MSFC-2022-PAPER

IAC-08-C4.1.02

LIQUID OXYGEN/LIQUID METHANE ASCENT MAIN ENGINE TECHNOLOGY DEVELOPMENT

Joel W. Robinson
David D. Stephenson
National Aeronautics & Space Administration
Marshall Space Flight Center
United States of America
joel.w.robinson@nasa.gov
david.d.stephenson@nasa.gov

ABSTRACT

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). The technology is estimated to have higher performance and lower overall systems mass compared to existing hypergolic propulsion systems. The current application considering this technology is the lunar ascent main engine (AME). AME is anticipated to be an expendable, pressure-fed engine to provide ascent from the moon at the completion of a 210 day lunar stay. The engine is expected to produce 5,500 lbf (24,465 N) thrust with variable inlet temperatures due to the cryogenic nature of the fuel and oxidizer. The primary technology risks include establishing reliable and robust ignition in vacuum conditions, maximizing specific impulse, developing rapid start capability for the descent abort, providing the capability for two starts and producing a total engine burn time over 500 seconds. This paper will highlight the efforts of the Marshall Space Flight Center (MSFC) in addressing risk reduction activities for this technology.

FULL TEXT

1.0 Summary of ESAS

With the selection of a new NASA administrator in April 2005, NASA began the process of restructuring the NASA Exploration Program to accelerate development of the Crew Exploration Vehicle (CEV) 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).

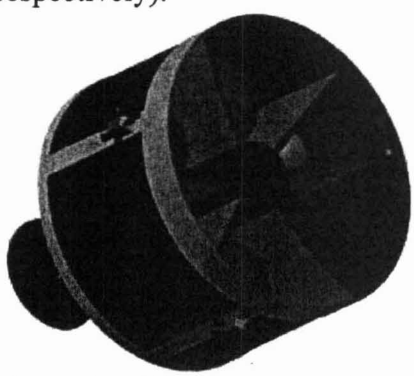


Figure 1 – ESAS Crew Exploration Vehicle Service Module Configuration

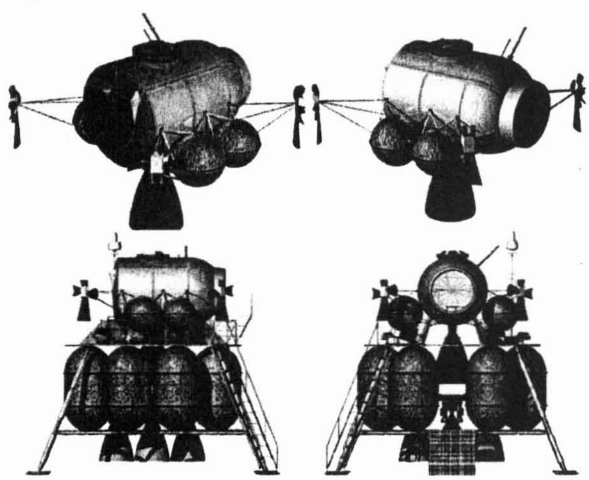


Figure 2 – ESAS Lunar Surface Access Module Configuration

The ESAS team had to identify key technologies which would enable and significantly enhance the reference exploration systems and prioritize near and far term investments.

For the assessment, ESAS identified what technologies were needed and when they would be available 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).

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 and LSAM (now referred to as 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. 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 throttable LO2/liquid hydrogen (LH2) engines for lunar descent and LO2/LCH4 ascent main engine and RCS.

An initial PCAD investment in early 2006 was made in developing LO2/LCH4 technologies for application to the CEV 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 and issues with manufacturing were also encountered[2].

During this time, a decision was made at NASA headquarters to reduce schedule risk for the CEV 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 mature[3]. 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.

3.0 MSFC In-house Efforts

In concert with LO2/LCH4 technology development efforts at the GRC, MSFC developed a plan for providing main engine performance data. The Altair Lunar Lander Project Office had identified a February 2009 milestone for assessing the progress of technologies that are being considered for the lander.

The industry effort on LO2/LCH4 for the CEV SM propulsion system was in the process of being shut down while efforts were underway to develop a new request for proposal (RFP) which was now responsive to only Altair requirements. Since the process of developing a RFP, receiving industry feedback, reviewing industry proposals and selecting the offeror would delay receipt of performance data past the February milestone, the MSFC team devised a plan to achieve early vacuum performance data as risk reduction for the contracted effort by the use of MSFC developed in-house assets.

The MSFC team began the process of identifying the key technology risks with GRC. Based upon those discussions, the in-house activities would concentrate on 3 primary areas.

First was reliable and repeatable ignition in a relevant environment. This led to developing test plans to pursue simulated vacuum testing at the NASA White Sands Test Facility (WSTF) in New Mexico. Second was to design an injector capable of providing 98% combustion efficiency. Given existing work on ablative type engines (as opposed to regeneratively cooled concepts), there existed the potential to require fuel film cooling (FFC) to avoid chamber hot spots or localized oxidation. Maximizing the combustion efficiency and maintaining adequate chamber conditions could prove to be challenging. The third area to explore was the potential to reach a specific impulse of 355 seconds.

3.1 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 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 LO2/LH2 service to LO2/LCH4. 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 3, the swirl coaxial injector showed promising results compared to our design goal of 98% combustion efficiency[4]. Based upon these results, MSFC decided to modify an existing 40 element injector to promote more efficient mixing.

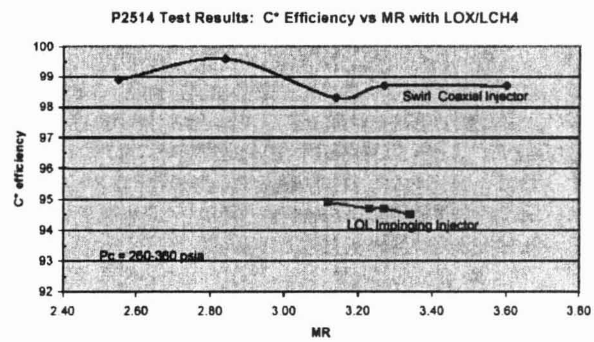


Figure 3 – Summer 2007 Combustion efficiency test results

In recent testing (January 2008) of a 40 element swirl coaxial injector, 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.

From a fuel perspective, a higher ΔP/chamber pressure (Pc) 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. This latest testing is providing insight into additional design changes as MSFC fabricates a 5,500 lbf (24,465 N) LO2/LCH4 swirl coaxial injector for further sea level and eventual simulated vacuum testing.

3.2 Ignition Testing

In the summer of 2007, ignition component testing was performed to evaluate three ignition sources: direct spark plug, microwave and torch. The first set of tests used TEA/TEB for ignition. 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 4 is the torch igniter installed in MSFC Test Stand 115 (TS115).

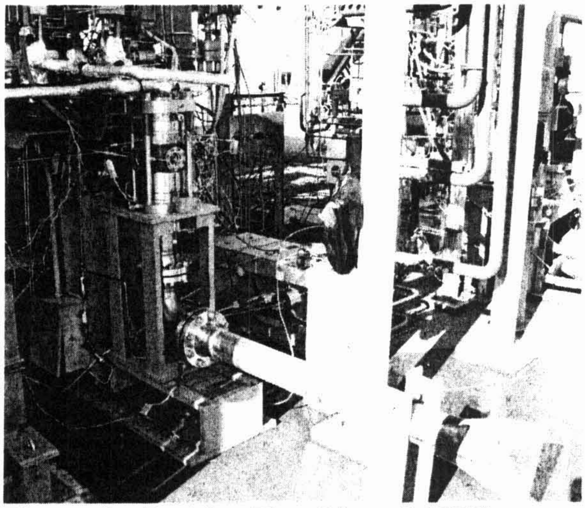


Figure 4 – Ignition Test Rig at MSFC

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.

3.3 Thrust Chamber Assembly Configurations

Figure 5 is an example of the test setup for the ablative testing performed for the injector configurations. The area ratio of the hardware for sea level testing at MSFC was 2:1 to prevent flow separation.

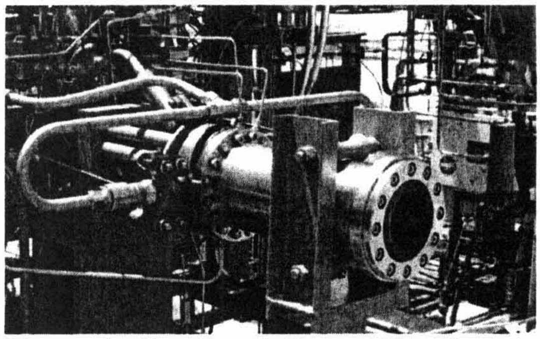


Figure 5 – Sea Level Thrust Chamber Assembly

Figure 6 shows an example of a hotfire conducted in January 2008. This is an appropriate size for early technology demonstration but larger area ratio nozzles would be needed to further demonstrate scaling and performance. To date, testing has demonstrated the first two major objectives of in-house testing at sea level: reliable ignition and combustion efficiency. What has yet to be demonstrated is achieving the specific impulse of 355 seconds.

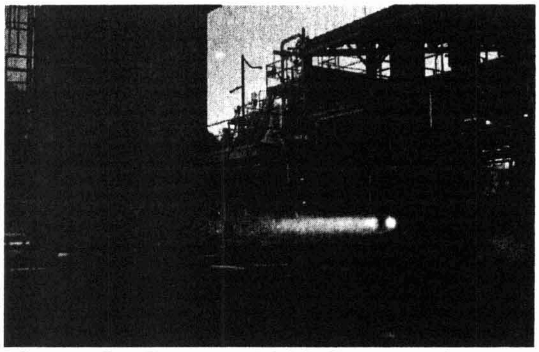


Figure 6 – January 2008 Sea Level Test

To increase the technology progress, chamber and nozzle trades were performed to evaluate what was technically possible within the budget and schedule constraints allocated to the MSFC team. Consideration was given to utilizing existing orbital maneuvering system (OMS) nozzles from the Space Shuttle Program since they were of similar thrust class and would provide test data for an area ratio range that was more flight-like. The calculated area ratio required for the LO2/LCH4 engine system is 150:1. After technical evaluation, it was determined that the nozzle contour mismatch could actually penalize the specific impulse.

The design that was chosen within the budget and time constraints was a 20:1 nozzle configuration. The MSFC team could utilize vacuum test data resulting from this nozzle and extrapolate to the desired area ratio. Figure 7 shows the present design of this chamber/nozzle combination.

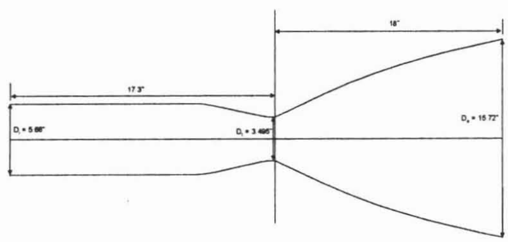


Figure 7 – 20:1 Nozzle for Vacuum Testing

3.4 TCA Testing

Future tests of the MSFC hardware are planned in the winter of 2008 at the WSTF in Las Cruces, New Mexico. Efforts are underway to prepare for both the 2:1 and 20:1 nozzles in the simulated vacuum environment of Test Stand 401 (TS401, Figure 8).

TS401 is a single position, vertical firing carbon steel altitude chamber[5]. It is capable of maintaining a 100,000 ft (30,487 m) altitude simulation by utilizing a steam ejector system.

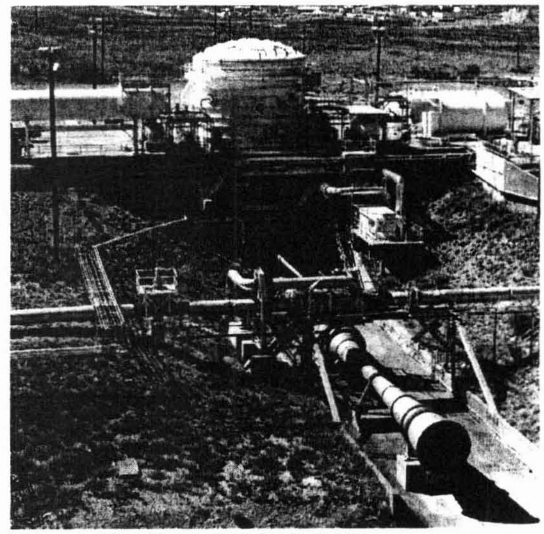


Figure 8 – WSTF TS401 Vacuum Test Chamber

Inside the chamber is a screw-jack precision test article positioning system that can accommodate engine or small vehicle testing.

For early hardware checkout testing, a separate Small Altitude Simulation System (SASS) utilizes three boilers to power small two-stage ejector sets for lower thrust levels. The number of boilers fired, the selection of the ejector combination, and the interchangeable diffusers allow optimization of the entire steam system to engine requirements.

During the hotfire testing that will occur after propellant coldflows and torch igniter tests, the Large Altitude Simulation System (LASS) is utilized to achieve simulated vacuum conditions for thrust levels up to 15,000 lbf (66,723 N). LASS uses a three-module chemical steam generator which powers large, two-stage ejector sets of the system. The number of modules fired, the replaceable nozzles and throat sections of the large ejectors and the interchangeable diffusers allow optimization for engine requirements.

The test hardware will go through a progressive test schedule to perform cryogenic blowdowns, igniter tests and TCA mainstage tests (approximately 5 seconds in duration). Multiple tests are planned for mixture ratio and Pc excursions to compare against sea level test results for the 2:1 nozzle configuration as well as extrapolating vacuum data for flight-like performance from the 20:1 nozzle. Further testing with durations ranging from 30 to 100 seconds is anticipated to evaluate longer duration exposure to the injector face and ablative chamber wear.

Given the higher Pc required of the MSFC hardware, modifications will be needed to operate the WSTF propellant run tanks at higher pressure to accommodate the inlet test conditions. As a backup, industry test facilities are being investigated to mitigate any risk of test slippage. Potential use of other facilities will be more limited on test duration and have limitations on maintaining simulated vacuum conditions required to evaluate the three major objectives of the test program.

4.0 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 three major objectives, the vacuum testing at TS401 is paramount to proving that this technology is viable. Vacuum testing may further show FFC may be required to mitigate injector/chamber heating which would have an adverse effect on combustion efficiency or perhaps generate more questions about this technology. 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.

5.0 Acknowledgements

The authors would like to recognize the PCAD project managers at the NASA Glenn Research Center, Mark Klem and Tim Smith, for their guidance. Test planning and data acquisition for evaluating this technology would be unsuccessful without the persistence, dedication and hard work of Sandy Elam, Dr. Huu Trinh and the MSFC TS115 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 – WSTF TS401 Website
http://www.nasa.gov/centers/wstf/propul
sion/401-OLD.html

IAC-08-C4.1.02

LIQUID OXYGEN/LIQUID METHANE ASCENT MAIN ENGINE TECHNOLOGY DEVELOPMENT

NASA/MSFC SCIENCE & MISSION SYSTEMS DIRECTORATE

Presented by Garry Lyles

Authors: Joel W. Robinson
& David D. Stephenson

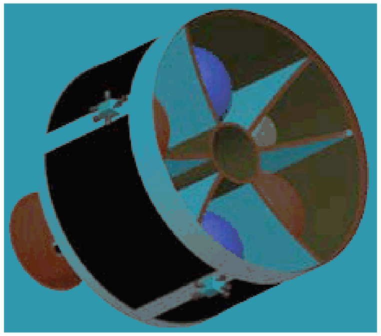
Presented to the 59th International Astronautical Congress
Sept 29, 2008
Glasgow, Scotland

Introduction

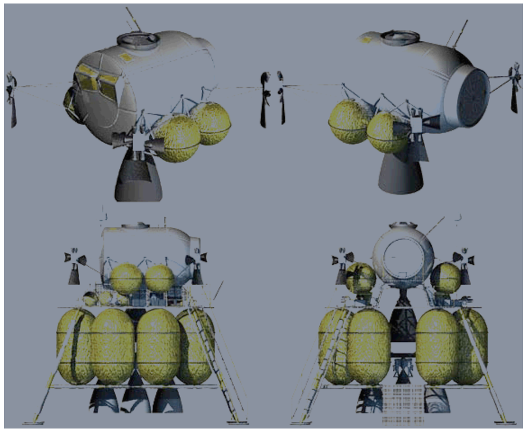
- The National Aeronautics & Space Administration (NASA) has identified Liquid Oxygen (LO2) / Liquid Methane (LCH4) as a potential propellant combination for future space vehicles based upon the Exploration Systems Architecture Study (ESAS).
- A lunar lander LO2/LCH4 Ascent Main Engine is being considered 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 (Isp), 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.



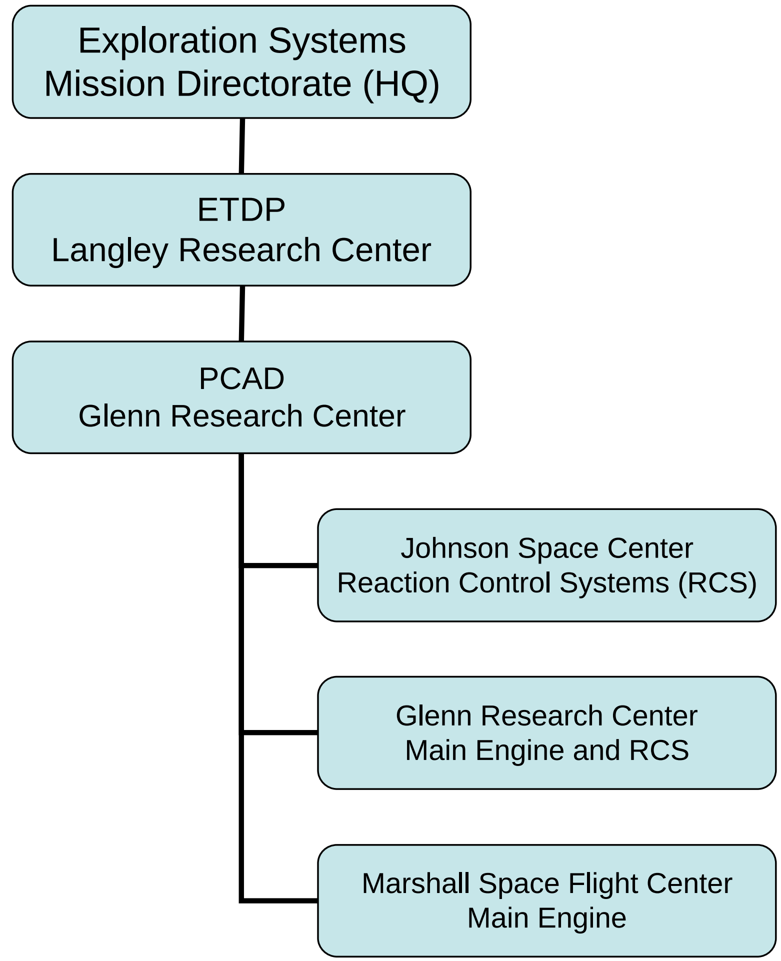
ESAS CEV Service Module (SM)



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.

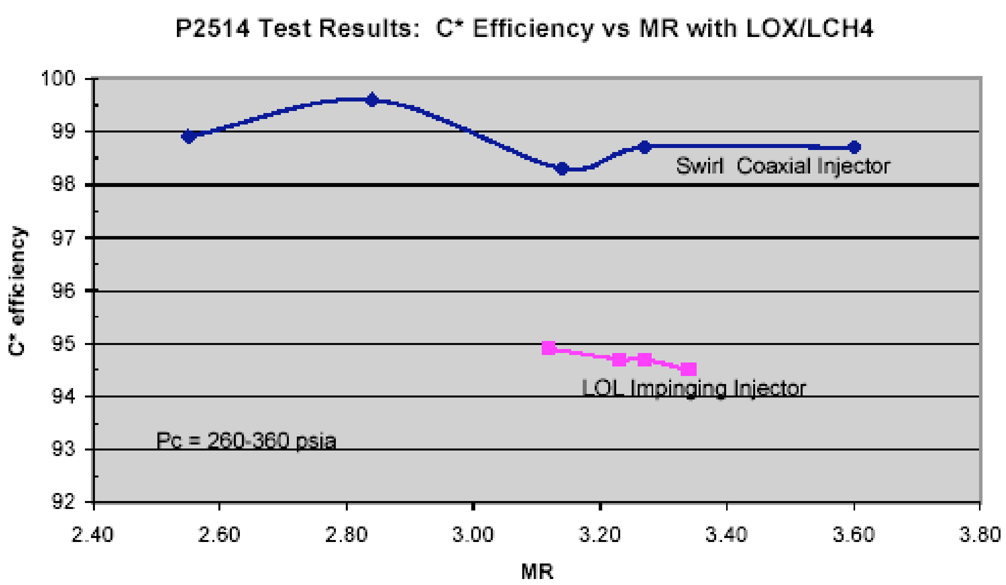


MSFC In-House Efforts

- MSFC devised a plan to achieve early vacuum performance data as risk reduction for future contracted efforts by the use of MSFC developed in-house assets.
- 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 Isp.
- For the last 2 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.
- Current efforts are underway to combine these subsystems into a systems level test.

MSFC Injector Testing

- Testing in the summer of 2007 evaluated a like-on-like impinging concept and a swirl coaxial injector configuration.
- Tests were conducted at various chamber pressures, mixture ratios and different levels of fuel film cooling to evaluate chamber heating.
- Based upon these results, the 28 element swirl configuration was chosen for further testing in a 40 element configuration.
- 40 element testing in 2008 has resulted in low frequency chugging that is being overcome by modifying injector orifices.



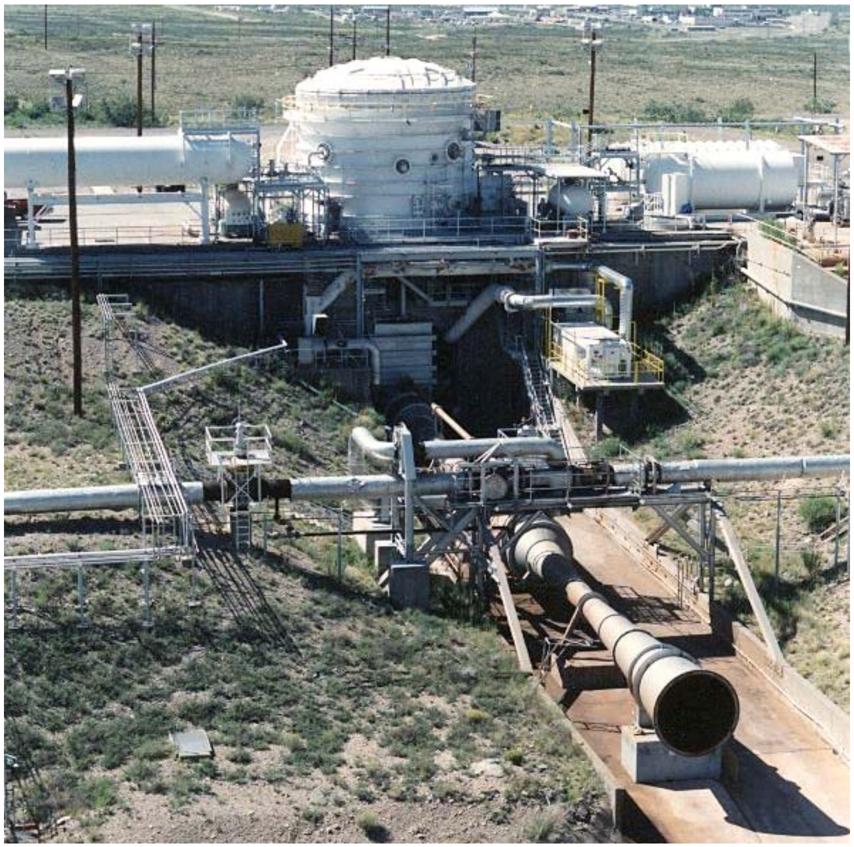
2008 Injector Test Video

Ignition Sea Level Testing

- Also 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

TS401 Overview



WSTF TS401

- Future testing to evaluate reliable ignition in vacuum and maximizing Isp will be performed at the NASA White Sands Test Facility (WSTF).
- TS401 is a vertical firing, carbon steel altitude chamber capable of simulating 100,000 ft (30,487 m) conditions.
- Initially used for Apollo lunar lander testing, the test stand has been modified for LO2/LCH4 and has already tested multiple thrust classes.
- The test stand awaits an industry engine concept tentatively scheduled for testing in the summer of 2009.

Conclusions

Igniter

- 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

- Improved mixing from the higher element density did increase combustion efficiency.
- Modification of the swirl orifices eliminated the low frequency chugging instability observed in earlier testing of 40 element.

Specific Impulse (Isp)

- With the capability to achieve 98% combustion efficiency, the technology awaits testing of a larger nozzle configuration in a relevant environment.
- Partnering with industry, NASA should have simulated vacuum Isp data by the Summer of 2009 to compare to the 355 second goal.