

Abstract for ESA-3AF Space Propulsion 2010

Title: Liquid Oxygen/Liquid Methane Component Technology Development at MSFC

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The National Aeronautics & Space Administration (NASA) has identified Liquid Oxygen (LOX)/Liquid Methane (LCH₄) as a potential propellant combination for future space vehicles based upon exploration studies. The technology is estimated to have higher performance and lower overall systems mass compared to existing hypergolic propulsion systems. Besides existing in-house risk reduction activities, NASA has solicited from industry their participation on component technologies based on the potential application to the lunar ascent main engine (AME).

Contracted and NASA efforts have ranged from valve technologies to engine system testbeds. The application for the AME is anticipated to be an expendable, pressure-fed engine for ascent from the moon at completion of its lunar stay. Additionally, the hardware is expected to provide an abort capability prior to landing, in the event that descent systems malfunction.

For the past 4 years, MSFC has been working with the Glenn Research Center and the Johnson Space Center on methane technology development. This paper will focus on efforts specific to MSFC in pursuing ignition, injector performance, chamber material assessments and cryogenic valve technologies. Ignition studies have examined characteristics for torch, spark and microwave systems. Injector testing has yielded insight into combustion performance for shear, swirl and impinging type injectors. The majority of chamber testing has been conducted with ablative and radiatively cooled chambers with planned activities for regenerative and transpiration cooled chambers. Lastly, an effort is underway to examine the long duration exposure issues of cryogenic valve internal components. The paper will summarize the status of these efforts.

LIQUID OXYGEN/LIQUID METHANE COMPONENT TECHNOLOGY DEVELOPMENT AT MSFC

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1.0 SUMMARY OF ESAS

In April 2005, the National Aeronautics & Space Administration (NASA) began restructuring the NASA Exploration Program to accelerate development of the Crew Exploration Vehicle (CEV, now known as Orion) to reduce the gap of United States human access to space. To reduce the number of required launches and ease the transition after Space Shuttle retirement in 2010, the Agency examined the cost and benefits of developing a Shuttle-derived Heavy-Lift Launch Vehicle to be used in lunar and Mars exploration.

The Exploration Systems Architecture Study (ESAS)¹ team was chartered with determining the best exploration architecture and strategy to implement these changes. The ESAS team commenced work in May 2005 with a 90 day Agency-wide study to a) assess the CEV requirements, b) define top level requirements for crew & cargo launch systems, c) develop a reference exploration architecture and d) identify key technologies to enable and enhance these exploration systems.

The ESAS team examined a wide variety of propulsion system types and delta velocity allocations for each architecture element. To achieve a high reliability lunar ascent propulsion system and to establish the linkage to in-situ propellant use, common pressure-fed LO₂/LCH₄ engines were chosen for the CEV service module (SM) and lunar ascent stage propulsion systems (Figures 1 and 2, respectively).

For the assessment, ESAS identified what technologies were needed and the schedule needed to support the development projects, developed an objective prioritization and planning process, and developed research &

technology investment recommendations. Of the many technology recommendations, ESAS recommended further work for human-rated LO₂/LCH₄ main engines and reaction control system (RCS) for the CEV SM and the Lunar Surface Access Module (LSAM, now known as Altair).

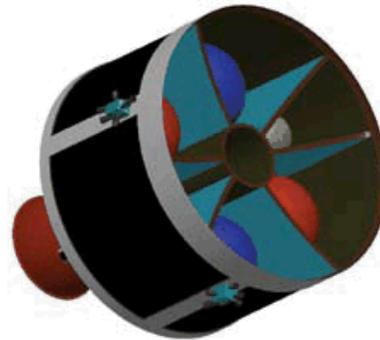


Figure 1 – ESAS Crew Exploration Vehicle Service Module Configuration

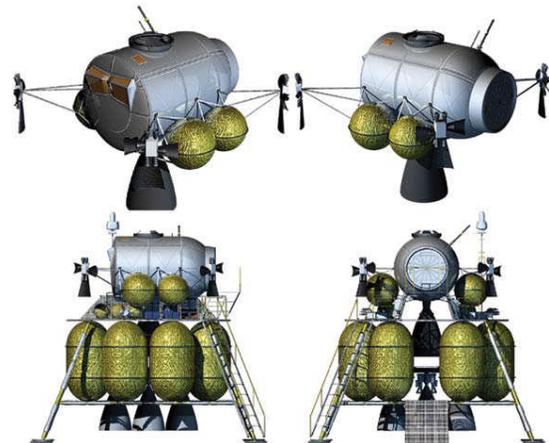


Figure 2 – ESAS Lunar Surface Access Module Configuration

2.0 TECHNOLOGY DEVELOPMENT PROGRAM

The Exploration Technology Development Program (ETDP), managed at the NASA Langley

Research Center, became the mechanism for pursuing the technologies identified during the ESAS study. ETDP provides cross cutting technologies that are being considered and/or used by the elements of the Constellation Program: Ares I, Ares V, Orion and Altair.

Multiple NASA Centers have leadership and support roles for areas such as propulsion, structures, materials, life support systems and avionics. Within ETDP is the Propulsion and Cryogenic Advanced Development Project Office (PCAD) managed at the NASA Glenn Research Center (GRC). PCAD is performing experimental and analytical evaluation of several propulsion systems to enable safe and cost effective exploration missions. The Project has elements that are engaged in technology development of throtttable LO₂/liquid hydrogen (LH₂) engines for lunar descent and LO₂/LCH₄ ascent main engine and RCS. GRC, MSFC and the Johnson Space Center (JSC) participate in providing technical insight into contracted activities as well as providing in-house research capability.

An initial PCAD investment in early 2006 was made in developing LO₂/LCH₄ technologies for application to the Orion SM. During the conduct of two industry contracts, the test results provided initial performance and igniter results for LO₂/LCH₄ main engines. These test results did not meet required combustion efficiency goals and issues with manufacturing were also encountered².

Given the challenges of initial testing, the Agency decided to reduce schedule risk for the Orion architecture by altering the acquisition strategy. Because this technology is key to NASA's long term strategy for Mars, the goal was to introduce this technology into Constellation once it is considered mature³. This propellant combination could result in performance increases over existing in-space propulsion technologies, thereby lowering the overall vehicle system mass or allow more payload delivery to the lunar surface by Altair.

In the Fall of 2008, PCAD developed a request for proposal (RFP) with a focus on Altair lander requirements for an ascent main engine. It is anticipated that this application would be an expendable, pressure-fed engine. Beyond the performance goals of 98% combustion efficiency

and a vacuum specific impulse of 355 seconds, the engine would require reliable ignition especially in the event an abort during the descent phase occurred. Aerojet was selected during this competition, has completed sea level testing and is continuing vacuum testing at the NASA White Sands Test Facility (WSTF). The remainder of this paper will now focus on LO₂/CH₄ technology development at MSFC.

3.0 MSFC IN-HOUSE EFFORTS

Supplementing and sometimes complementing contracted activities, MSFC has worked on an array of component technologies that are essential to meeting the Altair mission. MSFC has conducted ignition, injector configuration, long duration exposure to cryogenic valves and chamber material assessments through sea level and simulated vacuum testing. This testing has provided insight into ignition and injector performance with sea level test data. Contracted activities are pursuing the specific impulse data in a relevant environment (simulated vacuum test conditions at WSTF).

4.0 IGNITION TESTING

In the summer of 2007, ignition component testing was performed to evaluate three ignition sources: direct spark plug, microwave and torch. Each igniter was demonstrated at similar conditions to verify that they could successfully and reliably ignite LO₂/LCH₄ at sea level. Eventually these components were coupled with the swirl and impinging injectors to obtain sea level hotfire test results. Based upon the results of these tests, the torch and microwave were selected for further component testing in simulated vacuum conditions.

Additional testing of the torch and microwave igniters occurred in April/May 2008. The objective was to define the ignition limits and characterize the transient start-up performance under simulated vacuum conditions. Shown in Figure 3 is the torch igniter installed in MSFC Test Stand 115 (TS115).

Both igniters provided repeatable results however the power draw for microwave igniters may prove to be an issue for consideration in a lander design. This provided further insight into test

parameters for future injector design and thrust chamber hotfire tests.



Figure 3 – Ignition Test Rig at MSFC

4.1 Injector Testing

A test program was performed in the summer of 2007 to evaluate a LO₂/LCH₄ injector design. A new impinging injector was provided for testing at various chamber pressures, mixture ratios and with different levels of fuel film cooling (FFC). It was designed to mate with existing calorimeter chamber hardware. When testing of the 6 inch (15.24 cm) impinging injector was completed, a further review of previous MSFC testing suggested that higher performance may be available from testing with a coaxial injector design.

After evaluating the impinging injector with ablative and calorimeter hardware, a swirl coaxial injector was tested to further evaluate the performance potential for this propellant combination. Existing injector assets were brought to bear and were modified from high pressure LO₂/LH₂ service to low pressure LO₂/LCH₄ as shown in Figure 4. Since the 28 element coaxial injector did not provide a center port for the igniter like the impinging injector, the hypergolic fluid triethylaluminum / triethylboron (TEA/TEB) was used for ignition and it was provided through one of the ports in the side of the transition spool.

As shown by Figure 5, initial testing of the swirl coaxial injector showed promising results compared to our design goal of 98% combustion efficiency⁴.



Figure 4 – Sea Level Thrust Chamber Assembly

Based upon these results, MSFC decided to modify an existing 40 element injector to promote more efficient mixing.

In recent testing (January 2008) of a 40 element swirl coaxial injector shown in Figure 6, the team determined insufficient delta pressure (ΔP) was provided on the LO₂ side with the existing swirl orifices. Low frequency chugging was observed and back flow of combustion products behind the injector face likely occurred. A higher ΔP could be obtained with modified orifices.

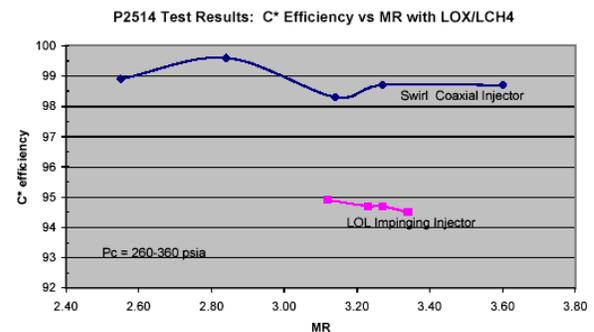


Figure 5 – Summer 2007 Combustion efficiency test results



Figure 6 – January 2008 Sea Level Test

From a fuel perspective, a higher ΔP /chamber pressure (P_c) helped provide more stable fuel flow compared to the 28 element swirl injector. Stability analysis suggested higher margin should be attempted to maintain stable flow and reduce

the potential for noise. Selected modifications were approved and tested again in May 2008.

Recent testing in the Spring of 2009 with the modified 40 element swirl coaxial injector with liquid oxygen/gaseous methane has met our combustion efficiency goal at more desirable chamber lengths (shorter). If there is interest in regenerative cycle engines, than additional liquid/gas testing may be pursued.

4.2 Cryogenic Valve Testing

A risk to extended duration missions is the effects of long duration exposure on cryogenic valves due to space environments. To investigate available valve technologies, MSFC generated a request for information⁵ (RFI) in Nov. 2009 to seek market information for planning purposes. In parallel to that activity, MSFC began working on existing off-the-shelf cryogenic valves to explore an expanded acceptance test procedures for long duration exposure.

The majority of spacecraft that are exposed to the space environments for a long duration utilize storable propellant systems which materials do not work in cryogenic applications. All standard cryogenic fluid controls utilized in propulsion systems today are focused on launch vehicles with minutes of life, unmanned scientific satellites with longer life, and a few space station applications where crew rescue or resupply is possible within days or weeks. Longer duration missions such as being considered for LO₂/CH₄ usage must have robust and reliable propulsion systems that work when needed.

Current testing of the existing valve at MSFC has led to the discovery of several issues. The seals in the actuator leaked as temperatures were lowered for long periods of time. The actuator and pilot valve response times were adversely affected to not operate reliably for an engines ability to start. Seal friction increased and the breakaway torque requirements exceeded the actuator capability as the temperature dropped. Lastly, the pilot valve leakage became unacceptable with lowered temperatures.

Further MSFC testing will explore effects in a simulated vacuum condition with ultraviolet radiation, charged particle radiation and thermal cycling between +150 to -150C. These tests will

be conducted over a 6 month simulated lunar exposure to baseline effects with existing valve. These issues coupled with industry responses to the valve RFI may be used in future months to explore remedies to these concerns.

4.3 Thrust Chamber Configurations

MSFC has also been evaluating a variety of chamber technologies in support of this propellant combination. Since inception of work in 2007, MSFC has conducted 89 ablative and 27 water cooled calorimeter tests accumulating over 350 seconds of mainstage injector performance data.

During the 2nd quarter of 2010, an industry partner provided a regenerative cycle engine for testing at MSFC. A mixture of standard and composite chamber materials are being evaluated through sea level testing. Likewise, a 1000 lbf (4,448 N) and 6,000 lbf (26,689 N) class high temperature material chambers are beginning testing as well. Given the Altair design with a submerged ascent main engine nozzle, it may not be feasible to consider this radiatively cooled technology for that application. However, other applications like the Orion SM could be more practical given that the nozzle is openly exposed to space conditions.

Lastly as shown in Figure 7, an effort is underway with an industry partner looking at transpiration chamber cooling. Multiple, tiny holes are drilled into the chamber for methane injection. Although the technology will provide active cooling, there is the concern on decrementing the combustion efficiency due to unburned methane. MSFC provided the contractor with calorimeter hardware data for a given injector configuration and await testing with the transpiration chamber to assess performance against known combustion data with ablatives.



Figure 7 – Example of transpiration chamber

5.0 CONCLUSIONS

The MSFC team has been diligently pursuing an understanding of this propellant combination for consideration as the ascent main engine for the Altair Lunar Lander. As stated earlier, there are three major objectives being evaluated with this in-house hardware: reliable and repeatable ignition in a relevant environment, achieving 98% combustion efficiency and providing a specific impulse of 355 seconds. Current sea level testing at the component level has shown demonstration of 98% combustion efficiency and two different igniter concepts are showing promise for repeatable performance as well as identifying inlet condition bounds.

To prove out the final performance objective, the vacuum testing at WSTF is paramount to proving that this technology is viable. Analytical tool predictions have been limited without acquiring empirical data. Future work will also include development of analytical models to predict engine operation and performance.

6.0 ACKNOWLEDGEMENTS

Test planning and data acquisition for evaluating this technology would be unsuccessful without the persistence, dedication and hard work of Sandy Elam, James Richard and the MSFC Test Stand 115 Test Team.

REFERENCES

- 1 – NASA's Exploration Systems Architecture Study, NASA-TM-2005-214062, Nov 2005
- 2 – Briefing to the National Research Council, Dec. 11, 2007
- 3 – Fiscal Year 2007 Budget Press Conference, transcript Feb. 6, 2006
- 4 – Test Summary Report For Test Program P2514, 6 Inch LOX/LCH4 Injector Demonstration, Aug. 7, 2007
- 5- NASA RFI NNM10ZPS001L Request for Information on Long Term Space Exposure Cryogenic Valve Technologies

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**LIQUID OXYGEN/LIQUID METHANE COMPONENT
TECHNOLOGY DEVELOPMENT AT MSFC**

NASA/MSFC SCIENCE & MISSION SYSTEMS DIRECTORATE



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Introduction



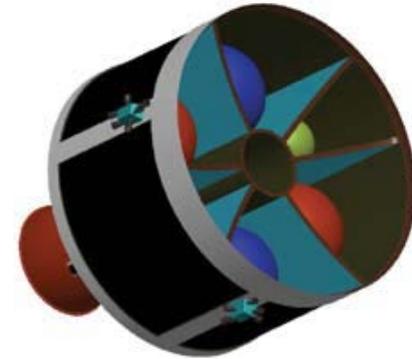
- The National Aeronautics & Space Administration (NASA) has identified Liquid Oxygen (LO₂) / Liquid Methane (LCH₄) as a potential propellant combination for future space vehicles based upon the Exploration Systems Architecture Study (ESAS).
- A lunar lander LO₂/LCH₄ Ascent Main Engine is being considered as an expendable, pressure-fed engine capable of 5,500 lbf (24,465 N) thrust.
- Primary technology risks include establishing ignition in vacuum conditions, maximizing specific impulse (I_{sp}), developing rapid start for descent abort, capability to perform multiple starts and producing a total engine burn time over 500 seconds.
- This presentation will highlight activities underway at the NASA Marshall Space Flight Center (MSFC) to address risk reduction activities for this technology.



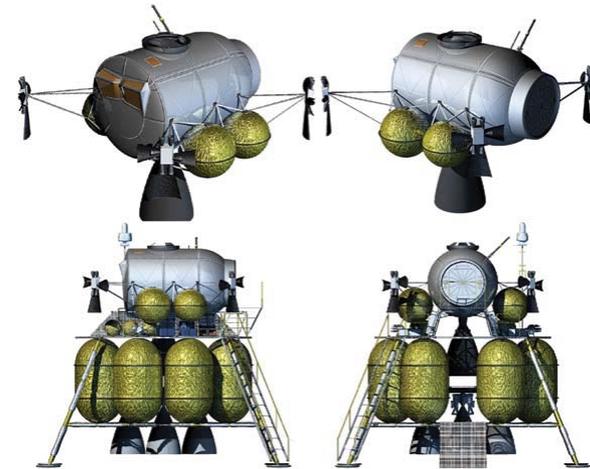
ESAS Overview



- The ESAS team was chartered in May 2005 with determining the best strategy for reducing the gap of United States human access to space.
- For each architecture examined, a wide variety of propulsion systems and delta velocity allocations were considered.
- To achieve a high reliability lunar ascent propulsion system and to establish the linkage to in-situ propellant use, common pressure-fed LO₂/LCH₄ engines were chosen.
- As a result of the ESAS study, LO₂/LCH₄ technology development was recommended for application to the Crew Exploration Vehicle (CEV) Service Module and the Lunar Lander.



ESAS CEV Service Module (SM)



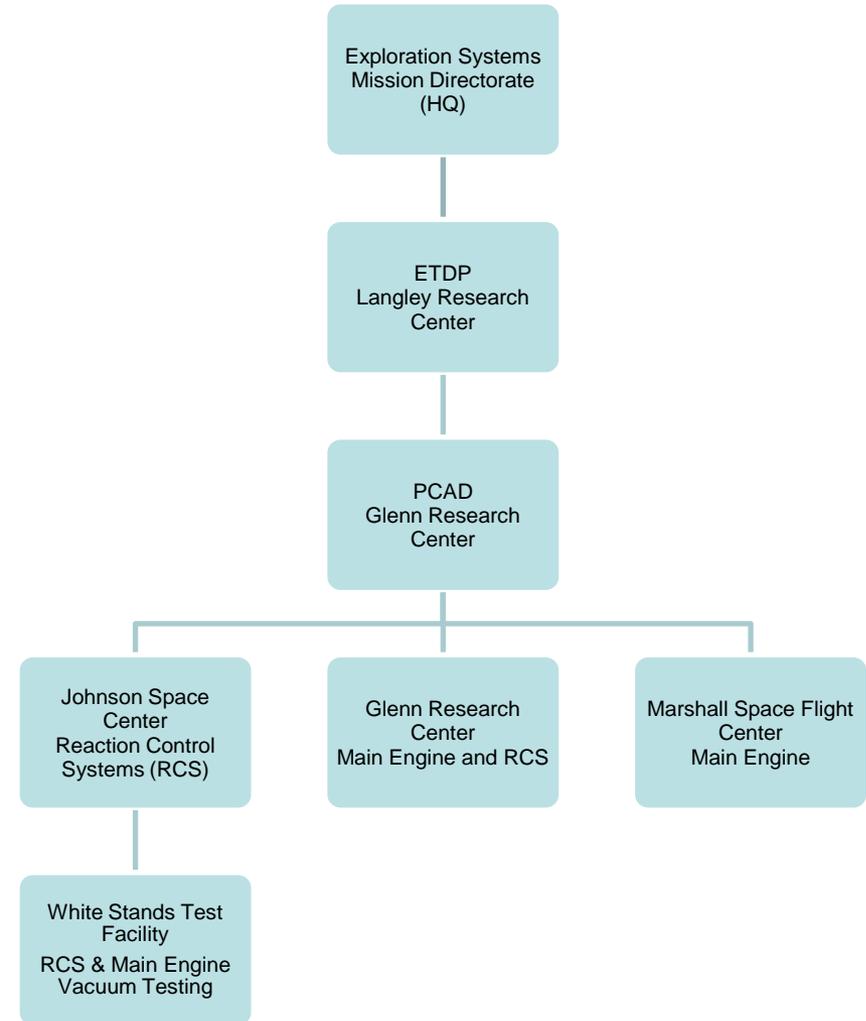
ESAS Lunar Surface Access Module



Technology Development Organization



- The Exploration Technology Development Program (ETDP) is pursuing technologies being considered by multiple elements of the Exploration Architecture.
- Specific to propulsion, the Propulsion & Cryogenic Advanced Development (PCAD) Project Office is performing experimental and analytical evaluation of several systems.
- In early 2006, an initial investment in LO2/LCH4 was made for application to the CEV SM.
- These early test results did not meet required combustion efficiency.
- Furthermore, a decision to alter the acquisition strategy to reduce schedule risk moved the application from the CEV SM to Altair.





MSFC In-House Efforts



- For risk reduction of LO₂/CH₄ technologies, MSFC has performed work on the following:
 - Ignition
 - Injector configurations
 - Long duration exposure to cryogenic valves
 - Chamber materials
- These activities focused on:
 - Reliable and repeatable ignition in a relevant environment.
 - Design an injector capable of 98% combustion efficiency.
 - Explore the potential to reach 355 sec of vacuum Isp.
- For the last 4 years, MSFC has been conducting sea level testing of igniter and injector hardware at the component level.
 - Igniter tests have evaluated ignition limits and characterized the transient start-up performance for multiple concepts.
 - Injector tests have shown a swirl concept as a high performer.



Ignition Sea Level Testing



- In the summer of 2007, MSFC evaluated spark plug, microwave and torch igniters.
- After sea level component tests, each configuration was tested with an injector concept.
- The torch and microwave were selected for further simulated vacuum testing.
- The igniter test rig includes an ejector which, under the appropriate flow conditions, pumps down the test article to pressure less than ambient.
- Recently completed igniter testing has shown repeatable ignitions and these units are now being prepared for combined systems test.



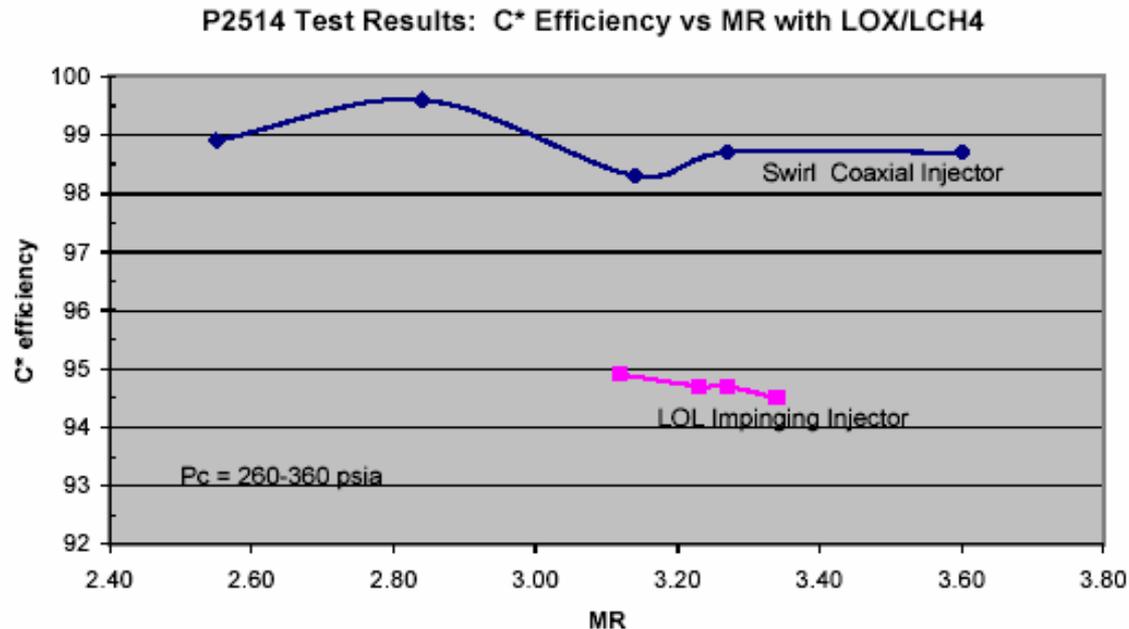
MSFC Igniter Test Rig



MSFC Injector Testing

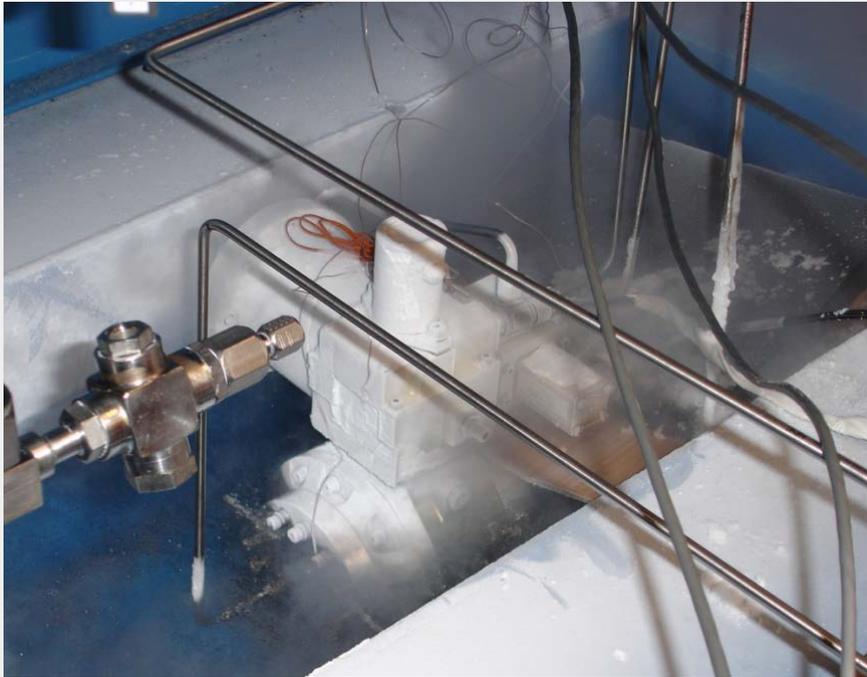


- Testing in 2007 evaluated a like-on-like impinging concept and a swirl coaxial injector configuration.
- Tests were conducted at various element densities, chamber pressures, chamber lengths, mixture ratios and fuel film cooling.
- Further work has progressed from liquid/liquid to liquid/gas injection to minimize chamber lengths while keeping same element density.
- Since inception, MSFC has conducted 89 ablative and 27 calorimeter tests accumulating over 350 seconds of mainstage data.





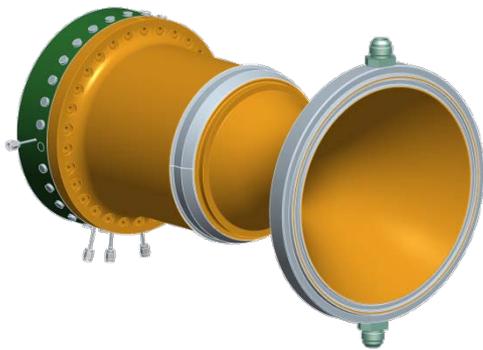
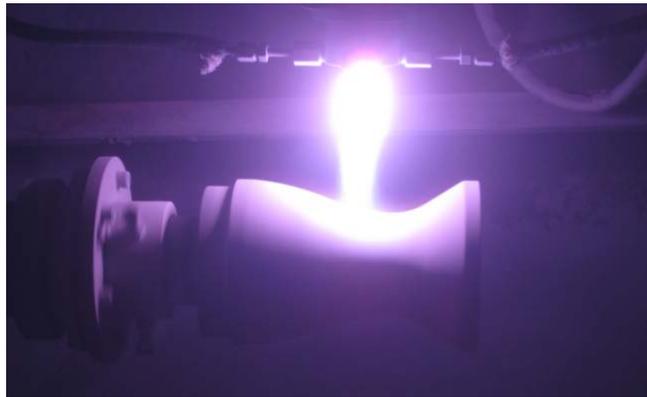
Cryogenic Valve Work



- Cryogenic valves have not been used on manned vehicles for long duration missions.
- Although storable propellant systems have long history, their materials are not compatible for cryogenic use.
- MSFC conducted expanded acceptance test procedures on an existing valve leading to seal leakage, reduced valve response times and increased seal friction.
- Future testing will examine effects of lunar environment including UV radiation and thermal cycling.
- This work coupled with industry feedback can lead to mitigation of these concerns.



Thrust Chambers



- High temperature materials for radiative cooling have been produced and are being tested the summer of 2009.
- These chambers may be better suited to exposed nozzle as opposed to Altair configuration.
- An industry partner provided test assets for a regenerative cooled engine system which is evaluating up to 4 chamber materials.
- Another industry partner is providing a transpiration cooled chamber for comparison to sea level ablative test results.



Ignition

- MSFC testing of the torch and microwave igniter explored the ignition limits and characterized the transient start-up performance as a function of mixture ratios, propellant flow rates, propellant temperatures and igniter chamber pre-ignition pressures.
- The ignition testing appear to be as robust in vacuum as what was observed in previous component sea level testing.

Injector Performance

- Improved mixing from the higher element density did increase combustion efficiency.
- Modification of the swirl orifices did improve performance at decreased chamber lengths, especially with liquid/gas injection.

System Performance

- With the capability to achieve 98% combustion efficiency, the technology awaits testing of a larger nozzle configuration in a relevant environment.
- Consideration of long duration exposure to cryogenic valves coupled with demonstration of vacuum performance can lead to maturation of this propellant combination for future exploration vehicles.