The Peroxide Pathway

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NASA's current focus on technology roadmaps as a tool for guiding investment decisions leads naturally to a discussion of NASA's roadmap for peroxide propulsion system development. NASA's new Second Generation Space Transportation System roadmap calls for an integrated Reusable Upper-Stage (RUS) engine technology demonstration in the FY03/FY04 time period. Preceding this integrated demonstration are several years of component developments and subsystem technology demonstrations. NASA and the Air Force took the first steps at developing focused upper stage technologies with the initiation of the Upper Stage Flight Experiment with Orbital Sciences in December 1997. A review of this program's peroxide propulsion development is a useful first step in establishing the peroxide propulsion pathway that could lead to a RUS demonstration in 2004.

Upper Stage Flight Experiment

The state of the art in peroxide propulsion technology has two potential representatives: 1) the still-in-development Orbital Sciences Upper Stage Flight Experiment (USFE) 10k Engine, and 2) the previously operational Boeing Rocketdyne AR2-3. The Boeing Rocketdyne AR2-3 engine is a man-rated reusable peroxide/RP engine that delivers a reliable 6600 lbs. thrust. The AR2-3 has in fact been selected by the Boeing-PhantomWorks to power their X-37 Advanced Technology Demonstrator (ATV). But the engine's design and development cycle dates back to 1950's, and it would be inappropriate to label it as representative of today's state-of-the-art in design practices or material utilization. Consequently the USFE 10K engine will be examined and it's shortcomings in regards to NASA's ultimate goals for peroxide propulsion systems discussed.

The USFE 10k engine is a new pressure fed peroxide/JP8 design, which is totally focused on low cost expendable mission, profiles. The initial design mission for this engine was the Air Force Research Laboratory (AFRL) Modular Insertion Stage (MIS) annex to the Space Operations Vehicle (SOV) Systems Requirement Document (SRD). Subsequent studies[1] by Boeing Rocketdyne validated the choice of pressure fed engine design for this mission.

Orbital, and their technical partners Kaiser Marquardt, General Kinetics and Advanced Automated Engineering, has established a simple, traditional pressure fed engine layout for the USFE program. The engine is illustrated in Figure 1. Peroxide flows from the tanks into a distribution dome on top of the engine. The peroxide then flows down through a silver screen based catalyst system where the peroxide is catalyzed into oxygen

[1] AFRL-VS-PS-TR-1998-1049, Modular Insertion Stage Conceptual Design Study, Frederick Widman, Boeing North American, Inc., Rocketdyne Propulsion and Power, 6633 Canoga Ave., Canoga, Ca. 91309

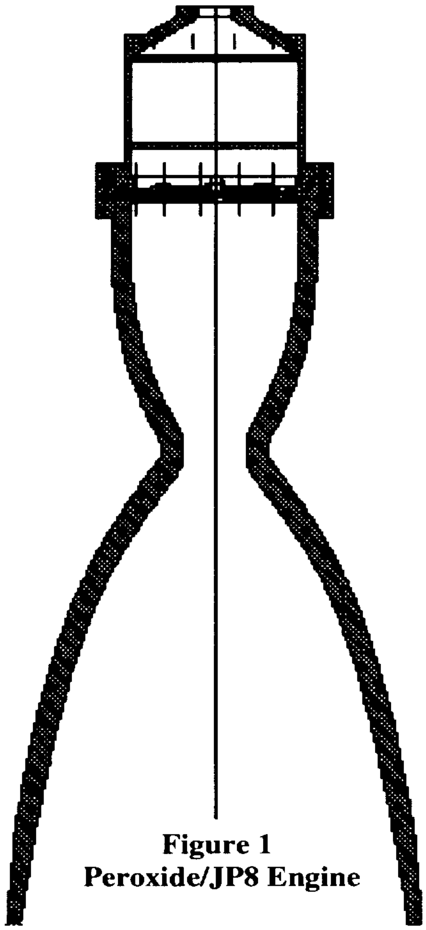


Figure 1
Peroxide/JP8 Engine

and super heated steam. The catalyzed gas then flows into the injector where the JP8 is added. Ignition is almost instantaneous, with the combustion process being completed in the combustion chamber. The combustion gases are then accelerated through the nozzle throat and expanded in a 40:1 nozzle. The nozzle construction is based on the ablative engine nozzle developed at the Marshall Space Flight Center for the Lox/RP Fastrac engine. Major component weights are presented in Table 1. Engine operating parameters are shown in Table 2. The engine has already undergone tests (Figure 2) at the Stennis Space Center E3 Test Complex and has achieved good results:

- accumulated over 300 seconds of bi-propellant operation using ablative chambers
- accumulated over 700 seconds of run time on GK cat bed without performance degradation
- demonstrated throat recession rates of less than 0.001 in/s at O/F=6
- demonstrated C* efficiencies greater than 0.97
- demonstrated multiple restarts
- demonstrated throttling to 10% in mono-propellant mode and to 20% in bi- propellant mode
- maintained perfect safety

Engine Component	Material	Weight Estimate
Gimbal Mount	SS304L	7
Distribution Dome	7075AL	25
Catalyst Housing	SS304L	37
Catalyst System	SS304L/Ag/Ni	39
Injector	SS304L	30
Chamber/Nozzle	F554 Fiber	103
Miscellaneous	SS304L/7075Al	17
Total		258

Table 1. Component Weights of USFE Engine

Figure 2: Orbital USFE 10k engine test at Stennis Space Center E3 Complex

Parameter	Value
Propellants	85% HTP/JP-8
Vacuum Thrust, lbf	10,000
Chamber Pressure, psia	500
Mixture Ratio	6.0
Nozzle Expansion Ratio	40 (five for ground tests)
Chamber Contraction Ratio	7.1
Delivered Specific Impulse, s	278
Flow rate, lb/s	36.0
Burn Time, s	200
Engine Envelope	60 in. long, 40 in. diameter

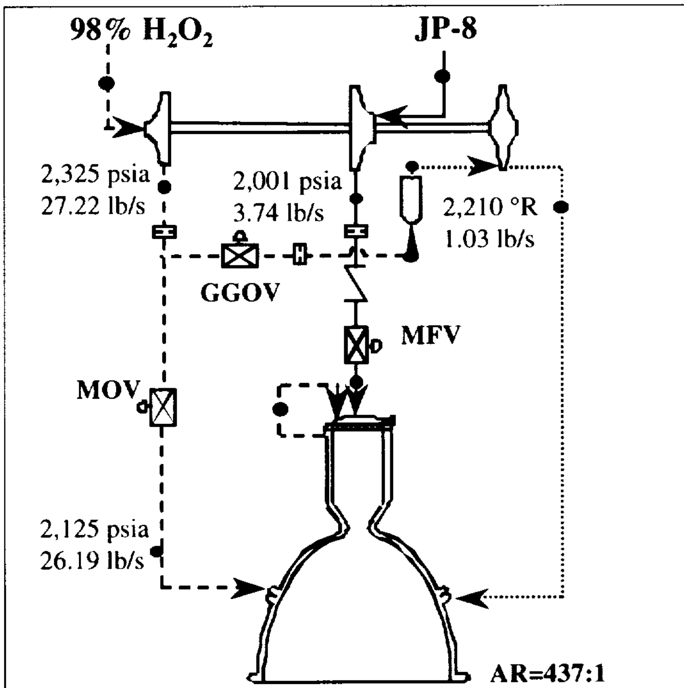
Table 2. Design and Operating Parameters of USFE Engine

The Goal

NASA's interest in peroxide propulsion is fostered by the need to achieve order of magnitude reductions in transportation costs to space. Two stage to orbit (TSTO) systems will need more operable, lower cost, reusable upper-stage propulsion systems than those presently available in the commercial marketplace. Even single stage to orbit (SSTO) systems will need orbital transfer stages with the same operating, cost, and performance characteristics as their TSTO competitors. An early decision by the designers of these RUS systems to utilize storable, non-cryogenic, environmental safe propellant systems, like peroxide/RP, can have significant impacts on operations costs for years to come. Storable propellants will enable off-line RUS fueling, and storage of fueled stages to respond to short turn-around mission requirements. Non-cryogenic RUS will allow off-line installation of payloads and eliminate the need for cryogenic safety procedures and special equipment. Environmentally safe RUS will allow elimination of dangerous and potentially harmful propellant combinations, and their attendant costs, on which today's space transportation systems are dependent. But before tomorrow's RUS designers can begin their design they must have an engine system around which to design their airframe and its many subsystems. What might that ideal peroxide/RP engine look like?

An ideal storable upper stage engine for the second half of the first decade of the new century would have the following features:

1) It would utilize 98% peroxide as the oxidizer, and JP8 as the fuel. 98% peroxide because no RUS designer can ask the booster, TSTO or SSTO, to carry any amount of water to orbit or the staging altitude. Peroxide/RP systems are only competitive with other traditional propellant systems on a density I_{SP} basis when the water is limited in the peroxide. It would utilize JP8 because it is the most readily available and low cost of the RP propellants.



Parameter	Engine	Chamber	Gas Gen.
Thrust, LbF	10,000	9,855	145
Isp, sec	323	329.2	140.6
MR	7.3	7.0	---
Pc	---	1500	671

Figure 3: Representative Engine Power Balance

2) It would be turbopump driven. The use of a turbopump allows higher engine pressures, higher I_{SP}, lower stage structural weights, and more flexibility in stage design. The turbopump would be a minimal parts count, low cost, decomposed peroxide gas generator driven design. The turbopump would be robust, but have a recurring price below $100,000. The turbopump would feature composite and ceramic materials, eliminating all metallic parts and their associated weights. It would feature a liquid/liquid injector system. Decomposition of large amounts of peroxide by catalyst prior to JP8 injection is an unnecessary process step when thermal decomposition can be accomplished with proper injector and chamber design.
3) It would utilize an expansion deflection nozzle. Packaging the engine within the stage structure in order to maximize the available booster or RUS volume for payload will eliminate the use of today's large bell nozzles.
4) It will utilize composites and ceramics throughout the design to lower engine weight and approach thrust to weight ratios of 100 without boosting engine thrust levels beyond robust design limits.
5) It will be reusable, with a useful life exceeding 100 missions between out-of-airframe maintenance actions. It will be designed for ease of maintenance while installed in the airframe.

A Critical Assessment of the USFE Engine

The USFE 10k Engine has been designed for the very low cost MIS mission and will, at the completion of its development, fulfill that mission requirement admirably. But a critical examination of the USFE 10k engine as a first step toward NASA's goal of reusable upper stage propulsion reveals a number of shortcomings:

1) The USFE 10k engine is designed for 85% peroxide. When the USFE program was initiated 85% peroxide was the highest grade of peroxide available in bulk quantities. Now 90% peroxide is available from Degussa, and tests are planned this fall at Stennis with 90% peroxide to re-baseline the USFE engine with the higher grade peroxide. But 98% is still available only from specialty suppliers.
2) The USFE 10k engine utilizes silver-based catalyst screens. Even if 98% peroxide were readily available, the silver -based catalyst screens would melt at the higher decomposition temperatures.
3) The USFE 10k engine is pressure fed. The advent of integral composite structures like those planned for demonstration in the USFE program make pressure fed designs optimal for some applications. But reusable upper stages, with complex re-entry shapes and internal payload bays will require turbopump driven engines.
4) The USFE engine is a gas/liquid injection design, requiring decomposition of the peroxide prior to entry into the injector.
5) The USFE engine is expendable. The head end of the USFE engine is reusable, and has demonstrated reuse in its Stennis test program. But the ablative chamber/nozzle is expendable by design, although it contributes to the MIS cost goals.
6) The USFE 10k engine utilizes a 40:1 expansion bell nozzle. With the launch of the USFE planned from the top of a two stage Minuteman rocket motor stack, there is no real design constraint on motor length.

7) The USFE 10k engine is metal heavy, with all components except the chamber/nozzle fabricated from aluminum or stainless steel.

The Peroxide Pathway

With a clear, and critical, understanding of the starting point for our technology journey, and a clear vision of the destination for peroxide propulsion development, the steps along the peroxide pathway can be established.

1) Step 1: Secure a reliable source of bulk quantities of high concentration peroxide. NASA, the Air Force, and industry will invest more than $50million in the development of peroxide technology in the next decade in order to achieve the potential of peroxide propulsion. That level of investment will be constantly at risk if the supply of 98% peroxide remains the product of a single specialty supplier with no history of successful delivery performance. And with cost a driving design factor in transportation system design, a single supplier can not be allowed to dictate propellant costs.
2) Step 2: Develop catalyst systems compatible with 98% peroxide. Catalyst systems are the key component in the integrated use of peroxide on future RUS. Catalyst will be used to generate gas to power the turbopump on the engine and to drive turbo generators for electrical power, to provide an ignition gas for initial thermal decomposition of peroxide in the engine, to decompose 98% peroxide for mono and bi-propellant attitude control thrusters, to generate warm gas heat for some systems, and to generate pressurization gas for tanks. A robust, long life, insensitive catalyst is the key to almost every liquid and gas system onboard future RUS. Preliminary work on 98% peroxide catalyst was done in the 50s and 60s, but none of it resulted in definitive fielded systems.
3) Step 3: Develop 98% compatible turbopumps. The USFE engine will re-establish the state of the art in pressure fed systems. The next development step must be an advanced, low parts count, low recurring price, 98% material compatible, turbopump. This is the longest lead time component in the rocket engine and must be started as early as possible. Once developed it can be used to support pure rocket system development, as well as peroxide/RP Rocket Based Combined Cycle (RBCC) demonstrations and peroxide/hybrid development.
4) Step 4: Develop light weight non-metallic reusable liquid/liquid injectors and combustion chambers. Elimination of the large catalyst packs will contribute significantly to lower engine weight and reduced engine maintenance. Liquid/liquid injection will eliminate energy losses occurring in the pre-chamber decomposition of the peroxide. And use of advanced non-metallic materials will substantially lower the weight of the engine.
5) Step 5: Develop a light weight non-metallic reusable expansion deflection nozzle. Axial length to cross-sectional diameter ratios in excess of 1:3 will be necessary to meet future engine packaging requirements. Bell nozzles can not hang out the back of re-entering upper stage flight vehicles the way SSMEs do on the Shuttle.
6) Step 6: Develop light weight non-metallic engine components, such as valves, regulators, actuators, etc. NASA and industry took a step in this direction by

designing, fabricating, and flight testing a composite hydrogen control valve on the NASA/McDonnell Douglas DC-XA program in 1996. But more than fabrication of individual valves must be done. Consolidation of functions, elimination of brackets and tubing, and relocation of components for ease of maintenance and test must dominate new designs.

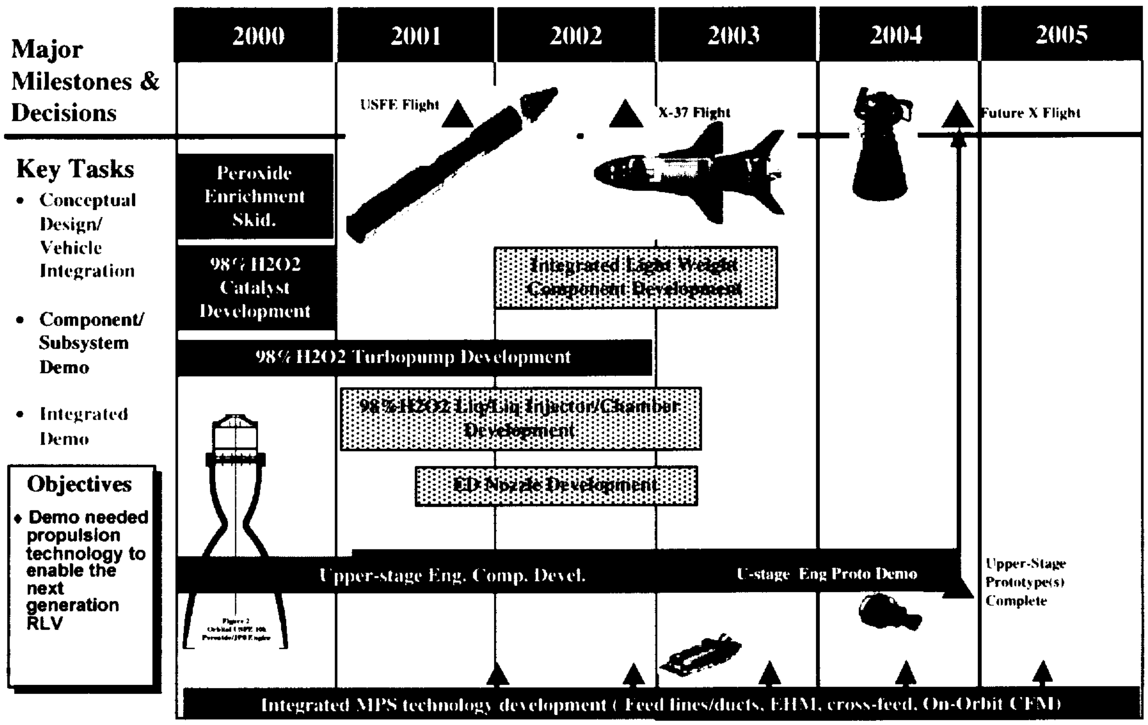


Figure 4: A Technology Roadmap for Reusable Peroxide Propulsion Development

NRA8-21: We Begin the Journey

On February 17, 1999 NASA issued amendment 4 to NRA8-21 inviting proposals for cycle 2 evaluation. The NRA sought "**Proposals ... for the application of advanced materials and design processes to reduce the weight of the peroxide propulsion system elements, increase the combustion system efficiencies, and to lower the cost of delivered stages. ... Industry proposals may address the production of higher concentrations of peroxide, more efficient injectors, peroxide compatible turbo-machinery, advanced catalyst, and advanced chamber/nozzles.**" Proposals were received through 15 April, 1999, and then evaluated by technical personnel from both the Air Force and NASA. The selections were announced in late June. Were the selections a step down the peroxide pathway?

Orbital Sciences was selected to design, fabricate, and demonstrate a portable peroxide enrichment skid. Why portable? Why enrich peroxide? Because we need 98% peroxide at the Stennis Space Center to support engine and component development tests. Because we need 98% peroxide at contractor facilities in California to support engine and component development tests. Because we need 90% peroxide in Alaska to support the USFE launch. Because we need 90% peroxide at the Cape to launch the X-37. Because we have only one bulk supplier of 90% peroxide, Degussa Huls, and he ships the material from Europe. If Degussa decides to devote their resources to other profit opportunities, NASA must have an alternative way to produce high grade peroxide in support of our technology investments. NASA will not operate this skid in competition with private industry so long as private industry meets our supply needs at reasonable prices. Because it is safer to enrich peroxide on site, and be able to control its quality, than it is to expose the general public to the shipment of 98% peroxide. Because **Step 1 is secure a reliable source of bulk quantities of high concentration peroxide.**

Figure 5: Monolythic Catalyst Bed

Aerojet, Boeing Rocketdyne, TRW, TRW partner General Kinetics, and TRW partner Purdue University were all selected to work on advanced catalyst for decomposition of 98% peroxide. Why so many? Because competition is desirable. Competition is responsible for more technical innovation in the United States than any other factor. Because every one offered a different solution. Because the costs to explore these many potential solutions are moderate. Because the 98% catalyst is the key development on which the future of reusable peroxide propulsion rests, and the more approaches tried the higher the chance of success. Because **Step 2 is develop catalyst systems compatible with 98% peroxide.**

Boeing Rocketdyne was selected to design, fabricate, and demonstrate a state-of-the-art low cost, low parts count, 98% compatible, gas generator driven turbopump. Boeing recently successfully designed, fabricated, and tested a 60K pound thrust Lox/RP turbopump for the Low Cost Boost Technology program with a projected recurring cost approaching $100,000. And Boeing designed, produced, and fielded a man rated turbopump in the AR2-3 several decades ago. With this success base to draw on, Rocketdyne will still be challenged to produce a modern pump with recurring costs approaching $50,000 to support future NASA and Air Force missions. But it will still not be the non-metallic light weight low parts count pump that is our final destination. That will take additional design and development cycles. Why go forward with

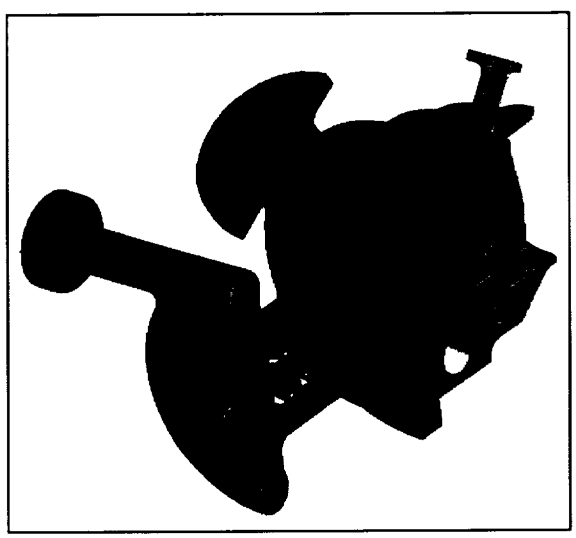


Figure 6 Peroxide Turbopump

an interim design? Because this pump will adequately support second generation X-37 and USFE mission plans. Because **Step 3 is develop 98% compatible turbopumps.**

FMC Corporation was selected to perform hazardous materials testing of 98% concentration peroxide. Safety is always a foremost consideration. Almost all of the data pertaining to safe handling and storage of 98% peroxide is three or more decades old. More current data will be required to satisfy today's range and flight safety boards for the USFE and X-37 flights. FMC, as a past American supplier of high concentration peroxide, is eminently qualified to perform these tests and establish the required safety data.

Proposals were also received for liquid/liquid injectors, regeneratively cooled chambers and nozzles, complete engines, and complete flight vehicles. These proposals will have to wait for additional funds to become available, or be resubmitted against a new NASA Research Announcement in the future.

Conclusion

There is an orderly plan, a technology roadmap, for NASA's peroxide technology investments. The NRA 8-21 proposal selections are a start down the path toward the goal of a storable propellant, reusable, low cost, non-cryogenic propulsion system to meet future Reusable Upper Stage mission needs. More work will be needed to approach the ideal engine solution. But continued consistent investments by industry, NASA, and the Air Force, working together, can get us to the end of our development path in time to satisfy prime contractor needs.

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