NASA s Space Launch Initiative Targets Toxic Propellants

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Abstract

When manned and unmanned space flight first began, the clear and over riding design consideration was performance. Consequently, propellant combinations of all kinds were considered, tested, and, when they lifted the payload a kilometer higher, or an extra kilogram to the same altitude, they became part of our operational inventory. Cost was not considered. And with virtually all of the early work being performed by the military, safety was hardly a consideration. After all, fighting wars has always been dangerous.

Those days are past now. With space flight, and the products of space flight, a regular part of our lives today, safety and cost are being re-examined. NASA s focus turns naturally to its Shuttle Space Transportation System. Designed, built, and flown for the first time in the 1970s, this system remains today America s workhorse for manned space flight. Without its tremendous lift capability and mission flexibility, the International Space Station would not exist. And the Hubble telescope would be a monument to shortsighted management, rather than the clear penetrating eye on the stars it is today.

But the Shuttle system fully represents the design philosophy of its period: it is too costly to operate, and not safe enough for regular long term access to space. And one of the key reasons is the utilization of toxic propellants. This paper will present an overview of the utilization of toxic propellants on the current Shuttle system.

NASA has launched the Space Launch Initiative to address the cost and safety short comings of the current Shuttle Space Transportation System. Marshall Space Flight Center s 2nd Generation Reusable Launch Vehicle (RLV) office has been given the lead in this initiative and is coordinating an agency wide attack on the Shuttle safety and cost issues. 2nd Generation RLV options include both the evolution of the current shuttle design, and new clean sheet designs. With a five year budget of more than $5 billion, and a mandate to attack safety first, the toxic propellants of the current Shuttle system are receiving intense scrutiny. Plans are being formulated and executed to make toxic propellants a dim memory.

This paper will present an overview of how lox/ethanol and peroxide/RP propellants may be used in new design or evolved 2nd Generation RLVs and NASA s plan to mature these technologies for industry s inclusion in their final commercial RLV designs.

2nd Generation RLV Program Overveiw

NASA has launched the Space Launch Initiative to address the cost and safety short comings of the current Shuttle Space Transportation System. Marshall Space Flight Center s 2nd Generation Reusable Launch Vehicle (RLV) office has been given the lead in this initiative and is coordinating an agency wide attack on Shuttle safety and cost issues. With a five year budget of more than $5 billion, and a mandate to improve safety first, the toxic propellants of the current Shuttle system are receiving intense scrutiny.

The current 2nd Gen RLV program is being executed in two phases. The first phase is a broad systems analysis of the 2nd Generation Reusable Launch Vehicle (RLV) system requirements coupled with a broad risk reduction effort across key technologies. The second phase will include a more focused technology risk reduction effort coupled with initial design of the most promising 2nd Gen RLV system designs. The first phase of the program began in the summer of 2000 with program planning. This planning focused on initiation of risk reduction activities both within NASA and with our industry partners. This culminated in 2001 with NASA Research Announcement (NRA) 8-30. The most publicly reported result of this NRA was the cancellation of both the X-33 and the X-34 flight vehicle programs. These two programs were begun in an era when learning from the flight experience itself was the objective. Measured against the more stringent 2nd Generation RLV technology support requirements both programs were judged as not cost effective.

Although the systems studies have not provided a definitive choice of replacement propellant systems, there is clear consensus that toxic propellants will not be part of any 2nd Generation RLV design. Consequently, the 2nd Generation RLV Program is sponsoring the development of both cryogenic LOX/ethanol and non-cryogenic peroxide/RP propulsion systems.

Shuttle Orbital Maneuvering System (OMS) and Reaction Control System (RCS)

The Space Shuttle OMS/RCS currently uses monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO). These propellants were selected over oxygen and hydrogen in 1970s. The benefits of non-toxic propellants such as O2/H2 were recognized, but the technology readiness level for an oxygen and hydrogen system was not adequate at that time. Numerous tests were conducted, even on pulsing liquid oxygen and liquid hydrogen RCS engines, but the program elected to utilize the MMH and NTO propellants which had been proven in the Apollo program. The operational impacts of these toxic propellants were mitigated in part by making the OMS/RCS pods and modules removable so that maintenance and preparation of these systems could be worked offline.

Since that time, the experience of over 100 flights of the Shuttle has shown the system to be reliable in flight, although some thruster failures have occurred due to iron nitrate contamination. The OMS/RCS system is pressure-fed and uses a 6000 lbf thrust engine, thirty-eight 870 lbf engines, and six 25 lbf vernier engines. The ground operations currently require extensive safety procedures, which add substantial cost. The current yearly labor cost of this system runs to 500,000 man-hours for 7 flights, or about $35 million. The propellants require 2 days to load in serial operations that require clearing the work areas. The RCS engines are removed and flushed with water periodically to remove iron nitrates and intermediate reaction products. Maintenance of the vehicle and GSE is critical since these propellants are corrosive and capable of auto-decomposition.

Shuttle OMS/RCS Lessons Learned

New reusable vehicles must have highly operable systems that are safe, reliable, and cost effective in both flight and ground operations. Grounds operations can be improved by using non-toxic propellants, eliminating direct handling of propellants in processing operations, automating checkout, and using common fluids. For flight operations, the system must provide the necessary performance, minimize hazards to the crew, minimize the number of critical components, and must be reliable.

OMS/RCS typically provides orbit adjust, re-boost, docking, attitude control, deorbit capability, and entry control. Propellant utilization varies depending on mission and changing events during a mission. For maximum mission flexibility, the OMS and RCS propellants should be integrated into one set of tanks and utilized at the same mixture ratio. The RCS engines may also need to provide high thrust for entry control and low thrust for docking and re-boost of orbiting platforms. The system should have minimum impact to other operations, such as EVA.

Shuttle Auxiliary Power Units

Today s Space Shuttle uses a hydraulic system powered by a triply redundant hydrazine auxiliary power units (APUs) to actuate SSME valves, aerodynamic control surface, landing brakes, and thrust vector actuators. Almost 1000 lbms of hydrazine are stored in three blow-down positive expulsion tanks using elastomeric diaphragms. The APUs have a fuel pump, catalyst bed, and a two-pass turbine wheel. Since hydrazine thermally decomposes, it can not be used as a coolant for this application. Consequently, the APUs are cooled with a water boiler system which adds another 960 lbms of mass and complexity.

The hydrazine APU has numerous hazards and criticality 1 failure modes and therefore requires complex controls to maintain safety. In 1997 the Shuttle Program selected an electric APU and batteries for a feasibility study to replace the hydrazine APU. An electric APU can dramatically improve safety and reliability by eliminating the fire potential of hydrazine, the turbine over speed issues, and the adiabatic detonation hazards associated with hydrazine. The electric APU is cost effective and could be implemented by 2005. The electric APU eliminates the cost of rebuilding hydrazine APUs due to life limitations. In addition, the electric APU project integrates well with future EMAs by providing 270 volt switching systems, motor technology, battery technology, and 270 V corona investigations.

Oxygen Based OMS/RCS Technology

Numerous non-toxic propellants have been investigated since the 1960s[1]. For safety, simplicity, and reliability, the system proposed here is pressure-fed oxygen and ethanol. Safety is enhanced since ethanol and oxygen do not auto-decompose, such as with hydrazine or MMH, thereby reducing the potential for fire due to leaking propellants. Safety standards for oxygen system design and material selection are utilized. Fortunately, high strength stainless steels, inconel, and aluminum alloys for tanks are acceptable for use with oxygen at the conditions proposed for Lox/ethanol OMS/RCS. The system is operated at relatively low pressures and temperatures, which reduces potential hazards with oxygen. The fuel selected is ethanol for non-toxic, clean combustion, and no plume contamination of spacecraft surfaces.

For improved ground operations, the oxygen is common with main propulsion propellants. The LO2 is loaded with MPS and the fuel is topped off during parallel pad loading operations. Although cryogenic, liquid oxygen can meet the mission duration requirements for RLVs using passive insulation techniques. Post flight all oxidizer is vented before entering the processing facility, and the fuel tank is drained and purged.

The key principle of operation of this cryogenic system is the use of sub-cooled liquid oxygen. Sub-cooled liquid oxygen is produced by loading the Lox at 14.7 psia and 163 R, and then pressurizing the tanks to 250 psi. This results in over 60 R of subcooling. Boil-off will not occur until the bulk liquid has risen 60 deg R. Composite structures and insulators such MLI are then used to limit the heat into the system. The result is a very slow rise in bulk liquid oxygen temperature. Normal thruster usage will keep the feedlines below the boil-off temperature. In the event the temperature has risen above the saturation temperature, the vent system will be activated and the warm gas will be vented. However, to make the system robust, the RCS engines are being designed to ignite with either gas or liquid oxygen.

To meet mission duration requirements, the RCS engines can either be gas fed or liquid oxygen fed. For longer duration missions of greater than 2 weeks up to several years, the reaction control propellant can be first converted to gas for distribution. The oxygen flow is gasified using heat from the ethanol flow by operating at a mixture ratio of one through a heat exchanger. For shorter missions, the RCS engines are fed using highly subcooled liquid oxygen.

Status of Technology Development

System architecture studies[2,3] have been completed to understand the requirements, address vehicle integration, perform trades, analyze the systems for feasibility, and to develop operational procedures. To better define the system architecture, a real time flight and ground simulation has been conducted. An end-to-end flight simulation using a real-time lox/ethanol OMS/RCS model was conducted with flight controllers. A virtual reality ground processing simulation test with KSC technicians has also been completed. The results of these simulations were 24 suggestions for improvements to the design and system architecture.

Liquid Oxygen Tank

The tanks are required to acquire propellants during ascent, on-orbit, and re-entry. Two designs were completed in earlier studies[4]. The liquid acquisition device (LAD) consists of screens and entry collectors in the lower compartment and vanes in the upper compartment as shown figure 1. The lower compartment is used for on-orbit maneuvers and acquires propellant using surface tension screen technology. The upper compartment stores the OMS propellant and vane devices keep replenishing the lower compartment during most on-orbit maneuvers. The entry collector is used during re-entry when the vehicle is experiencing high de-acceleration forces. Tank shell materials such as aluminum alloys, aluminum lithium, inconel, and composites can be used. A composite over-wrap of a metallic liner was also considered. Thermal insulation for RLV type missions consists of purged multi-layer insulation (MLI). To understand thermal stratification in the propellant tank, a LO2 tank

3-d fluid and thermal model of the propellant tank was completed at Rice University. The results show that the OMS LO2 tank propellants and GHe do not stratify in zero-g. This determined that a mixing pump on the tank is not needed. A passive thermodynamic vent system will be all that is required.

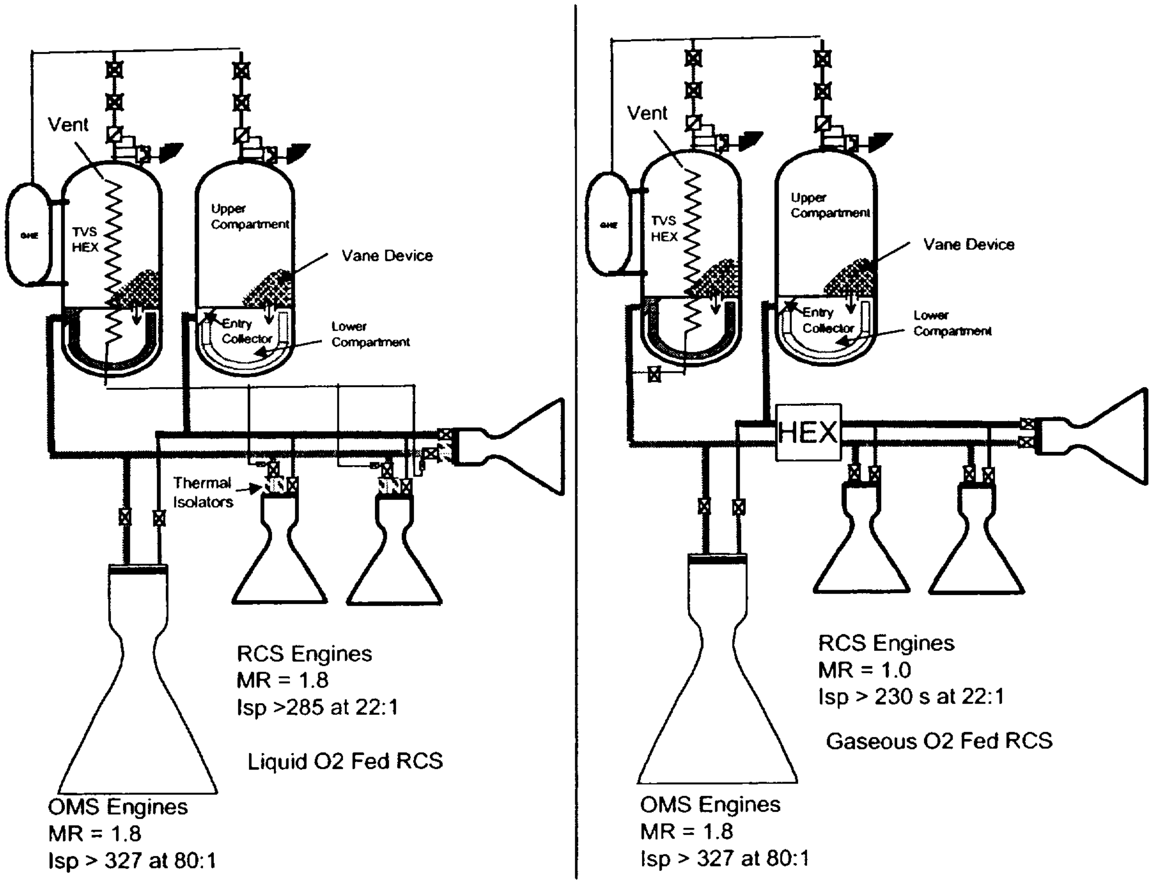

Figure 1 Gaseous O2 and Liquid Oxygen RCS Depending on Application

RCS Feedsystem — Cryogenic or Gaseous Oxygen

For a shuttle type application with a two week or less duration, the system architecture studies recommend a cryogenic oxygen feed system as the simplest, most feasible approach. Analysis shows that it is possible to insulate and thermally condition the liquid oxygen lines[5]. In addition, normal vernier and primary RCS engine usage will keep the lines conditioned. If needed the O2 vapor can be vented

Tests of a LO2 RCS feed system are currently being conducted. The purpose of these tests is to evaluate different thermal conditioning techniques and to deliver cryogenic oxygen to the thruster inlets. A RCS LO2 manifold has been built that simulates 3 RCS engines and the heat soak back from the injector. The test also evaluates a 110 ft long LO2 vacuum jacketed line with a RCS thruster manifold. Preliminary results with non-optimum insulation and relatively high ambient pressures show that subcooled liquid oxygen can be maintained at the thruster inlets.

For long duration mission, a gaseous oxygen fed RCS may be more practical. It is possible to gasify liquid oxygen with the ethanol flow at a mixture ratio of 1.04 or less. This is shown in figure 1.

RCS and OMS Engine

The RCS engine is envisioned to be a dual thrust 870 lbf and 25 lbf engine with greater than 280 sec Isp at a mixture ratio of 1.8. In 1998, TRW[6] evaluated an 870 GO2/ethanol pintle engine shown in figure 2. The pintle offers advantages in combustion stability 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 over a mixture ratio of 0.8 to 1.9, and one of the engines reached 283 s at 1.8 and chamber temperature of 2030 F. TRW also successfully tested a LO2 cooled engine, and successfully tested a direct LO2 injection engine.

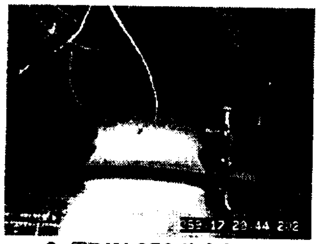

Figure 2. TRW 870 lbf Gox/ethanol

Aerojet[7] successfully demonstrated a pulsing liquid oxygen fed engine. The tests demonstrated that < 80 millisecond pulses are possible. There was no problem with delivering subcooled liquid oxygen into the chamber quickly. 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, which is critical for reducing heat soak back.

A dual thrust engine test was completed at NASA s White Sands Test Facility (WSTF). WSTF modified the 620 lbf engine to include a 22:1 nozzle and low-thrust. The results demonstrated 25 to 50 lbf at up to 297 sec Isp

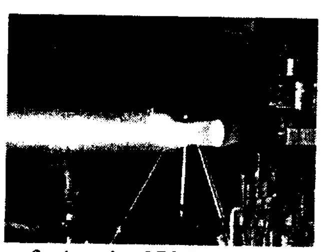

Figure 3. Aerojet 870 Lox/ethanol

in vernier mode. This successful demonstration supports the advanced development of a flight prototype dual-thrust engine as part of the NASA Space Launch Initiative.

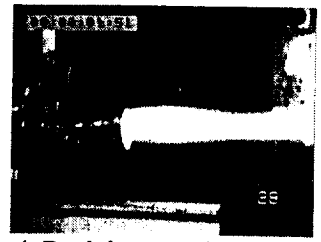

Figure 4. Dual thrust engine test at WSTF

Hot fire testing of a modified Aestus 6000 lbf engine was conducted at the Rocketdyne test facility and measured performance of approx. 325sec[8].

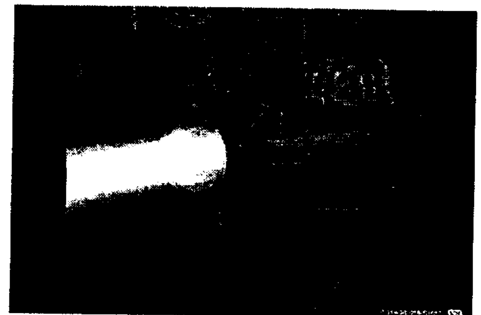

Figure 5. 6000 lbf LO2/Ethanol OMS Engine

A long-life critical heat flux test was conducted at GRC[9] to demonstrate ethanol compatibility with OME chamber materials. The results validated that coking did not affect cooling of the OMS engine chamber after 15 hours of operation.

Future Cryogenic Technology Developments

The focus of future technology development activities will be to develop the dual thrust RCS engines, the cryogenic feedsystem, OMS engine, and the propellant tanks. These components will then be tested in a space vacuum environment as an integrated system as shown in figure 7 to demonstrate a technology readiness level of 6. Initial tests will use run tanks and representative feedsystem to demonstrate the engines at a system level. Future testing will require industry to develop flight-weight feedsystems, propellant tanks, and OMS engines.

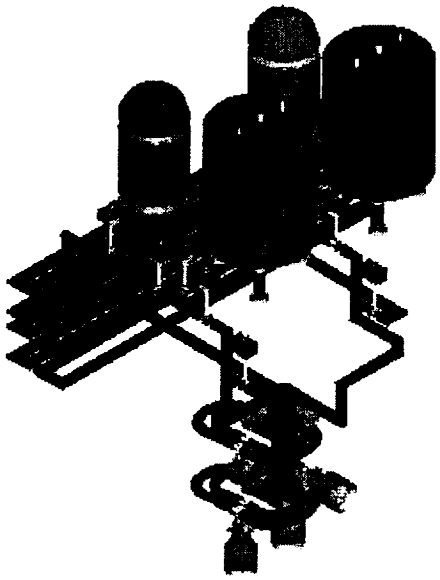

Figure 6. System Test Article

Peroxide/RP Propulsion Development

The 2[nd] Generation RLV Program is also sponsoring additional component related peroxide/RP propulsion research that continues the work begun by NASA s Advanced Space Transportation Program (ASTP). ASTP initiated research to develop two core capabilities and to develop one long lead component. The two core capabilities were long life catalyst systems and onsite peroxide enrichment. The Degussa Corporation was selected to design, fabricate, and develop a portable enrichment skid based on fractional crystallization. That work has been completed successfully at Degussa s Mobile, Alabama facility and the skid, shown in Figure 7, is now being installed at NASA s Stennis Space Center (SSC). The skid will produce more than 2000 pounds of 98% concentration peroxide from 90% feedstock each day. Operational experience gained at SSC will be used to evaluate the future utilization of on-site enrichment in 2[nd] Generation RLV operational concepts.

Catalysts development activities were pursued with four teams and three eventually succeeded: 1) Boeing Rocketdyne, 2) Pratt & Whitney teamed with PCI, and 3) TRW teamed with General Kinetics. Catalyst life in excess of 1000 seconds has been demonstrated. Development of these proprietary catalysts continues.

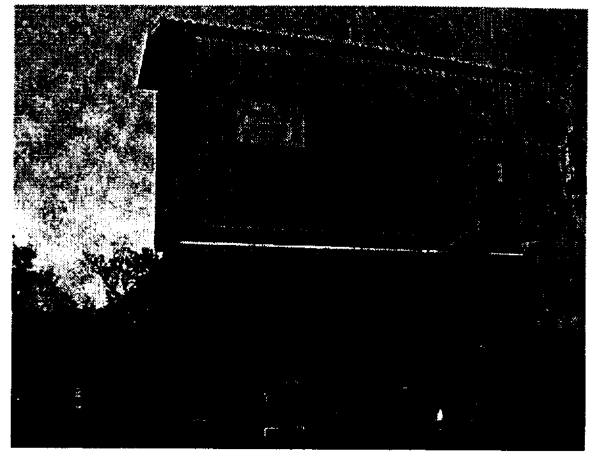

Figure 7. Peroxide Enrichment Skid at Degussa s Mobile Facility

Boeing Rocketdyne was selected to develop the long lead advanced turbopump needed to perform a potential high performance engine demonstration. That pump has been designed for three operating levels utilizing 98% concentration peroxide and JP8: 12000, 6000, and 3000 pounds thrust. Conceptual and preliminary design reviews have been performed, and the critical design review is planned in June 2001. Three pumps will be manufactured in the second half of this year, and testing will commence at SSC in early 2002.

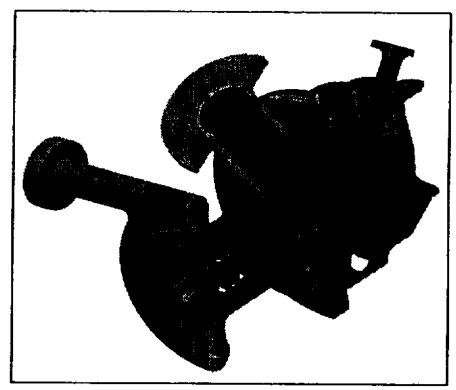

Figure 8. Advanced Peroxide/RP Turbopump

In the first two years of the 2[nd] Generation RLV program broad risk reduction efforts are being undertaken which are applicable to multiple RLV concepts. Common to all of the clean sheet RLV concepts is the use of peroxide/RP for manned space flight operations. Based on the risk reduction recommendations of industry, and the competitive NRA8-30 source selection process, the next phase of NASA s peroxide/RP development will consist of 5 elements: 1) Catalyst Sensitivity Testing; 2) Advanced Turbopump Development; 3) Chamber Materials Development; 4) Hypergolic Injector Development; and 5) Integrated Fluid/Gas Controller Conceptual Development.

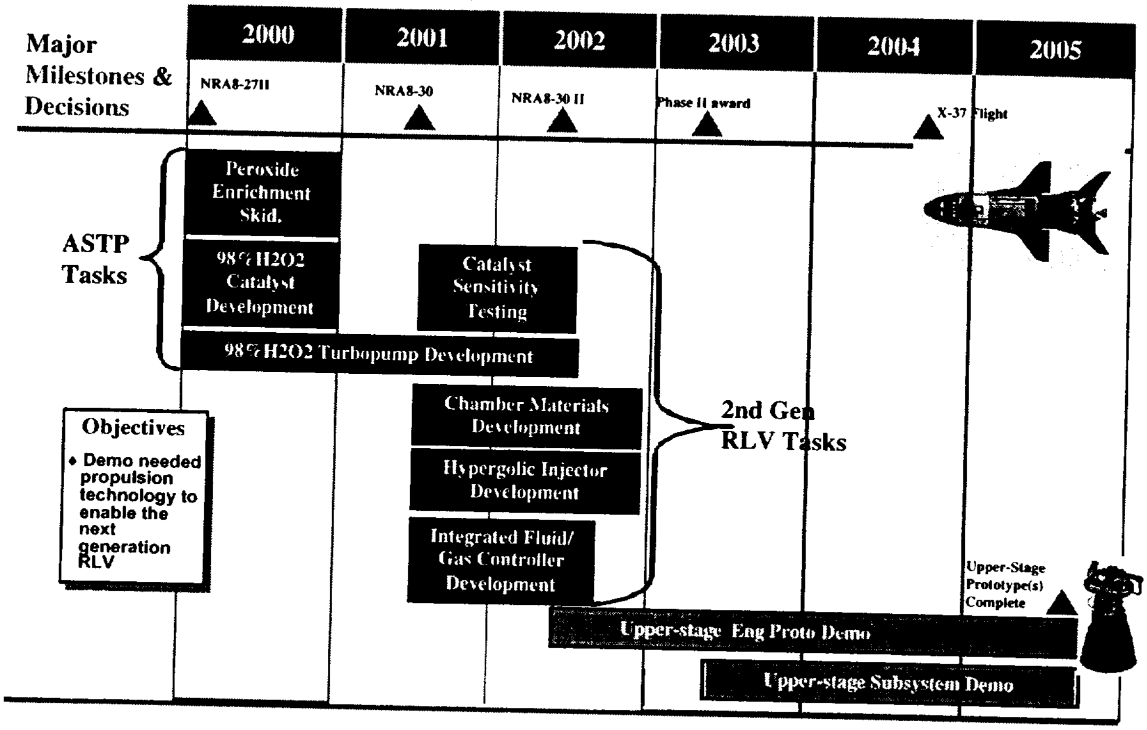

Figure 9. 2nd Generation RLV Peroxide/RP Propulsion Risk Reduction

Although long life 98% concentration catalysts systems have been developed by industry, their sensitivity to potential poisoning by stabilizers and contaminates has not yet been established. This is compounded by the lack of a current specification to control stabilizers and contaminants by the producer community. General Kinetics has been selected to resolve this issue by testing multiple industry catalyst systems to determine their sensitivity to poisoning. The initial list of stabilizers and contaminants include carbon, tin, phosphate, nitrate, aluminum, and a combination of elements likely to be leached from stainless steel during processing. The list will be reviewed and adjusted by the supplier and user communities. After performing baseline tests for the industry catalyst systems the peroxide will be doped with excess amounts of the selected material and the catalysts re-tested to determine the effects on the catalyst performance. These tests will generate the data needed to establish a new 98% concentration peroxide specification.

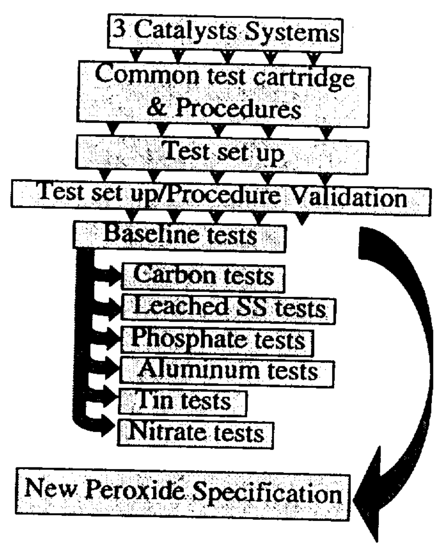

Figure 10. Catalyst Test Plan

The advanced turbopump work begun by ASTP will be completed by the 2nd Generation RLV program. Although the final propulsion requirements of the new design RLVs are not yet known, the flexibility of the current pump design ensures it will support any required engine demonstration.

Two efforts are being initiated in the regeneratively cooled main combustion chamber area. Boeing Rocketdyne will undertake an analysis of available peroxide compatible materials and built 2D test specimens for the most promising material candidates. The key issues are thermal efficiency, peroxide compatibility, and structural life. Rocketdyne will test the speciems in a proprietary 2D flow rig which allows replication of thrust chamber operating conditions. Following the flow tests the specimens will be destructive tested to determine their structural degradation.

Pratt & Whitney will undertake a parametric study and test of key thrust chamber coolant design variables. These include coolant flow rate, coolant channel geometry, wall thickness, wall roughness, fluid temperature, and fluid pressure. In each test case the variables will be controlled and manipulated until detonation of the cooling fluid is detected. The result of this work is planned to be a design guide for future 98% concentration regeneratively cooled chambers.

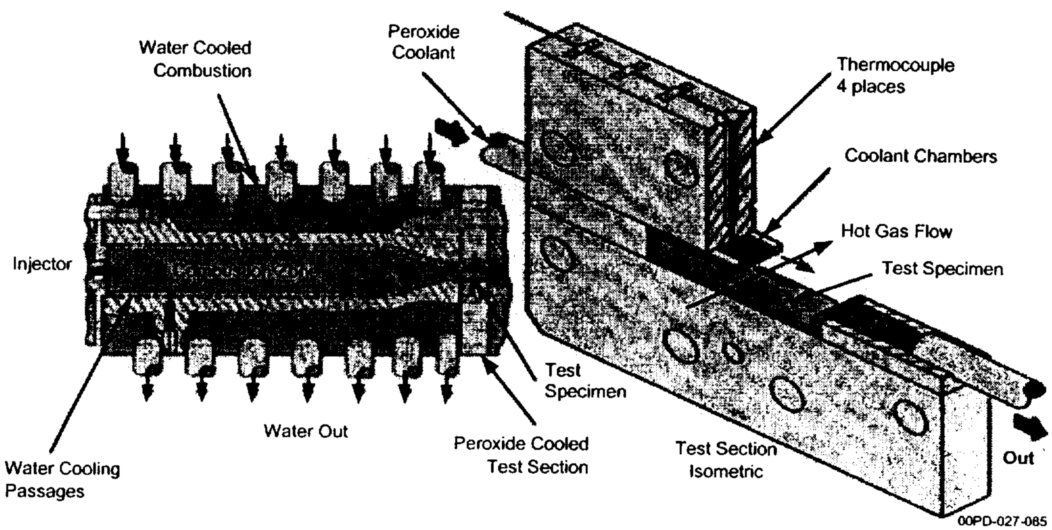

Figure 11. Boeing Rocketdyne 2-D Flow Chamber Material Test Rig

Boeing Rocketdyne has also been selected to develop a hypergolic injector for orbital propulsion. Rocketdyne has previously developed a JP8 based fuel that is hypergolic when in contact with 98% peroxide. This effort will extend their proprietary work from maneuvering thrusters to main axial thrust mission requirements. The development of this key technology will allow the use of common oxidizer and fuel tanks for RCS/ACS and orbital maneuvering. It will also simplify engine design by deletion of igniter systems and decrease ignition delay foe axial thrust by an order of magninude. Injectors will be designed, built, and then tested at SSC in 2002.

The Achillies heel of most engine development programs is the fluid and gas control system. The valves, sensors, actuators, and control systems that control the start, operation, and shutdown of the engine invariably require extensive development and modification before the engine can begin to operate nominally. Then, reliability must be developed over a long period of operation. This situation is a direct product of today s design process wherein individual devices are procured in the hope that low cost can be obtained through competition. But the system costs and reliability are sacrificed by this approach. In an era when integrated product teams dominate our design process, the fluid gas controller should be an integrated device, rather then a collection of individual devices. Moog, Inc., with assistance from Boeing Rocketdyne will undertake a study of an integrated fluid/gas controller for an advanced peroxide/RP engine. Their goal will be to define a safer control system, with fewer parts, higher reliability, and lower recurring costs than traditional systems. Moog will contribute their component expertise to the study while Boeing will bring its engine system expertise to the evaluation. The results will be available to industry to incorporate in their 2nd Generation RLV engine designs.

Future Peroxide Propulsion Development

With cross cutting technology development now underway, the next phase of the program will be more application specific. With injectors, chamber materials, a turbopump, and gas generator demonstrations complete, an engine demonstration becomes the next logical step in the development progression. The final engine requirements for the 2nd Generation RLV will be generated through the system studies performed both by industry and NASA, but the core requirements for the engine demonstration are already known. They include: 1) a continued focus on safety via robust design; 2) a continued focus on low operating cost through long recurring use; 3) high reliability; 4) high operability; and 5) engine performance levels in excess of 320 sec ISP. A demonstration of an engine with these attributes is planned for 2005.

But engines are not the only subsystems that must be designed and tested to realize the full potential of peroxide propulsion. On the airframe side of the flight vehicle, propellant management devices must be developed, tank self-pressurization systems must be developed, ACS/RCS thrusters for 98% peroxide must be designed and tested, and peroxide powered APUs must be demonstrated. Only through the full integration of all of these airframe subsystems operating from common propellant tanks can 2nd Generation RLV goals be met.

Conclusion

Toxic propellants have performed an important role in development of manned and unmanned space flight. But their direct costs and safety related costs are too great. Their time is quickly fading. NASA s 2nd Generation RLV program is developing both cryogenic and non-cryogenic replacements for today s toxic propellants. Designers and developers of the next generation of reusable launch vehicles will have new, safer, technically mature Lox/ethanol and peroxide/RP alternatives from which to choose. The next decade will see the first full operational use of exclusively green propellants for space flight.

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