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Report to the Administrator, National Aeronautics and Space Administration

October 1993

SPACE SHUTTLE MAIN ENGINE

NASA Has Not Evaluated the Alternate Fuel Turbopump Costs and Benefits

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GAO

United States
General Accounting Office
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National Security and
International Affairs Division

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October 29, 1993

The Honorable Daniel S. Goldin
Administrator
National Aeronautics and
Space Administration

Dear Mr. Goldin:

As a part of our evaluation of the Space Shuttle Safety and Obsolescence Upgrade program, we assessed the National Aeronautics and Space Administration's (NASA) plans to develop an alternate high pressure fuel turbopump for the Shuttle's main engines. Our objective was to determine whether NASA has adequately analyzed cost, performance, and benefits that are expected to result from this program in comparison to other alternatives before resuming development of the alternate pump, which was suspended in 1992.

Results in Brief

NASA's policy is to base acquisition decisions on competition between system design concepts throughout the entire acquisition process and to estimate program life-cycle costs to ensure that appropriate trade-offs are accomplished among investment costs, ownership costs, schedules, and performance. However, NASA had not analyzed the costs and benefits of possible modifications to the existing fuel pump prior to its decision to resume development of the alternate pump. The alternate pump may be more desirable from a cost, performance, and safety perspective than the current design or a modified version of the design; however, NASA has not performed a comparative study of the various alternatives that would focus on cost as well as safety considerations. Also, such information is essential so NASA can determine whether this program is affordable in the context of its overall budget.

The alternate fuel pump's design may prove to be more rugged than the current pump's, but according to NASA and outside experts, with existing safety controls, the current pump is safe to fly. The alternate fuel pump is one of five improvements being developed or planned to significantly enhance safety margins of the engines. However, NASA has not quantified the contribution of the fuel pump to the increase in Shuttle reliability expected to result from the improvements. Many flights and a large number of tests will be required to determine whether the alternate pump will be as reliable as the current pump. A 1991 NASA study concluded that there is potential for further improvement to the current pump, but NASA has not conducted an in-depth evaluation of the potential improvements.

Also, NASA has not estimated the life-cycle costs of the alternate fuel pump or improvements to the existing pump. Excluding testing costs, NASA estimates that about $314 million will be needed to complete development and purchase 18 alternate pumps. By reducing the amount of inspection and maintenance, the alternate pump should reduce Shuttle operating costs, but NASA has not estimated the amount of these expected savings.

Background

The Space Shuttle is the world's first reusable space transportation system. It consists of a reusable orbiter with three liquid-fueled main engines, two solid rocket boosters, and an expendable liquid propellant tank. The three main engines and two solid rocket boosters generate the power that is needed to launch the Shuttle and carry it to orbit.

The Shuttle's main engines were developed by the Rocketdyne Division of Rockwell International Corporation under contract to NASA's Marshall Space Flight Center. The development contract was signed in August 1972. Each engine includes two high pressure turbopumps—one to pump oxygen and the other to pump hydrogen fuel into the engine's combustion chamber, where they mix and burn to generate power. The fuel pump is about the size and weight of an automobile engine but must produce the horsepower equivalent to 28 diesel locomotive engines.

The original goal for the high pressure turbopumps was about 55 flights. However, they failed to meet that goal and had to be overhauled after every two flights. The turbopumps proved difficult to manufacture and caused main engine failures during testing, some of which would have been catastrophic if the failures had occurred during flight.

To improve performance and reduce operating costs, NASA contracted with Pratt & Whitney in 1986 to develop alternate turbopumps for the engines. The goal for the alternate turbopumps was also about 55 flights, but that goal has been reduced to about 30 flights.

In 1988 NASA modified its main engine contract to improve the existing high pressure turbopumps. The program was successful in improving the fuel pump (now referred to as the 10K pump), but was not successful with the oxygen pump. The upgrade increased the fuel pump's life to about seven flights.

In its fiscal year 1992 report, the Appropriations Conference Committee stated it believed that the alternate fuel pump development should be terminated. The Committee cited the success of the 10K fuel pump development and the substantial cost increase in the alternate turbopump program as reasons for its conclusion. Development cost estimates for the turbopumps had increased from $198.2 million to $649.3 million.

Rather than cancel the program, NASA suspended fuel pump development to concentrate on developing the oxygen pump, and initially planned to resume development of the fuel pump in fiscal year 1995. Even though not included in the President's fiscal year 1994 budget request, NASA was evaluating the feasibility of restarting the development effort in fiscal year 1994 to improve the program's efficiency. However, the Appropriations Conference Committee instructed NASA not to resume the development in fiscal year 1994 because of budget constraints.

The alternate oxygen and hydrogen turbopumps are two of five modifications under development or planned to improve the safety margin of the main engine. The other modifications are (1) a two-duct powerhead designed to improve the uniformity of fuel flow, decrease turbulence levels and pressure drops, and improve ruggedness of the assembly; (2) a single tube heat exchanger to eliminate welds in this component, which converts liquid oxygen to gaseous oxygen; and (3) a large throat main combustion chamber to lower pressure in the combustion chamber, reduce operating temperatures, and create a less severe operating environment for the engine. The modifications are to be incorporated in two blocks. Development of the first block of improvements—the new powerhead, the heat exchanger, and the oxygen pump—is nearing completion, and certification testing is expected to begin in January 1994. The large throat main combustion chamber and the alternate fuel pump are to be incorporated in the second block.

Assessment of Current Fuel Pump Safety

According to an independent task force formed by NASA's Aerospace Safety Advisory Panel at the request of the House Committee on Science, Space, and Technology to study the main engine and the planned improvements to it,[1] the engine is safe to fly with the current fuel pump, provided that all safety controls such as tests, inspections, and life limits are effectively implemented. The current fuel pump's design is based on 17 years of development and a history that includes over 500,000 seconds of testing

[1]The task force reported directly to the Chairman, House Committee on Science, Space, and Technology. See Report of the SSME Assessment Team, National Aeronautics and Space Administration (Jan. 1993).

and operation. Past turbopump failures have resulted in successful redesigns or the establishment of inspections and controls to ensure safe flight.

NASA does not have a quantitative estimate of the reliability of the current fuel pump. However, estimates prepared by both Marshall Space Flight Center and the main engine contractor show that the demonstrated reliability of the total engine is very high. According to a reliability engineer at the Marshall Space Flight Center, a three-engine cluster operating at the 104-percent power level has a demonstrated reliability of at least 0.9922. Using a different methodology, the engine contractor calculates the engine's reliability to be at least 0.98965.

According to the task force, the demonstrated reliability calculations mean that the probability of a catastrophic failure of the engines is about 1 in 120 flights. However, the task force concluded that the actual single flight reliability of the engine is probably higher than the numbers indicate because of the special controls and precautions currently taken with the engines and that the engines are safe to fly provided the safety controls are properly implemented.

Both NASA and the task force support continued development of the alternate fuel pump because of safety concerns about some aspects of the current pump's design. The current pump requires extreme care during manufacture. For example, the pump housing is welded together in a number of areas, some of which are impossible to inspect after the pumps are manufactured. Engineers are concerned that if there were flaws in some of the welds, the flaws could increase in size and allow fuel to escape. To protect against such flaws, rigid process controls are imposed during pump manufacture, and no engine test failures have yet been attributed to the welds.

Safe operation of the current pump requires (1) careful inspections and maintenance between flights and (2) limits on the number of times pumps can be used before being overhauled. For example, the fuel pumps are removed after each flight and inspected for problems such as cracks in the turbine housing sheet metal. Any unacceptable cracks are repaired before the pump is used again. NASA imposes conservative life limits to help ensure safety. For example, even though tests have shown that the current pumps can be safely operated for 8,400 seconds, or the equivalent of 16 flights, NASA requires that the pumps be overhauled after about 7 flights, or no more than half of the certification time. No components can be used for more than one-half of the safe operating time actually demonstrated for similar components during testing.

Additional measures are imposed both on the ground and in flight to provide a safety margin. These measures are designed to shut down an engine if it encounters conditions that could lead to a catastrophic failure. For example, during engine start on the launch pad, if certain tolerances are exceeded, the controller will shut down the engine and will not issue the permission required for solid rocket booster ignition. During flight, if a tolerance is exceeded, the controller will shut down that engine and abort the mission.

NASA Has Not Studied Potential for Further Improvement in Current Fuel Pump

A 1991 study by NASA's Office of Safety and Mission Quality concluded that design solutions are available to correct the remaining major safety concerns with the current fuel pump. For example, the contractor has developed methods to improve the current pump's producibility and eliminate cracking in the sheet metal used in certain areas of the pump. Also, according to the study, new turbine blades that would provide safety margin increases equivalent to the alternate fuel pump can be installed.

NASA's main engine project manager told us that NASA has not performed an in-depth study of the potential for further improvement in the current pump. According to this official, the only way to eliminate all remaining safety concerns is to develop the alternate fuel pump. This official pointed out that any major upgrade to the existing pumps would require a full certification test program that would be expensive.

Modifications Expected to Increase Engine Safety Margins

NASA expects that the five planned modifications will significantly increase the engine's operating and safety margins and should reduce the likelihood of an in-flight engine failure by a factor of between two and five. Although NASA expects the improvements to increase engine reliability, it has not quantified the contribution of each individual improvement. The main engine project manager stated that the large throat main combustion chamber will contribute most to the increased safety margins and that the modification will increase the reliability of the current turbopumps by creating a less severe operating environment for them. The task force strongly endorsed all five improvements but ranked the fuel pump as fourth priority.

Although NASA has not quantified the alternate fuel pump's contribution to increased safety margins, it is expected to be inherently safer than the current pump. The alternate pump is to have a designed-in safety margin, reducing the need to depend on inspections, sensors, and life-limit controls, and therefore reduce the possibility of human error. The alternate pump is expected to eliminate many features of the current pump design that cause safety concerns. For example, the new pump housing will be a single casting, thereby eliminating nearly all welds where fuel leaks could develop. The new design will also reduce the number of rotating parts and eliminate the need for protective coatings on such components as turbine blades to protect them against heat and hydrogen embrittlement. In addition, the new pumps are to have better bearings and a design that permits easier assembly and disassembly.

Alternate Fuel Pump Design Is Still Unproven

While NASA expects the alternate fuel pump to contribute to increased engine safety margins, its design is still unproven. At the time NASA suspended development of the alternate fuel pump in 1992, some technical problems had been identified that must be corrected. For example, according to NASA officials, the turbine inlet is too big, which causes the liquid oxygen pump to overheat. If not corrected, this overheating will cause the oxygen pump to wear out faster or could cause an engine to shut down during flight. Also, some cracks had developed in turbine blades. According to NASA officials, these cracks are not likely to cause a major engine operation problem but are undesirable.

NASA believes it has identified design changes that will resolve problems identified to date, but new problems will no doubt occur as tests resume. Incorporating changes to the engines, including the new fuel turbopump, can cause anomalies and new phenomena to occur as operating and testing experience is gained. The task force reported that even a small change within the engine can have dramatic effects.

Although NASA believes the alternate fuel pump promises a significant improvement in reliability, it will be some time before the pump has demonstrated the same level of reliability as the current pump. The alternate pump will have accumulated 60,000 seconds of testing by the time of its first flight versus over 500,000 seconds for the current pump in its various configurations.

NASA Has Not Compared the Cost and Benefits of Alternative Approaches

According to NASA policies on the acquisition of major systems such as the alternate fuel pump, acquisition decisions should be based on competition between system design concepts throughout the entire acquisition process, wherever economically feasible and beneficial. Also, life-cycle costs should be estimated to ensure that appropriate trade-offs are accomplished among investment costs, ownership costs, schedules, and performance. However, NASA has not estimated the life-cycle costs for the alternate fuel pump or the cost and benefits of further improvements to the current pump.

Marshall Space Flight Center estimates that the cost to develop and produce the alternate fuel turbopump is about $519 million. Of this amount, about $205 million was spent before development was suspended. The remainder ($314 million) will be needed to complete the development program and purchase 18 pumps to equip the Shuttle fleet. However, the $314 million estimate does not include testing costs, which will be funded from the Space Shuttle propulsion budget.

According to a Space Shuttle main engine project official, it would be difficult to isolate costs for testing the fuel pump because it will be certified during the same tests as the large throat main combustion chamber modification. However, there are some separately identifiable pump testing costs. Some development tests will be performed separately from the large throat modification, and certification testing of the pump will require about 20,000 seconds more test time than certification of the large throat modification. According to the task force, certification testing costs about $1,500 per second, making the additional certification testing costs alone total about $30 million.

NASA believes that incorporating the alternate fuel pump into the main engine will reduce Shuttle operating costs. However, it has not estimated the amount of the reduction. The principal reduction in operating costs will be the requirement for fewer people to inspect and maintain the alternate pump versus the current pump. For example, according to a Space Shuttle main engine project official, the number of Rocketdyne people required for the main engine will decrease from about 1,850 to about 1,250 by fiscal year 1997. However, NASA has not estimated how much of this reduction can be attributed to the alternate turbopump. A level of effort equivalent to 100 to 150 contractor personnel will be needed to support the alternate turbopump.

Also, NASA has not estimated the costs or effectiveness of incorporating additional modifications into the current fuel pump design. According to the 1991 Office of Safety and Mission Quality study, the engine development contractor has developed additional fuel pump safety enhancements using its independent research and development funds. The improvements include, for example, a bolt-in turbine that eliminates cracking of both struts and sheet metal and improves producibility. However, NASA has not estimated the cost of developing and certifying these improvements and incorporating them into the current fuel pump design.

Recommendation

We recommend that you require agency officials to estimate the life-cycle costs and benefits for the alternate fuel pump program and compare those with the costs and benefits of further improvements to the existing pump before deciding whether to resume development of the alternate fuel pump.

Agency Comments and Our Evaluation

In finalizing this report, we made a number of revisions to better emphasize cost and safety issues and to recognize NASA officials' points of view. NASA's comments are reprinted in full in appendix I.

NASA disagreed with our recommendation and stated that it believes it has sufficient data to support the decision to continue developing the alternate high pressure fuel turbopump. NASA stated that additional life-cycle cost or safety contribution evaluation is not justified. NASA said that while a life-cycle cost analysis can be a valuable and effective tool for programmatic decisions, it is not appropriate for the strong safety program to which NASA is committed. While we understand safety considerations must be heavily weighted in making program decisions, we cannot agree that cost data is not needed. Having such information is necessary to making a full comparison of competing programs and to determining whether the various alternatives are affordable within the context of NASA's overall budget.

In addition, NASA quoted a member of the Aerospace Safety Advisory Panel who reviewed our draft report. The member stated that the Panel rejects the thrust of the report that cost should be the determining factor as to whether resumption of alternate fuel pump development is justified. He also stated that our reasoning is flawed and that we had misinterpreted statements in a Special Assessment Team report. We believe our report clearly states that the comparative evaluation should include both cost and safety considerations, but that the evaluation is needed to aid decision makers. Regarding misinterpretation of the Special Assessment Team report, we point out that the team recommended continued development of the alternate turbopump for safety reasons. However, we still believe that cost information and information about modifications to the current design should be developed as well.

Scope and Methodology

To determine the safety of the current fuel pump and improvements expected from the alternate fuel pump development, we analyzed the pump test and flight history and reviewed reliability assessments conducted by both the engine development contractor and the Marshall Space Flight Center. We also reviewed engine safety assessments made by NASA's Office of Safety and Mission Quality, the Aerospace Safety Advisory Panel, and a special task force appointed by that Panel at the request of the House Committee on Science, Space, and Technology.

We evaluated development plans and status reports related to the alternate turbopump program as well as budget documents and cost estimates prepared by Marshall Space Flight Center. We also reviewed NASA and federal acquisition regulations and policies relating to the acquisition of major systems. We discussed various aspects of the current and alternate turbopumps with officials at Marshall Space Flight Center and NASA Headquarters responsible for managing the programs.

We conducted our review from November 1992 through September 1993 in accordance with generally accepted government auditing standards. NASA reviewed a draft of this report, and we incorporated its comments where appropriate.

This report contains a recommendation to you. The head of a federal agency is required under 31 U.S.C. 720 to submit a written statement on actions taken on our recommendations to the Senate Committee on Governmental Affairs and the House Committee on Government Operations not later than 60 days after the date of the report and to the Senate and House Committees on Appropriations with the agency's first request for appropriations made more than 60 days after the date of the report.

Copies of this report will be provided to the appropriate congressional committees and the Director of the Office of Management and Budget. We will also provide copies to others upon request.

Please contact me at (202) 512-8412 if you or your staff have any questions concerning this report. The major contributors to this report are listed in appendix II.

Sincerely yours,

Donna M. Heivilin
Director, Defense Management and
NASA Issues

Comments From the National Aeronautics and Space Administration

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

SEP 23 1993

Mr. Frank C. Conahan
Assistant Comptroller General
General Accounting Office
Washington, D.C. 20548

Dear Mr. Conahan:

We have reviewed the GAO draft report, "Space Shuttle Main Engine: NASA Has Not Justified Resuming Alternate Fuel Turbopump Development," and we believe we have sufficient data to support our decision to continue the development activities on the Alternate Turbopump Program (ATP) high pressure fuel turbopump (HPFTP), and that no additional life-cycle cost or safety contribution evaluation is justified.

The ATP pumps are being developed and implemented to improve the Space Shuttle Main Engine (SSME) safety margins and are considered essential to the long-term viability and safety of the Space Shuttle. The ATP pumps have been evaluated and supported by a number of independent groups, including the Aerospace Safety Advisory Panel (ASAP), Bryan O'Connor (NASA Deputy Associate Administrator for Space Flight) Shuttle Safety Improvement Team, George Rodney (Former NASA Associate Administrator for Safety and Mission Quality), and Dr. Michael Greenfield (current NASA Acting Associate Administrator for Safety and Mission Assurance).

The ASAP has repeatedly recommended implementation of the ATP HPFTP, including their latest annual report dated March 1993. In addition, Dr. Seymour C. Himmel writes in response to the GAO report (see enclosures 1 and 2), "First, and foremost, we reject the thrust of the report to the effect that cost should be the determining factor in deciding whether to resume the development of the ATP HPFTP. Their reasoning is flawed . . . The interpretation of the statement in the SSME Assessment Team's report that the current SSME was 'safe to fly' to mean that there was no risk and, hence, no need to reduce risk is absolutely erroneous. To the contrary, the Team recommended that the major improvements planned be developed and incorporated as soon as possible so that risk could be reduced!"

In November 1992, the Shuttle Safety Improvement Team, led by Mr. O'Connor, reported to the Administrator that of the top 20 potential vehicle system improvements, the ATP HPFTP was the number one priority.

Dr. Greenfield evaluated margin improvement considerations for the SSME in his October 29, 1991, letter (QT-92-04). "Although the newly-certified Rocketdyne 10K turbopumps represent an improvement over previous designs, considerable reliability issues remain that will not be ameliorated with either the II+ Powerhead or the Large Throat MCC." His first recommendation was to pursue development of the ATP HPFTP.

In his letter of October 31, 1991, Mr. Rodney attempted to develop a rationale that would support a decision to cancel the ATP HPFTP. He could not. He writes, "it is my position that we should take every possible measure to continue the development and future implementation of both" ATP pumps.

While we agree that a life-cycle cost analysis can be a valuable and effective tool when making programmatic decisions, it is not appropriate for the strong safety program to which we are committed. Although we believe the current SSME is safe to fly, we also believe we can and should significantly improve the system's safety when viable options exist. The ATP HPFTP is just such a safety improvement option. We do not believe an accurate cost-effectiveness study can be performed because the costs of losing a crew and orbiter are unquantifiable and override other considerations.

In regard to the current pump capabilities (see enclosure 3), it should be noted that after over 20 years of development the existing pumps continue to exhibit major deficiencies. Meticulous attention to detail is required at each step in both the manufacturing and operations processes to assure that the pumps are as safe as possible. The most recent of many redesign efforts, the "10K" design, was initiated to increase the life of the HPFTP from its limited life of 2,000 seconds (the life limit is now 4,200 seconds, far short of the intended 10,000 seconds). Any further redesign of the 10K HPFTP would result in a significant design, manufacture, and test program. Design, manufacture, and test of the ATP HPFTP were well under way prior to our decision to temporarily halt developmental activities. In addition, the design changes being proposed for the current pump by Rocketdyne do not address all the safety and limited life concerns with which we contend today. The ATP HPFTP is the only identified design which addresses all of the shortcomings of the current 10K HPFTP.

Reliability estimates of existing components of the SSME are extremely difficult to calculate. The application of statistical methods to hardware that is regularly undergoing modification is questionable at best. Accurate estimates for hardware still in the developmental stage simply do not exist.

NASA's top priority is to safely launch the Space Shuttle; therefore, we will continue to effectively develop viable system safety improvements to ensure that this priority is met.

Sincerely,

J. R. Dailey
Associate Deputy Administrator

3 Enclosures

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