterize specific impulse (Isp) and nozzle performance.

WBS 3.1.4 Igniter Vacuum Characterization (MSFC)
- Characterize torch igniter with in-space relevant environment (vacuum, low temperature) through hot-fire tests and CFD simulation
- Demonstrate and characterize microwave igniter in vacuum conditions

WBS 3.1.5 Dual Diverse Igniters (GRC)
Evaluate common components between main and redundant ignition system

WBS 3.1.6 High Temperature Materials (MSFC)
Characterize fabrication process for high temperature (possibly >4700°F) thrust chambers.
Accomplishments - Ascent Main Engine

**Key Accomplishment:**

- Continued work on two contracts for development of prototype engines along with in-house injector designs at NASA MSFC.
  - KT Engineering (Ablative chamber)
  - ATK GASL (Regenerative-cooled chamber)
- Design reviews completed for ATK 7500-lbf design (January 2007) and 3500-lbf design (June 2007)
- Completed ATK segmented engine testing at XCOR (March 2007)
- Completed 6” LOx/LCH4 Swirl Coax in-house injector testing at NASA MSFC (May 2007)
- Completed ATK workhorse engine testing at XCOR (July 2007)
- KTE workhorse engine testing at MSFC discontinued with contract performance period (Sept 2007)
- Issued RFP for follow-on contract addressing revised Altair requirements

**Significance:**

- Test results provide initial performance measures and igniter results for LOx/LCH4 main engines.
- Test results did not meet required combustion efficiency
- Additional workhorse class testing required
WBS 3.2 – Descent Main Engines

- **Demo 1.6 - Insulated/Revised area injector (PWR)**
  - Base RL10A-4 injector with **insulated inter-propellant plate** and backplate with a revised LOx flow area

- **Demo 1.7 Two stage injector (PWR)**
  - **Second LOx manifold** added to base RL10A-4 injector
  - Required for high thrust/deep throttle applications
  - System level test required to determine ultimate operability and effectiveness

- **Pintle Variable Area Injector Technology**
  - Fabricating injector

*Hot-fire test of deep throttling CECE engine in PWR E6 – West Palm Beach*
Accomplishments - Descent Main Engine

Key Accomplishment
• Successful Preliminary Design Review of NGST Pintle Injector Test Bed was completed (November 2006)
• NGST Pintle test bed injector critical design review (March 2007)
• Completed PWR CECE Demo 1.5. Conducted 4 hot fire tests, with total run time of approximately 2100 seconds. (April 2007)
• Completed Preliminary Design Review PWR CECE Demo 1.6 (January 2008)

Significance:
• Testing demonstrated stable operation to 20% (5:1) throttle point and throttling operability to 9.5% (11:1).
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WBS 4.1 – Orion CM 25-lbf Gas-Gas Thruster

- Dual regenerative cooled thruster with gaseous oxygen and gaseous methane as the propellants
- **Self-contained ignition** system that does not require interfaces with the vehicle’s electrical system
- Technology will lead to a non-toxic propulsion system that is **simple and reliable**
- Technology is transferable to Lunar Lander as option for improved vehicle control.
- Contract with PWR to obtain and modify 25-lbf thruster
  - Previously evaluated as a GOx/GH₂ ISS candidate thruster
- Test hardware at sea level and vacuum conditions.
  - Obtain thrust and heat transfer data to quantify engine performance and ignition reliability

**Key Accomplishment:**
- PDR completed

25lbf Rocketdyne GOx/GH2 ISS candidate thruster installed at GRC RCL11 in 1989
Summary

• Exploration mission is more ambitious than the Apollo mission
  – More people to the surface
  – Longer duration stays

• New technologies are required to meet more difficult missions
  – High performance LOX/LH2 deep throttle descent engines
  – High performance LOX/LCH4 ascent main and RCS engines

• The PCAD Project is on the path to provide those technologies
  – Reliable ignition
  – High efficiency engines
  – Reliable pulse RCS
  – Fast start
  – Stable deep throttling