Summary of LO2/Ethanol OMS/RCS Technology and Advanced Development

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NASA is pursuing non-toxic propellant technologies applicable to RLV and Space Shuttle orbital maneuvering system (OMS) and reaction control system (RCS). The primary objectives of making advancements in an OMS/RCS system are improved safety, reliability, and reduced operations and maintenance cost, while meeting basic operational and performance requirements. An OMS/RCS has a high degree of direct interaction with the vehicle and crew and requires subsystem and components that are compatible with integration into the vehicle with regard to external mold-line, power, and thermal control.

In July 1997, a Phase I effort for the technology and advanced development of an upgrade of the space shuttle was conducted to define the system architecture, propellant tank, feed system, RCS thrusters, and OMS engine. Phase I of the project ran from July 1997 to October 1998. Phase II is currently being planned for the development and test of full-scale prototype of the system in 1999 and 2000.

The choice of pressure-fed liquid oxygen (LO2) and ethanol is the result of numerous trade studies conducted from 1980 to 1996[1]. Liquid oxygen and ethanol are clean burning, high-density propellants that provide a high degree of commonality with other spacecraft subsystems including life support, power, and thermal control, and with future human exploration and development of space missions. The key to this pressure-fed system is the use of sub-cooled liquid oxygen at 350 psia. In this approach, there is 80 degrees R of sub-cooling, which means that boil-off will not occur until the temperature has risen 80 R.

The sub-cooling results naturally from loading propellants at 163 R, which is the saturation temperature at 14.7 psia, and then pressurizing to 350 psia on the launch pad. Thermal insulation and conditioning techniques are then used to limit the LO2 temperature to 185 R maximum, and maintain the sub-cooling. The other key is the wide temperature range of ethanol, -173 F to +300 F, which can provide heat to gasify liquid oxygen or provide a good coolant.

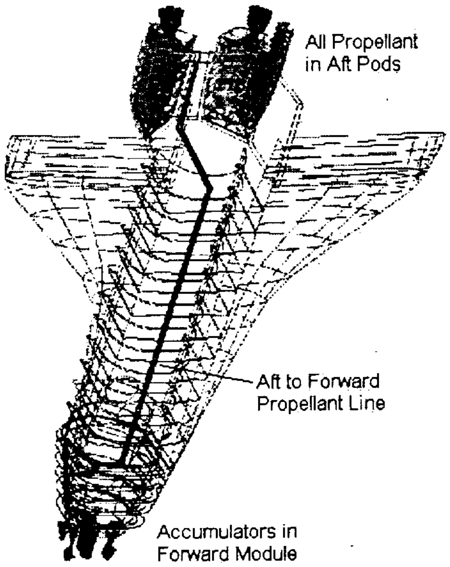

Figure 1. NT OMS/RCS Integrated with Orbiter

Major Goals and Metrics

Upgrades to the Space Shuttle orbiter are being evaluated to improve safety, reduce cost, increase flight rates, improve mission capability, and extend life. The non-toxic OMS/RCS addresses each of these goals. It reduces the ground hazards and the flight safety hazards due to the elimination of the toxic and corrosive propellants. The cost savings for ground operations are estimated to be over 20 M per year for 7 flights, and the savings increase with increasing flight rate. The payload capability is increased up to 2500 lbms due to increased OMS engine performance and due to improvements in the center of gravity resulting from moving the forward RCS propellant to the aft, which eliminates the need for ballast on some flights, as shown in figure 1. The non-toxic OMS/RCS also provides improved space station reboost capability up to 20 nautical miles from the current toxic system of 14 nautical miles. These benefits must be weighed against the estimated cost of the system in order to make an implementation decision. One of the objectives of the Phase II program is to provide a good cost estimate to use in this decision, that is based on well defined requirements and a proven prototype design. The results of Phase I, which do support continuing into Phase II, are discussed in this paper.

System Architecture Studies

The objectives of the system architecture studies are to understand the requirements, address orbiter integration, perform trades, analyze the systems for feasibility, and to develop operational plans. The studies were performed by Boeing North American (BNA)[2] and Lockheed Martin Astronautics (LMA)[3].

Boeing North American defined the requirements for the OMS/RCS in terms of the mission profile, propellant usage, accelerations, and duty cycle. BNA performed analysis on 4 basic options and recommended a liquid oxygen RCS with transfer from the aft pods to forward module. This forward transfer line dramatically increases the reboost capability. The forward line routing was investigated by examining OV-104 at Palmdale and found to be feasible. For each of these options, BNA completed thermodynamic analysis, developed hardware utilization lists, calculated launch operations labor, and assessed life cycle costs. CAD layouts showing all propellant and GHe in aft pods were also created, as shown in figure 2.

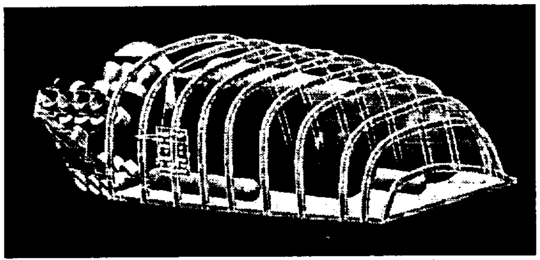

Figure 2. BNA NT OMS/RCS Pod Concept

Lockheed Martin developed similar requirements and posted these on a web page[4]. Information was also distributed through a working group, which Lockheed Martin organized. LMA then developed design details, fluid and thermal analysis, and schematics for all system options. LMA recommended a liquid oxygen system in the aft and a gaseous oxygen (GO2) system in the forward. This system uses a heat exchanger to gasify LO2 for the forward RCS. LMA further analyzed a unique concept for this heat exchanger using ethanol pumped from the OMS tank. A preliminary design for a tank strut and GHe pressurization system was completed to support system analysis at NASA. A conceptual design of a ground test system that demonstrates key technologies was also developed.

At the Johnson Space Center, an integrated system analysis was performed to verify packaging, structural load capability, thermal heat leak, and system line dynamics. A dynamic model of the feedsystem was completed by the BNA Houston Orbiter Dynamics Group. The entire aft OMS/RCS and forward RCS system was modeled. This model has approximately 3000 degrees of freedom and is capable of high-frequency line dynamics. Using this model, the accumulators and line diameters have been sized. This model found that both the LO2 and GO2 forward feedsystems are acceptable. The transient pressures at the tank outlet were also calculated to verify that they do not exceed propellant tank screen delta-P.

At JSC, a virtual environment was used to investigate the design, operations, fault detection, crew procedures, etc. To support this simulation, a math model for use in an end-to-end simulation environment of the integrated orbiter was created. An end-to-end simulation of an OMS engine rendezvous burn was completed that simulates the orbiter from the modified cockpit displays down to the engines.

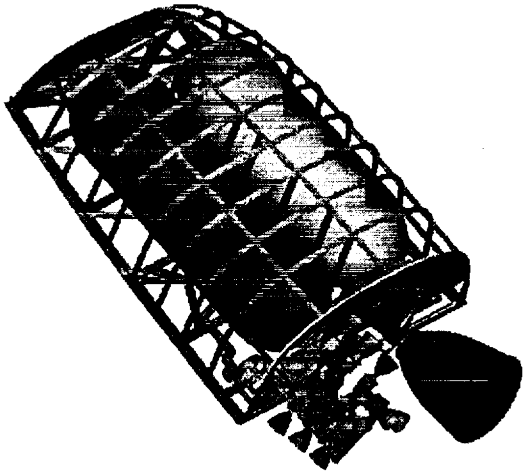

Figure 3. NT OMS/RCS Pod

A structural analysis of the integrated pod frames and tank struts was completed, as shown in figure 3. The total tank strut heat leak was found to be acceptable at less than 55 btu/hr for all 6 struts. This heat leak corresponds to a 0.05 degree R per hour rise in temperature for a 50% full LO2 tank. The orbiter and pod attach point loads were also found to be acceptable with the higher propellant capacity of 10,500 lbm of LO2 and 6250 lbm of ethanol per pod. Schematics of the two systems were created such as shown in figure 4.

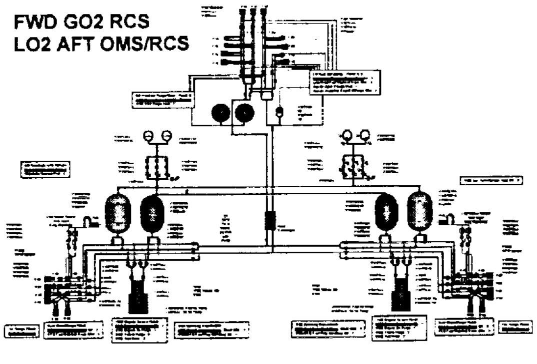

Figure 4. NT OMS/RCS Schematic

Cryogenic Liquid Oxygen Storage

There are 4 propellant tanks in the new system; two 10,500 lbm LO2 and two 6250 lbm ethanol tanks. These tanks are pressurized to 350 psia. The tanks are required to acquire propellants during ascent, on-orbit, and entry. The objectives of the propellant tank task were to design and analyze an integrated LO2 tank for both OMS and RCS, including the liquid acquisition device (LAD), pressure control system, insulation, and quantity guage. Boeing North American and Lockheed Martin each provided a design and analysis for this tank.

BNA[5] completed a tank specification, which clearly defined the tank outflow and accelerations. Details on the LO2 tank insulation and thermodynamic vent system design were provided. The tank design uses purged multi-layer insulation (MLI). The tank performance with LO2 was found to be acceptable for 7 to 21 days missions. There is no LO2 venting required for missions up to 11 days. After 11 days, the thermodynamic vent system is used to maintain LO2 temperatures at 195 R or less. Analysis and empirical data from tests at MSFC were used on the thermodynamic vent system, which uses a spray bar for pressure and temperature control. The LAD consists of screens and entry collectors in the lower compartment and vanes in the upper compartment as shown in figure 5. A 3-D fluid dynamic analysis was performed to analyze the use of vanes to position propellant over the lower compartment port. The analysis was also used to design the LAD channels that flow the propellants.

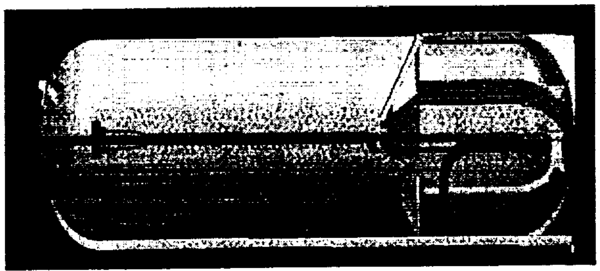

Figure 5. BNA Tank Cutaway

LMA[3] designed an integrated OMS and RCS LO2 tank, including the LAD, pressure control system, and tank shell. The design uses a graphite epoxy over-wrapped Inconel tank, for which a full structural analysis of tank shell has been performed. LMA also provided design and analysis details on the liquid acquisition device, which consists of screen device in the lower compartment and vane device for upper compartment as shown in figure 6. A 3-D analysis of the fluid behavior during RCS engine firings was performed to look at thermal stratification and mixing. LMA completed engineering drawings, which are ready for prototype manufacturing.

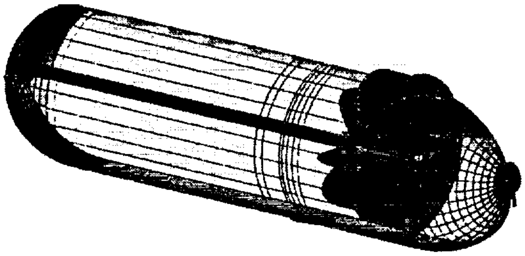

Figure 6. LMA Tank Cutaway

Cryogenic RCS Feedsystem

The system architecture studies have recommended a liquid oxygen feedsystem in the aft pods, since the aft RCS uses propellants at a high rate for ascent and entry maneuvers. The energy or power requirements to gasify liquid oxygen are found to be excessive. It is much easier to insulate and condition the liquid oxygen lines. Three different conditioning schemes are being pursued; bleed flow, recirculation, and vapor cooled lines. A view of the aft OMS/RCS feedsystem is shown in figure 7.

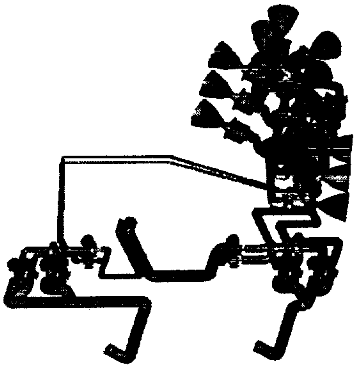

Figure 7. Aft OMS/RCS Cryogenic Feedsystem

The total length of plumbing for the shuttle OMS/RCS including a LO2 line to the forward RCS is ~350 feet of 1.5 inch diameter line. System analysis performed at JSC determined that a heat leak around 0.15 to 0.3 btu/hr per foot of line is desired[6]. In a vacuum, this is achievable using MLI or Aerogel materials.

During docked operations with the space station, the OMS/RCS flow will become stagnate. If temperatures are allowed to rise, the line temperature will increase from 163 R to 189 R in approximately 24 hours. A pump recirculation system, that is coupled with the LO2 tank TVS, can be used to periodically condition the lines when this happens. If the lines are held to 163 R using a vapor cooled shield, the entire shuttle cryogenic feedsystem would need to vent 25 to 50 lbm of oxygen per day. At other times the normal vernier and primary RCS engine usage will keep the lines conditioned.

The effort conducted at NASA JSC also focused on engine heat soak back[6]. Using heat soak-back thermal isolation similar to the current storable RCS engine, the heat soak-back was measured to be approximately 60 BTU/hr. The injector temperature was held at 500 F. The goal for the flight design of a cryogenic RCS engine will be approximately 3 BTU/hr. This should be possible by using composites and by taking advantage of the lower injector temperatures of 96 F for a cryogenic engine as measured during the Aerojet 870 lbf engine tests.

RCS Engine

The RCS engine is envisioned to be a dual thrust 870 lbf and 25 lbf engine with greater than 270 sec Isp at a mixture ratio of 1.6 to 1.8. The objectives of the RCS engine developments are to evaluate 1) low-cost engine manufacturing techniques, 2) characteristics of liquid versus gaseous oxygen engines, and 3) the ignition of liquid versus gaseous oxygen using spark and lasers.

Three engines were tested in this phase of the program; 1) Aerojet 600 lbf GO2/Ethanol Engine, 2) TRW 870 lbf Gox and LO2/Ethanol Pintle Engine, and 3) an Aerojet 870 lbf LO2/ethanol Engine. Over 1600 seconds and 300 ignitions were accumulated during the engine advanced development tests. The positive results supported that these durations and number of ignitions could be much extended.

The Aerojet 600 lbf engine was tested to evaluate ignition characteristics in a vacuum using a GO2/ethanol spark ignitor. Tests at the White Sands Test Facility were also performed using the ignitor torch to demonstrate the low thrust mode of a dual thrust engine that uses the torch ignitor as the vernier. All ignitions were successful except one at very low pressures. Later tests will validate thrust and performance as well as measure main chamber temperatures.

The RCS engine development at TRW evaluated a GO2/ethanol pintle engine[7]. The pintle offers advantages in combustion stability, since it does not require damping devices, and in ease of manufacturing. The pintle injector element could be changed out and the engine retested in approximately 1 hour. Several configurations of the pintle were tested, but one of the engines reached 290 s Isp at Mixture ratio of 1.6 and chamber temperature of 2100 F, and another achieved 283 s at 1.8 and chamber temperature of 2030 F. Steady state run durations of 30 seconds were completed. In parallel, a liquid oxygen cooled chamber was manufactured for this engine. Later tests will demonstrate this GO2 injector running on liquid oxygen that is gasified in the Nickel 200 heat exchanger chamber. This LO2 cooled chamber will potentaially allow the engine to be configured for GO2 or LO2.

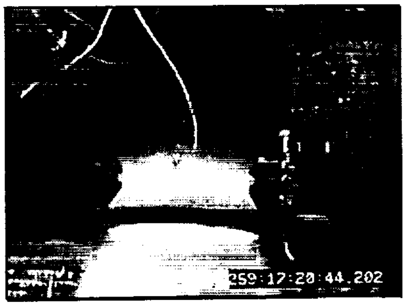

Figure 8. TRW GO2/Ethanol Engine

Aerojet succesfully demonstrated a pulsing liquid oxygen fed engine[8]. This engine is a modified engine from the Kistler commercial launch vehicle program, where it is being used as an orbital maneuvering engine to deorbit the second stage. The results were very favorable. The tests demonstrated pulse strings of 160 ms, 1 second, and a steady state firing of 60 seconds, as shown in figure 9. The subcooled liquid oxygen had no problem entering the chamber quickly. The chamber pressure rose in approximately 26 milliseconds, which supports the engine achieving 80 millisecond pulses with fast acting valves. The engine achieved greater than 280 seconds of Isp at a 1.6 MR, 22:1 expansion, and chamber temperature of 1950 F. The injector temperatures were very cool and never exceeded 96 F on the backside. This is critical for reducing heat soak back from the injector to the valves and back into the cryogenic feed system.

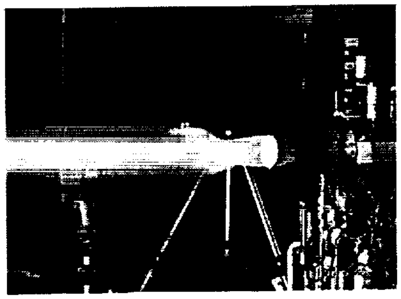

Figure 9. Aerojet LO2/Ethanol RCS Engine

In conclusion, all of the engine test programs were successful in demonstrating both LO2 and GO2 engines. Key data for designing these engine injectors was obtained. The work should lead to a substantially lower cost RCS engine, which is critical to achieving the cost goals necessary for program implementation.

OMS Engine

The OMS engine is a 6000 lbf, high-performance, long-life engine with 323 sec Isp minimum. The three areas of work that MSFC participated in for this Phase of Shuttle upgrades were: 1) Lox/Ethanol engine testing with Rocketdyne/Boeing, 2) Platelet chamber technology with Aerojet, and 3) Injector element characterization with Penn State University.

The Lox/Ethanol engine testing with Rocketdyne/Boeing is being pursued under a cooperative agreement with MSFC. The objective of this activity is to demonstrate that the Aestus engine, shown in figure 9, can be adapted to the use of Lox/ethanol with minimal modifications. Hot fire testing of the modified Aestus engine is being conducted at the Rocketdyne test facility. This demonstration program will establish a baseline and the feasibility to further optimize the Aestus engine for future Space Shuttle Lox/ethanol use.

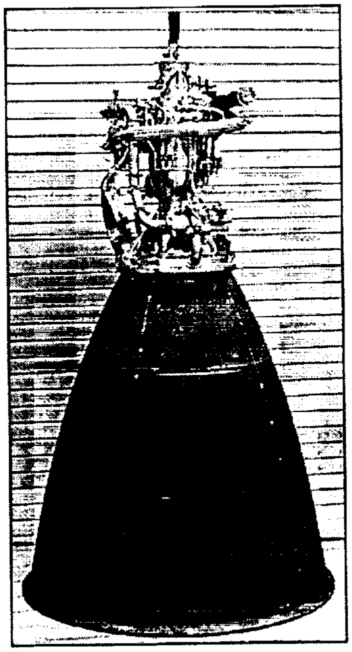

Figure 10. Rocketdyne/DASA OMS Engine

The Aestus engine, produced at Daimler-Benz Aerospace (Dasa), was provided to Rocketdyne for modification to operate with Lox/Ethanol. The primary modifications were incorporation of an ignition system, changing the seals in the oxidizer line, and modification of the thrust chamber assembly to ensure combustion stability. The objective of the full scale testing is to demonstrate that the modified Aestus engine will achieve the required chamber pressures, specific impulse and combustion stability. Additional Aestus engine testing will be performed to extend the performance database on the engine using Lox/ethanol and Lox/methanol. Ten additional full-scale thrust chamber assembly tests will be performed using Lox/ethanol to provide engine operations for different mixture ratios and main chamber pressures. This will provide data on performance over some of the expected operating ranges of the flight OMS engine. The additional hot-fire testing will also provide information on the off-design operating conditions for the Aestus engine. This will better characterize the engine in support of the Shuttle OMS propulsion design.

To support definition of future HEDS lander mission applications, eight full-scale thrust chamber assembly tests will be conducted using Lox/methanol. These tests will be conducted after minor modifications to the test set up at Rocketdyne. This data on Lox/methanol will support the decisions for lander engines to be made by the Exploration Transportation Office at MSFC. In addition a modification was made to the Rocketdyne work to perform a conceptual design and analysis to define the optimal engine cycle for a pump-fed version of the non-toxic OMS engine. This engine design will be used to support planetary exploration using Lox/methanol and Lox/methane as the baseline propellants instead of Lox/ethanol.

The platelet chamber technology with Aerojet is an effort to address a cost reducing fabrication technique that would allow non-toxic fuels, such as ethanol, to be used as a regenerative coolant for pressure ignitions and 1600 seconds of operation, all ignition attempts successful. Tests and analysis on a cryogenic feedsystem for the RCS engines shows that this is feasible. For the OMS engine, tests on ethanol critical heat flux for OMS engine has been completed, and high performance platelet chambers have been designed and subscales tested. Full scale tests of 6000 lbf engine were also successfully completed. Additional tests at other mixture ratios and with methanol are planned. Laboratory tests on various type injectors has led to a better understanding liquid oxygen and ethanol injectors. Overall, Phase I has provided a firm foundation for continuing with the Phase II program.

Acknowledgements

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