Shuttle Evolution: Improved Aft Propulsion System

Witalij Karakulko*
NASA Johnson Space Center, Houston, Texas 77058
and
Scott R. Frazier†
McDonnell Douglas Space Systems Company, Washington, D.C. 20024

Several proposals for improving the Space Shuttle orbital maneuvering subsystem (OMS) have been proposed. One of the principal concepts is a pump-fed orbital maneuvering engine (OME). The higher performance of this engine reduces the propellant requirements or allows higher Shuttle altitudes. Another concept integrates the OMS and the aft reaction control subsystem (RCS). This reduces Orbiter weight, propellant residuals, and dispersions, and allows the RCS propellant to be loaded to meet specific mission requirements. This paper analyzes the performance improvements for a typical Space Shuttle manifest in the 1990s and Shuttle high-altitude delivery/reboost missions for several improved OMS configurations. A brief description of each proposed new OMS configuration is presented along with performance calculations for each. The utility of these performance changes varies, depending on the availability of the advanced solid rocket motor and the orbital maneuvering vehicle. The expected cost and implementation issues are addressed and compared, yielding a list of possible alternatives and their respective enhancement to the Shuttle capabilities.

Introduction

IN a continuing effort to reduce the operating cost and to improve the performance of the Space Shuttle, NASA has implemented the concept of Shuttle evolution. It basically consists of reviewing the history of various subsystems, of noting their shortcomings and resulting effects on the program, and in devising cost-effective improvements. A multitude of subsystem changes has already been made to enhance Shuttle safety. The task of reducing the cost of ownership and enhancing operational capability without compromising safety is a continuous process, composed of studies, experiments, and debates, leading to beneficial modifications in specific areas. The process ripples through the total program and eventually results in improvement of the overall vehicle characteristics, hence the term evolution.

In the propulsion area, several proposals for improving the Space Shuttle OMS and RCS are under consideration. The OMS is the primary Space Shuttle propulsion system for major on-orbit maneuvers. This includes orbit insertion/circularization, deorbit, orbital transfer/rendezvous maneuvers, and abort maneuvers. The aft RCS is located in the same aft propulsion system (APS) pod structure as the OMS and is used on-orbit and during re-entry for attitude control, and occasionally for minor orbital maneuvers.

Two evolutionary concepts are considered in this study. The first option involves procuring a new pump-fed OME with higher specific impulse, which reduces the propellant necessary for a given mission, or enables higher velocity changes (altitude) using the existing tanks. The second option considers eliminating the separate RCS tank systems in the APS pods and feeding propellant directly from the OMS tanks to the RCS thrusters for on-orbit maneuvering. This requires adding special entry "sump" tanks to provide attitude control propellant during re-entry. This option yields a net structural weight savings, propellant savings due to reduced residuals, and flexible propellant loading options. It also reduces system complexity, but may require a change to the OMS tank capacity.

These two concepts are complementary and can be considered together. The study focuses on defining the tangible benefits provided by different OMS/RCS configuration combinations. A mid-1990s Shuttle manifest was formulated, and the different configurations were compared on the basis of increased payload capability. The advantages of altitude capability on satellite reboost or servicing missions were estimated. Finally, development and implementation costs were estimated and weighed against the benefits for the different configurations.

Existing OMS

The OMS is located in two APS pods mounted near the Orbiter's vertical tail and above the main propulsion system engines (see Fig. 1). The primary system elements in each pod include one 6000 lbf/26,700 N OME, propellant tankage for storing 4820 lbm/2185 kg of monomethylhydrazine (MMH), 7712 lbm/3500 kg nitrogen tetroxide (NTO), and a helium

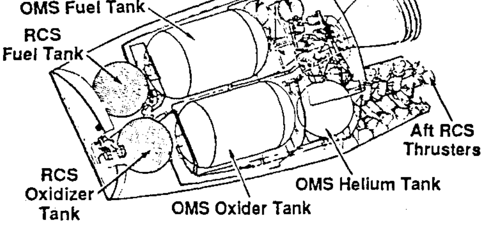

Fig. 1 Aft propulsion system.

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*Deputy Chief Propulsion and Power Division, Code EP. Member AIAA.

†Senior Engineer, Suite 301E, 600 Maryland Ave. S.W. Member AIAA.

Table 1 Uprated OME comparison

	Current OME	Uprated OME
Thrust (lbf)	6000	6000
Chamber pressure (psia)	125	350
Nozzle expansion ratio	55:1	155:1
Dry weight (lbm)	297	322
Specific impulse (s)	314	331
Mixture ratio	1.65:1	1.65:1
Start cycles (goal)	125	(500)

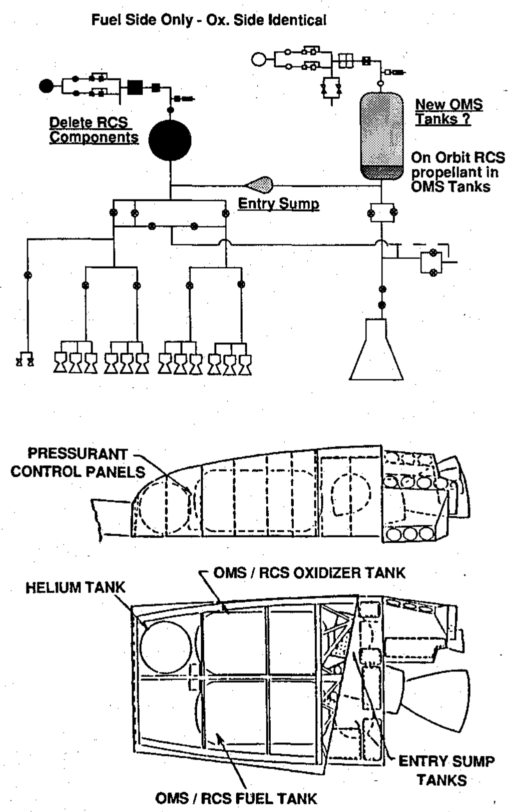

Fig. 2 Modifications for integrated OMS/RCS.

pressurization system used to maintain the OMS propellant tank pressure near 250 psia (1725 kPa).

The aft RCS located in each APS pod includes 12 primary thrusters (870 lbf/3870 N), 2 vernier thrusters (24 lbf/107 N), and an MMH tank and NTO tank, each with its own helium pressurization system. The aft RCS thrusters are connected to a manifold system that allows propellant use from the RCS tanks or the OMS tanks in either OMS pod. The aft RCS propellant load is 1547 lbm (702 kg) NTO and 938 lbm (425 kg) MMH per pod.

Uprated Orbital Maneuvering Engine (U/OME)

The effort to demonstrate the feasibility of a higher chamber pressure OME utilizing a turbopump assembly began in 1984.[1] The higher chamber pressure combined with an increased nozzle expansion ratio and other modifications improves the specific impulse of the engine approximately 5%. The characteristics of the existing OME are compared with the Uprated OME in Table 1.

The performance increase is directly attributable to a larger expansion ratio allowed with the higher combustion chamber pressure generated by the turbopump. Although performance improvement is the project goal, minimizing the net impact to the Orbiter is a primary consideration. The engine design is expected to meet the current requirements for physical envelope, reliability, and life cycle capability. A predevelopment engine has been assembled and significant hot fire testing has been completed to assess the reliability and performance of the new design. Several papers and studies have addressed this engine in several applications.[2–4]

Table 2 Integrated OMS/RCS weight changes

	Wt change, lbm
Deletions	
4 RCS propellant tanks	−330
4 RCS He tanks	−106
RCS pressurization systems (plumbing, structure, valves, regulators, couplings, etc.)	−218
Fluid plumbing, structure & misc.	−60
Additions	
4 Entry sump tanks	+110
Structure	+20
4 liquid interconnect lines	+10
Total Orbiter dry wt change	−574

Table 3 Propellant savings of integrated OMS/RCS

	Propellant reduction, lbm
RCS residuals	150
Gauging contingency	170
RCS dispersions	75–200
Load for mission requirement	0–600
Total propellant savings	395–1120

Integrated OMS/RCS Concept

The objective of this configuration is to reduce overall complexity and improve performance by using the proven OMS-to-RCS propellant feed mode system in the APS pods. Reentry sump tanks must be added to provide RCS propellant flow during "high" acceleration entry when the acceleration vector settles the propellant, exposing the OMS propellant feed line to the ullage gas. The changes to the aft propulsion system are shown in Fig. 2.

The entry sump tanks do not need the complex propellant acquisition system (surface tension devices that preclude gas ingestion in zero-*g*); they will be used only when the propellant has settled due to the entry acceleration forces on the vehicle. These tanks will be considerably smaller than the existing RCS tanks since they hold propellant for re-entry attitude control only. The OMS helium pressurization system provides the ullage pressure for all RCS firings, eliminating a total of four helium pressurization systems. A detailed listing of the removed/added items[5] and their weight can be found in Table 2. The removal of these items significantly reduces the RCS system complexity and saves mission-to-mission preparation and checkout cost (approximately 20%).[6]

This system offers several features that can improve the required propellant loading. Currently, the aft RCS tanks must be completely loaded to avoid gas ingestion through the acquisition screens during launch. Roughly one-half of the missions flown to date did not need full RCS tanks. Integrated OMS/RCS would allow loading only the propellant necessary for a given mission. Other benefits include the reduction in propellant residuals, tanking/gauging contingencies, and averaging the dispersions over one propellant system rather than two. These effects are detailed in Table 3.

Stretched OMS Tanks

The total bipropellant tankage decreases with integrated OMS/RCS (about 2800 lbm net usable), which is a potential drawback. This effectively reduces the maximum altitude of the Orbiter. (Higher altitudes require more velocity change for orbit circularization and deorbit.) A study by the existing APS pod contractor, McDonnell Douglas Missile Systems Co. in

St. Louis, investigated the modifications and costs associated with new "extended" OMS tanks.

The basic integrated OMS/RCS concept would simply modify the existing APS pods, which would reuse all of the expensive components and minimize cost. New OMS tanks are required if a tank stretch to increase propellant capacity is needed. Analysis indicates that four different tank stretches are possible. Two of these options are considered in the configuration analysis because they meet or exceed the current altitude capability of the Orbiter (one with U/OMEs and one with current OMEs).

The minor tank stretch option increases the total propellant capacity by 2082 lbm/944 kg, by adding 6.6 in./16.8 cm to the tank length. This requires modifying the APS pod aft bulkhead to allow additional tank penetration (4 in./10.2 cm) and extending the tank forward (2.6 in./6.6 cm) by using the available RCS tank mounting bracket for suspension. This option, when combined with the U/OME, slightly exceeds the existing altitude capability.

The major tank stretch option extends the tank to the maximum feasible length (11.6 in./29.5 cm) by utilizing the 4-in. aft stretch and changing the forward APS bulkhead location to allow a 7.6 in. forward stretch (limited by pod mold line/volumetric constraints). This modification also requires a change of the APS pod skin, due to the rearranged support frames and bulkheads. This option provides a modest altitude increase with the existing OMEs and a major improvement with the U/OMEs.

Mission Performance Enhancements

The performance advantages of these OMS improvements must be evaluated in the launch environment that is expected when the modifications become available. The uprated OME will increase payload capability as a direct function of the propellant loading. A 5% higher specific impulse roughly reduces the propellant required by 5%—allowing additional payload weight. OMS propellant loading is primarily driven by the desired mission altitude. The OMS loading and payload savings for the U/OME increase with altitude are illustrated in Fig. 3.

The propellant "saved" by the U/OME could be used to increase the altitude of the Orbiter instead of carrying additional payload. At the maximum OMS tank load, the U/OME yields an additional 60 fps/18 m/s or so (depending on vehicle/payload weight). This velocity would allow the Orbiter to initially attain an orbit about 17 nm/31 km higher than its present capability, or reboost a satellite about 11 nm/20 km higher. Reboost maneuvers use more OMS propellant because all of the energy required to raise the apogee and perigee, and then to lower the perigee for deorbit, is provided by the OMS. When directly launching to maximum altitude, the energy to raise apogee is provided by the main propulsion system (MPS).

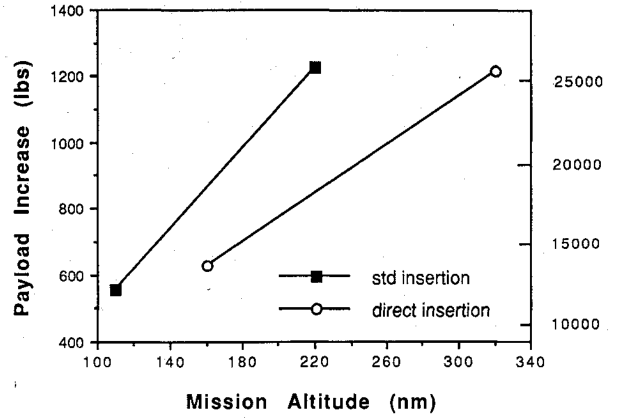

Fig. 3 Uprated OME savings vs altitude.

The data in Fig. 3 show a difference between standard insertion and direct insertion. Standard insertion has a main engine cut-off (MECO) velocity that is slightly lower than direct insertion, which therefore requires a larger OMS propellant loading, but improves second-stage performance. This means that more of the propulsive requirement is given to the OMS rather than the MPS. (The reason these insertion cases are not continuous is due to different external tank impact areas: standard insertion, Indian Ocean; direct insertion, Pacific Ocean.) Currently, the net performance is about the same with either method when the different factors are considered (different specific impulses, carrying of the external tank, targeting inefficiencies, etc.). The improved specific impulse of the U/OME changes the balance such that standard insertion improves the total payload capability vs direct insertion. However, standard insertion missions cannot fly as high as direct insertion missions, as shown in the figure.

The performance advantages of an integrated OMS/RCS do not vary with altitude. However, performance will vary depending on whether the mission requires significant attitude control. Rendezvous and proximity operations missions traditionally require considerable RCS maneuvering. These missions will not reap the benefits of variable RCS loading, but the structural weight reductions and dispersion reductions (Tables 2 and 3) will always improve performance.

Space Shuttle Missions in the 1990s

It is important to consider the expected Shuttle launch environment in the time frame that the modifications will become available. A typical annual manifest was formulated based on the predicted number of space station flights per year and the current manifest for the early 1990s. The target launch rate for 1994 is 14 flights per year. Space station will require 5 flights per year to assemble the station and rotate the astronaut crews. The average space station altitude is assumed to be 210 nm/390 km (although it will vary throughout its mission lifetime).[7] The current manifest indicates about one-third of the general missions go to high inclination (>40 deg) and two thirds to 28.5 deg (due east launch). Almost all of these "typical" missions fly to 160 nm (296 km) altitude. This composite manifest and the payload capability effects of the advanced solid rocket motor (ASRM) are summarized in Table 4.

Advanced Solid Rocket Motor

The ASRM is a new first-stage booster for the Space Shuttle. The performance goal for ASRM is an additional 12,000-lbm (5450 kg) payload capability available in 1994. This project significantly affects the possible savings from improved OMS in several ways. Primarily, the payload carrying capability of the Shuttle to typical altitudes (100–200 nm/185–370 km) will be constrained to about 56,000 lbm (25,400 kg) due to abort landing weight limits. (Landing weight must consider abort scenarios or contingencies where the payload is not deployed and is limited by structural loads during final approach and landing.) Reducing the OMS propellant loading for these missions will not reduce the abort landing weight because most OMS propellant is dumped/burned during an abort. Therefore, propellant savings will not increase payload capability for any missions that are abort weight constrained (below 200 nm/370 km), since the ASRM has already provided the maximum payload capability.

Table 4 Mid-1990s annual Shuttle manifest

				Payload capability	
Mission type	No., /yr	Inclination, deg	Altitudes, nm	Current, Klbm	ASRM, Klbm
Space Station	5	28.5	210	39	51
High inclination	3	50.0	160	38.5	50.5
Low inclination	6	28.5	160	49	55.9

Maximum Altitude Performance

In addition to the typical Shuttle missions, there may be an occasional need to use all of the altitude capability of the Shuttle. These types of missions are usually delivery, servicing, or reboost of low Earth orbit (LEO) satellites. Missions that require maximum altitude could become a major discriminator between various configurations. If the Space Shuttle is required to fly at or near its maximum altitude for these missions, the uprated OME will provide significant benefits. By contrast, the integrated OMS/RCS without a tank stretch will lose altitude capability (reduced tankage). The need for this type of mission will depend largely on the availability and capabilities of the planned orbital maneuvering vehicle (OMV).

Orbital Maneuvering Vehicle

The OMV is a reusable, remotely controlled, free-flying vehicle being developed by NASA as an integral part of the LEO/Space Station infrastructure. The vehicle is carried in the Orbiter payload bay or based at the Space Station and is used to deploy or retrieve satellites in LEO. Several of the reference missions scheduled for the OMV apply directly to reboost or servicing missions. If the OMV becomes available in 1993 as planned,[8] very few Shuttle flights should be going to altitudes above 250 nm/460 km. The OMV can provide the orbit transfer necessary to retrieve and reboost much more efficiently than accelerating 220,000 lbs/100,000 kg of Shuttle up for reboost and down for deorbit. Potential problems with using the OMV for reboost include payload bay limitations [center-of-gravity (CG) or volumetric constraints] or mission duration constraints on the Orbiter or OMV. The baseline analysis expects the OMV to be available; and, therefore, the additional Orbiter altitude capability is of lesser benefit.

If the OMV program should falter, the Shuttle program will need all the altitude capability it can get because the Hubble Space Telescope (HST) and other Great Observatories will need frequent reboost and occasional servicing. Therefore, the scenario with no OMV was briefly evaluated using the HST reboost problem to assess the effects of the Orbiter altitude constraint.

Shuttle Reboost of LEO Satellites

The Space Telescope will need reboosting numerous times throughout its lifetime and servicing every 3–5 years. The frequency of reboost will be a direct function of the altitude of the HST and the solar flux that expands the atmosphere. Solar radiation can vary widely, particularly during maximum activity periods. Predictions for reboost requirements will change depending on the solar activity assumptions. Graphical analysis of median data provided by the HST office at Goddard Space Flight Center indicated that one Shuttle flight every 5–10 years could be saved if the Shuttle was required to reboost HST using U/OME.

Modified APS Configurations (for Shuttle Fleet)

Even though the OMV should remove the need for "high altitude" Shuttle missions, reducing the capability of the Shuttle system would not be desirable. Therefore, all configurations are required to maintain (or improve) the current altitude capability on at least one Orbiter in the fleet. The configurations considered are listed in the following.

1) Uprated OME only. All four orbiters modified with U/OMEs. Analysis indicates that it is most cost effective to modify all of the Orbiters, since much of the U/OME cost is for development, not flight hardware.

2) Integrated OMS/RCS with U/OME. All four orbiters modified with U/OMEs, three pod sets integrate OMS/RCS, while one pod set incorporates stretched tanks to preserve high-altitude capability.

3) Integrated OMS/RCS with existing OME. Three pod sets integrate OMS/RCS, while one set remains unmodified to preserve existing altitude capabilty.

4) Integrated OMS/RCS with a minor tank stretch and U/OMEs. All four pod sets are outfitted with U/OMEs and integrated OMS/RCS. Only one pod set incorporates stretched tanks to preserve high-altitude capability.

5) Integrated OMS/RCS with a major tank stretch and existing OMEs. Four integrated pod sets. Only one pod set incorporates the major tank stretch to preserve high-altitude capability.

6) Integrated OMS/RCS with a major tank stretch and U/OMEs. Four pod sets with integrated OMS/RCS and U/OMEs. Only one pod set incorporates the major stretch to preserve high-altitude capability.

Orbiter CG Concern

There is increasing concern about the Orbiter CG on many future flights. The CG has specified limits to ensure sufficient aerodynamic control authority during entry. Modifications to the Orbiters have shifted the CG forward, and many missions such as Space Station and Spacelab have net CGs that exceed the existing limits. Correcting an adverse CG generally requires adding ballast, which reduces performance. The integrated OMS/RCS reduces the weight in the aft end of the vehicle, thereby magnifying the forward CG problem. None of the analysis presented in this study includes the impact of forward CG concerns on these enhancement concepts. (Significant portions of the potential savings may be lost due to ballasting requirements on forward CG missions.)

Configuration Performance

Table 5 summarizes the performance gains for the typical manifest shown in Table 4. Propellant savings include the effects of the higher specific impulse U/OME and the RCS savings of the integrated OMS/RCS. The propellant savings do not improve payload capability for low-inclination missions if

Table 5 Annual payload enhancements

		With ASRM				Without ASRM		
		Propellant savings						
Configuration	Dry wt. saved (14 flights), lbs	Space Station, lbm	High incl., lbm	Total saving, lbm	Yrs to save 1 flight,[a] yrs	Prop. saved low incl., lbm	Total savings, lbm	Yrs to save 1 flight,[a] yrs
U/OME only	−700	5850	2610	7,760	6.8	5,220	12,980	3.3
Int. OMS/RCS with U/OMEs	5340	7730	3960	16,980	3.1	8,820	25,800	1.7
Int. OMS/RCS with old OMEs	6040	1880	1350	9,270	5.7	3,600	12,870	3.4
Int. OMS/RCS with minor stretch and old OMEs	7100	8350	4410	19,860	2.7	10,020	29,880	1.4
Int. OMS/RCS with major stretch and old OMEs	6920	2500	1800	11,220	4.7	4,800	16,020	2.7
Int. OMS/RCS with major stretch and U/OMEs	6220	8350	4410	18,980	2.8	10,020	29,000	1.5

[a]Average payload = 53,000 lbs with ASRM, 43,000 lbm without ASRM.

Table 6 Configuration costs and benefits

Configuration	Total costs, $M	Veh. w/ uprated OMEs	Veh. w/ integral pods	Veh. w/ str. tank sets	Ave. PL gain w/ ASRM, lbm	Ave. PL gain w/o ASRM, lbm	Max. alt., nm	Max. reboost, nm	Net system complexity
U/OME only	160	4	0	0	560	930	+16	+11	worse
Int. OMS/RCS w/ U/OMEs	200	4	3	0	1210	1840	+16	+11	mixed
Int. OMS/RCS w/ old OMEs	45	0	3	0	660	920	0	0	better
Int. OMS/RCS w/ minor stretch and U/OMEs	225	4	4	1	1430	2130	+7	+4	mixed
Int. OMS/RCS w/ major stretch and old OMEs	70	0	4	1	800	1140	+11	+7	better
Int. OMS/RCS w/ major stretch and U/OMEs	230	4	4	1	1360	2070	+28	+19	mixed

the ASRM is available. The right side of the table shows the results for no ASRM.

Assumptions for payload capability changes are 1) standard insertion launches; 2) net additional weight of U/OMEs = 50 lb (23 kg); 3) 575 lbm (260 kg) dry weight savings for integrated OMS/RCS; 4) 72 lbm (33 kg) total dry weight increase for a minor tank stretch; 5) 324 lbm total (145 kg) dry weight increase for a major tank stretch; and 6) net average RCS offload due to reduced residuals, requirements, and dispersions is[9] 500 lbm (225 kg) space station, 600 lbm (270 kg) high inclination, and 800 lbm (360 kg) low inclination.

Project Costs

Total program costs for the modifications under consideration were evaluated by contacting the applicable contractors and the Propulsion and Power Division at Johnson Space Center The estimates included the following: 1) design, development, test, and engineering (DDTE); 2) flight hardware—cost of hardware and/or modifications to each Orbiter—and 3) NASA costs—cost of White Sands Test Facility operation, project oversight, and software and operations costs. The total costs of the selected configurations are very preliminary, rough-order-of-magnitude estimates and are summarized in Table 6.

Summary

The decision whether to proceed with any of these configurations will depend on the cost of the project weighed against the benefits. The cost of each configuration, the typical average payload increase, any altitude capability increase, and the change in net system complexity are summarized in Table 6. The U/OME will be more complex due to the addition of turbopumps and the associated plumbing and control hardware. The integrated OMS/RCS will be simpler, since four complex pressurization systems are removed and very little is added. Mixed complexity refers to the combined effects of the more complex U/OME and the simpler integrated OMS/RCS.

These results indicate that the integrated OMS/RCS configurations result in the following significant savings: payload capability, systems complexity (easier to maintain, reduced turnaround, and more reliable), and possibly a slight increase in altitude capability. Further analysis may be needed to assess whether new stretched tanks should be built vs leaving one pod set unmodified (tank cost vs software and operations cost). Work on the structural spare/OV-106 pod set is scheduled to begin in 1990 and would be a good candidate for implementing integrated OMS/RCS. Seven million dollars could be saved by not purchasing the RCS components eliminated by integration.

The uprated OME will add additional payload capability and a significant altitude increase. However, the new configuration will be more complex—actual changes in operations, maintenance, and reliability are difficult to determine at this point in the project development.

Since the uprated OME and integrated OMS/RCS are complementary, serious consideration should be given to starting detailed development of the integrated OMS/RCS concept. The payload benefits are greater than the uprated OME and the cost appears to be significantly lower—with reduced Orbiter complexity. The U/OME project also provides additional benefits, and if these gains justify the cost and increased complexity, then the development of the U/OME should continue to complement the integrated OMS/RCS aft propulsion system.

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James A. Martin
Associate Editor