NON-TOXIC REACTION CONTROL SYSTEM FOR THE REUSABLE FIRST STAGE VEHICLE

E. L. Keith and W. J. Rothschild

The Boeing Company
Seal Beach, California

ABSTRACT

This paper presents the Boeing Reusable Space Systems vision of a Reaction Control System (RCS) for the Reusable First Stage (RFS) being considered as a replacement for the Solid Rocket Booster for the Space Shuttle. The requirement is to achieve reliable vehicle control during the upper atmospheric portion of the RFS trajectory while enabling more efficient ground operations, unhindered by constraints caused by operating with highly toxic RCS propellants. Boeing's objective for this effort is to develop a safer, more efficient and environmentally friendly RCS design approach that is suitable for the RFS concept of operations, including a low cost, efficient turnaround cycle. The Boeing RCS concept utilizes ethanol and liquid oxygen in place of the highly toxic, suspected carcinogen, ozone-depleting mono-methyl-hydrazine and highly toxic nitrogen tetroxide. The Space Shuttle Upgrade program, under the leadership of the NASA Johnson Space Flight Center, is currently developing liquid oxygen and ethanol (ethyl alcohol) technology for use as non-toxic orbital maneuvering system (OMS) and RCS. The development of this liquid oxygen and ethanol technology for the Space Shuttle offers a significant leverage to select much of the same technology for the RFS program. There are significant design and development issues involved with bringing this liquid oxygen and ethanol technology to a state of maturity suitable for an operational RCS. The risks associated with a new LOX and Ethanol RCS are mitigated by maintaining kerosene and hydrogen peroxide RCS technology as an alternative. These issues, presented within this paper, include managing the oxygen supply and achieving reliable ignition in the short pulse mode of engine operation. Performance, reliability and operations requirements are presented along with a specific RCS design concept to satisfying these requirements. The work reported in this paper was performed under NASA Marshal Space Flight Center Contract Number NAS8-97272 to define Reusable First Stage design concepts for the Space Shuttle.

INTRODUCTION

The Boeing Reusable First Stage (RFS) concept is for a liquid rocket-powered vehicle which flies back to the launch site as a jet propelled, winged vehicle (see Figure 1). In such a mission, the vehicle will travel beyond the atmospheric limits for which aerodynamic forces can be used to maintain vehicle attitude. After the RFS passes through a ballistic arc, it must be in the correct attitude as it reenters denser atmosphere (see Figure 2). A reaction control system (RCS) is required to alter and maintain the RFS vehicle attitude until such time as the vehicle is controllable using aerodynamic surfaces.

The RCS consists of several small rocket engines to provide the rotational torque needed to maintain correct attitude. Traditionally, these small rocket engines have used high-density storable propellants with hypergolic (self-igniting) properties[1]. These fuels include hydrazine [N_2H_4], monomethyl hydrazine or MMH [CH_3NHNH_2] and unsymmetrical dimethylhydrazine or UDMH [$(CH_3)_2NNH_2$]. All of the hydrazine fuels are extremely toxic and are suspected liver carcinogens. The traditional RCS oxidizers include nitrogen tetroxide (N_2O_4), nitric acid (HNO_3) and other chemical mixtures containing these strong oxides of nitrogen. All of these strong oxides of nitrogen are extremely toxic and are classed as ozone depleting chemicals. Boeing is working to eliminate the use of toxic propellants on board reusable launch vehicles for operational reasons.

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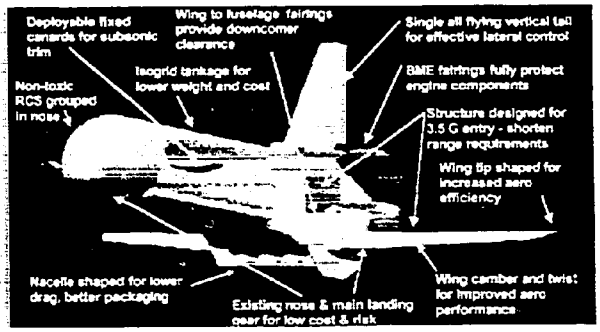

Figure 1 – An Innovative Combination of Proven Elements Results in a Feasible Effective Reusable First Stage

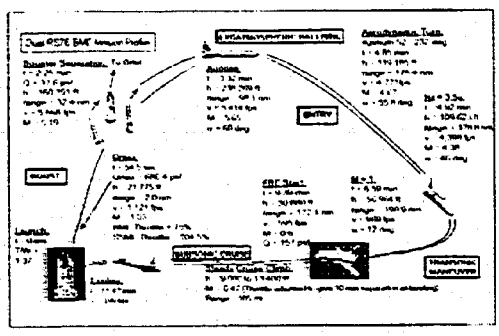

Figure 2 – The RFS / Shuttle Flies in Five Different Flight Regimes

WHY TOXIC RCS PROPELLANTS ARE IN CURRENT USE

Toxic RCS propellants have excellent properties ideally matched to reaction control system requirements. The toxic propellants are dense, allowing for easy packaging in the limited-volume available on launch vehicles. The toxic propellants are energetic, resulting in specific impulse in the 300 to 320-second range. The toxic propellants are hypergolic, eliminating the need for an ignition system, and eliminating ignition reliability issues. The toxic propellants are easy to store on a permanent basis. None of the toxic storable propellants tend to boil, react, or change chemically, even if stored for years at ambient temperature and pressure. Alternative propellants lack one or more of the positive attributes of toxic storable propellants. The critical attributes, usually associated with reaction control engines, are simplicity, high performance, high propellant density, easy propellant storage and hypergolic ignition. Some of these properties are at least partially absent in alternative propellants.

PROBLEMS WITH TOXIC RCS PROPELLANTS

The Boeing approach is to avoid using these storable RCS propellants because they are highly toxic, making special handling and operational procedures mandatory. Normally, all operations at a work site must be suspended when these toxic propellants are being loaded aboard a rocket vehicle. These special precautions include evacuation of a wide area of all non-essential personnel, and use of special safety suits which employ self-contained breathing capability. The evacuation procedure significantly disrupts the normal work process on a rocket vehicle. These work flow disruptions would have a substantial negative effect on the economies required to make reusable launch vehicles viable. The objective of eliminating the toxic propellants on the next-generation reusable rocket vehicles is to eliminate the operational disruptions required during the handling of toxic propellants.

ALTERNATIVES PROPELLANTS

The next decision, once toxic propellants are ground-ruled out for RCS applications, is to select an alternative. There are two environmentally friendly oxidizers to choose from, liquid oxygen and hydrogen peroxide. Liquid oxygen (O_2) had the advantage of very high performance, but has the disadvantage of being cryogenic. Hydrogen peroxide (H_2O_2) is very dense and is not cryogenic, but exhibits lower performance. The LOX and ethanol RCS concept, similar to that being applied to the Space Shuttle, has been adapted as the baseline. The alternative of using hydrogen peroxide as the oxidizer has been selected as a back up for the Reusable First Stage RCS.

The choices for non-toxic fuels are wider. The light alcohols such as methanol (CH_3OH), ethanol (C_2H_5OH) and isopropyl alcohol (C_3H_7OH)) are safe to handle and very common in industrial applications. Petroleum-based hydrocarbon fuels such as JP-8 grade kerosene ($CH_{1.95}$) are also widely used in both industrial and rocket applications. While these fuels are somewhat toxic, they are common industrial and aerospace products where safe handling is relatively easy compared to the extremely toxic hydrazine compounds and strong oxides of nitrogen.

CRITICAL METRICS

The requirements for the RFS include providing for angular rotational acceleration of 2.5 degrees per second per second in pitch and yaw, and 2.0 degrees per second per second in roll. The RCS must be fully redundant for a fail-safe operation. The RCS engine thrust of 870 pounds is matched to the Space Shuttle requirements, with the number of engines being determined by the required torque force. The minimum impulse bit is 80-miliseconds, identical with the Space Shuttle requirements.

Specific impulse performance for the Reusable First Stage RCS is important, but not extremely critical. The RCS must operate for only four to six minutes, reducing the impact of variations in specific impulse compared to other factors. It is very important to have a lightweight, reliable and easy-to-maintain RCS. Development cost and technical risk is also very important. Concerns for development cost and risks have eliminated all but two candidate systems, one based on liquid oxygen and ethanol and an alternative using hydrogen peroxide and possibly a non-toxic fuel to improve overall performance. The key RCS characteristics for the Reusable First Stage are summarized in Figure 3.

- **Efficient operations consistent with a reusable system**
- **No highly toxic propellants**
- **Existing technology for low development cost and risk**
- **Engine-out Mission Reliability**
- **Thrust per Main RCS Engine – 870 lbf**
- **Total Impulse – 35,000 lbf-sec over a 200 - 300 second operating timeframe**
- **Pulse Rate – 80 msec**
- **Reliable Ignition**

Figure 3 – Key RCS Characteristics for the Reusable First Stage

The most critical parameter in determining the RCS approach for the RFS was to reduce development cost and risk by leveraging to the greatest extent existing technology, especially technology currently under development. Again there were two choices. First, Boeing is already involved in development of LOX and ethanol OMS and Reaction Control to upgrade the Space Shuttle. Boeing is also involved in hydrogen peroxide and kerosene engines for the X-37 Future-X prototype.

The RCS concept for the RFS is to place all control thrusters in the nose section. The center of gravity is aft near the main propulsion system, providing a long moment arm for the RCS pitch and yaw torque. The roll torque is lower than for an in-wing roll RCS thruster design, but the roll moments of inertia are low. Concentrating the RCS

into one zone of the RFS is seen as an effective cost and weight lowering strategy. The actual RCS concept is simply a pressure-fed propulsion system with multiple thrust chambers (see Figure 4).

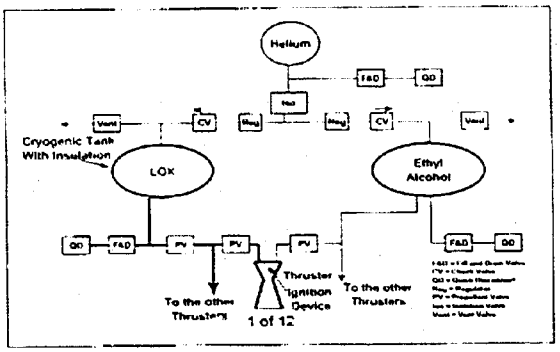

Figure 4 – Primary Oxygen / Ethanol RCS Concept Schematic

ENVIRONMENTALLY FRIENDLY RCS

Use of either liquid oxygen or hydrogen peroxide to replace highly toxic nitrogen tetroxide is one huge step in the creation of an environmentally friendly RCS. If liquid oxygen is spilled, it simply vaporizes into environmentally harmless oxygen. If hydrogen peroxide spills, it breaks down into oxygen and water. Use of ethanol or other hydrocarbon fuel in place of the extremely toxic hydrazine, Monomethyl hydrazine or UDMH, is the other huge step to an environmentally friendly RCS

ENGINE AVAILABILITY

A LOX and ethanol RCS is particularly attractive because the engine is in commercial development plus a similar RCS concept is under development for the Space Shuttle. Both Aerojet and TRW are working on LOX and ethanol rocket engines that are appropriate for RCS operations on the RFS. For the purposes of this study, Boeing has selected the Aerojet engine, which is very similar to one being developed for the Kistler launch vehicle orbital maneuvering system (OMS). The Aerojet LOX and ethanol engine has been successfully tested in both the steady state and the pulsed mode, and the igniter system has been characterized for high reliability (see Figure 5). The LOX and ethanol pulsed-mode engines are somewhat heavier than the hypergolic MMH/NTO engines they would replace due to the requirement for a separate ignition system.

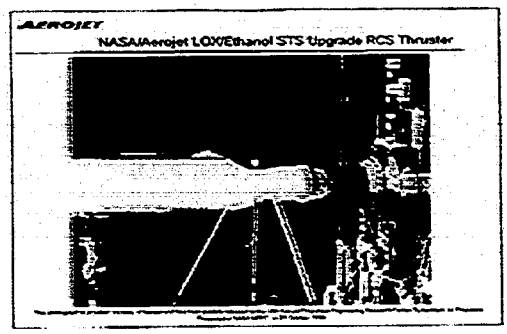

Figure 5 - RFS Oxygen / Ethanol RCS Concept Uses Existing Rocket Engines

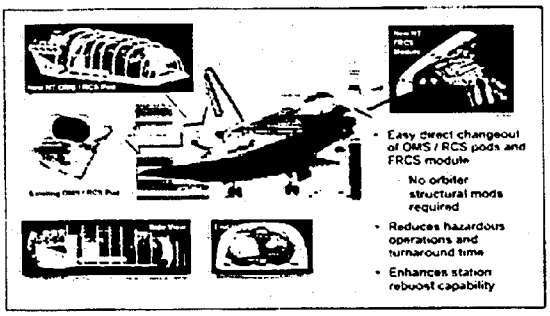

Figure 6 – Primary Oxygen / Ethanol Concept Derived from the Space Shuttle RCS

The greatest advantage of a LOX and ethanol RCS system lies in the fact that it is currently under development for Space Shuttle applications (see Figure 6). This effort is justified because the loading of toxic propellants requires that all other Space Shuttle operations on the launch pad halt for six shifts, while 10 metric tons of toxic MMH, hydrazine and nitrogen tetroxide are loaded onboard the Space Shuttle.

The Shuttle RCS development is more complex than the RCS for RFS would be. The Shuttle RCS has connected forward and aft systems, and it is fully integrated into the OMS. The RFS would have RCS in the nose only, without an OMS. The Space Shuttle must operate for 14 days in the micro-gravity of space. The RFS must operate for a few minutes after liftoff in a low gravity environment compared to weeks in orbit prior to re-entry for the Shuttle. Since the RFS RCS is far simpler then the Space Shuttle forward and aft RCS and OMS, then the derivation of shuttle RCS to RFS application should be of lower cost and risk to develop.

SMV DERIVED RCS

Another excellent oxidizer that is not classified as being toxic is hydrogen peroxide. Hydrogen peroxide has much higher density than liquid oxygen. There are, however, significant technical risks to hydrogen peroxide technology. Modern hydrogen peroxide contains stabilizing chemicals that tend to "poison" silver screen catalyst beds. The silver screen catalyst bed technology, while mature, went unused for nearly three decades during which many of the lessons learned have been lost. There are additional limitations, such as exclusion of peroxide beyond 92% concentration, when using silver screens to decompose peroxide. Once decomposed, peroxide can be used in the mono-propellant mode, or a suitable fuel can be injected into the hot steam/oxygen stream to provide additional energy from combustion. The backup peroxide RCS approach, derived from the X-37A, is shown in Figure 7.

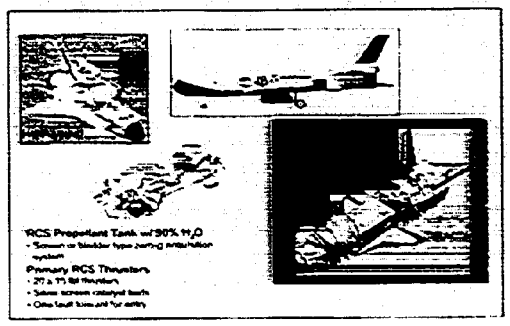

Figure 7 – X-37 Back Up Peroxide RCS Approach from X-37A

Boeing is developing the X-37A Future-X prototype vehicle that utilizes hydrogen peroxide and kerosene propulsion. While the X-37A uses a pump-fed engine, smaller pressure-fed thrusters can be developed that operate on the same principle. A hydrogen peroxide RCS thruster could operate either as a mono-propellant system or as a bi-propellant rocket. Hydrogen peroxide RCS propulsion would be low risk by the time the X-37 flight test demonstrations are completed.

CONCEPT OF OPERATIONS

The RSF RCS differs from any Space Shuttle configuration in that there are very low time in space requirements for an RFS. Whereas a Space Shuttle mission may operate for two weeks, an RFS mission RCS function lasts only for a few minutes beginning at first stage separation. Therefore, the problem of managing liquid oxygen over a long duration is not present. While liquid oxygen is not permanently storable, it is readily storable for the several hour maximum duration required for on-pad storage plus the mission duration of a few minutes. The short-term storage requirement allows the RCS system for the RFS to be designed with less stringent insulation requirements for the liquid oxygen tank and the cryogenic feed lines than those required for the Space Shuttle. The concept of operation is to fill the RCS system with LOX during the main propellant loading operation, most likely from a branch of the same fill and drain lines used to fill the main propulsion system. Like the main propellant loading, the RCS would require constant LOX replenishment until shortly prior to launch. The replenishment of LOX would be used to replace liquid oxygen that vaporizes from heat leaking into the storage tank and propellant lines. The replenishment would also allow a slow purge, in order to keep lines charged with near normal boiling point liquid oxygen, and to chill hardware. Once the main LOX tank is sealed for flight, the auxiliary RCS LOX tank will also be sealed.

The RFS vehicle stays within the sensible atmosphere to the extent that fluids tend to accumulate in predictable locations. Therefore, no new propellant management technology is needed to control the liquid oxygen.

There is no problem anticipated with the long-term storage of ethanol. Ethanol will not vaporize in a sealed system and will not change chemically. Therefore, the ethanol can be loaded at any convenient time during the several-week period between RFS missions. There are no known problems of toxicity or safety, other than flammability, that requires special handling of ethanol during refueling operations.

RISKS

A non-toxic reaction control system is desirable, but there are some risks. The toxic storable propellants are well characterized, well understood, are hypergolic (self-igniting) and are rich in existing space-qualified hardware. The toxic propellants are permanently storable, that is they do not boil away and they do not change chemically with time. Ethanol is also permanently storable, but liquid oxygen is not. Liquid oxygen boils at 297 degrees below zero Fahrenheit and will vaporize over time in space or on the ground without active refrigeration. The storage risk caused by the cryogenic nature of liquid oxygen is minimal. The propellant management risk is also small, since the vehicle is always under at least some predictable drag force.

The most significant risk is that the reliability will be lower due to the need for an ignition system. The hypergolic rocket engine systems can undergo tens of thousands of pulsed firings, with virtually no risk of ignition failure. A LOX ethanol system may be made reliable, but it will always be subject to failure modes, which do not exist where the propellants are hypergolic. These risks include specific failure of the ignition system as well as the possibility of a hard start following an ignition delay.

RISK MITIGATION

The primary risk mitigation is testing the LOX and Ethanol system. The test plan included qualifying the RCS components for the RFS environments, verifying ignition reliability with long-term pulsed firing demonstrations and conducting combined systems testing to validate the integrated RCS. An extensive test program will assure the LOX and ethanol RCS meets all the requirements for a RFS.

The risk-mitigation strategy includes investigating alternatives to the use of liquid oxygen as the oxidizer. Hydrogen peroxide could be used with ethanol, although the most common fuel in peroxide applications is kerosene.

The last resort would be to revert to a toxic propellant design. The nature of existing space qualified bi-propellant thruster engines, and the wide choice of existing hardware thrust levels, minimizes the difficulty of reverting to a conventional toxic propellant system should the baseline LOX/Ethanol or alternative peroxide/JP-8 approach prove too difficult or costly to implement.

CONCLUSIONS

The current storable propellants have excellent properties for a reaction control system, except for the problems of handling such toxic and environmentally dangerous chemicals. The handling problems are severe enough to make the toxic propellants undesirable for next-generation reusable rocket-vehicles. There are technical problems with any new application for a propellant combination used for short-duration pulsed-mode rocket engine firings. A careful examination of the technical problems suggests that these problems can be overcome, and that non-toxic Reaction Control system for next-generation reusable rocket-vehicles is practical. Boeing has established a baseline RCS design concept based on LOX/Ethanol technology currently under development for the Space Shuttle, with a backup approach based on peroxide/JP-8 under development for the X-37A.

REFERENCES

[1] Sutton, George P. Rocket Propulsion Elements. New York: John Wiley & Sons, Inc. (1986).