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Technical Status of the Space Shuttle Main Engine (Second Review)

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Second Review— Technical Status of the Space Shuttle Main Engine

Ad Hoc Committee for Review of the
Space Shuttle Main Engine Development Program

Assembly of Engineering

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This is the second of two reports of the Assembly of Engineering's ad hoc Committee for Review of the Space Shuttle Main Engine Development Program. A follow-up study was requested by the Subcommittee on Science, Technology, and Space of the U.S. Senate Committee on Commerce, Science, and Transportation as the result of technical development uncertainties that were pointed out in the committee's first report. This report presents the committee's assessment of problems considered in its earlier review as well as others that arose subsequently and makes recommendations for their solution. This second report addresses longer-range issues whereas the first report was concerned primarily with safety aspects of the first manned flight of the shuttle. Damaging malfunctions in two main engines while under test during the period of the committee's study are described together with a discussion of their implications to development of the engine.

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Second Review—Technical Status of the Space Shuttle Main Engine

A Report of the
Ad Hoc Committee for Review of the
Space Shuttle Main Engine Development Program

Assembly of Engineering
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. February 1979

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study and report were supported by Contract No. NASW-3189 between the National Aeronautics and Space Administration and the National Academy of Sciences.

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IN MEMORIAM

As this report was going to press early in February 1979, the members of the committee were saddened by the death of Robert B. Young, a distinguished colleague and a major contributor to their deliberations and conclusions.

PREFACE

In December 1977, concerned with delays in the development of the main engines for the maiden voyage of the space shuttle, the Subcommittee on Science, Technology, and Space of the U.S. Senate Committee on Commerce, Science, and Transportation asked the National Research Council to review the situation. In January 1978, the Research Council established the ad hoc Committee for the Review of the Space Shuttle Main Engine Development Program, under the Assembly of Engineering. By the end of March of that year, the ad hoc Committee had issued its report, Technical Status of the Space Shuttle Main Engine, and its chairman, Eugene E. Covert, had testified before the Senate Subcommittee.

In view of the concerns about several critical components in the main engine and the uncertainties in maintaining the planned schedule for the first manned flight of the space shuttle, Senator Adlai E. Stevenson, the Subcommittee's chairman, requested at the conclusion of the public hearing on March 31, 1978, that the ad hoc Committee should perform another examination of the development program in the fall of 1978. Accordingly, the review committee met October 30-31, 1978, at the National Space Technology Laboratories, Bay St. Louis, Mississippi, where the main engine is being tested.

The committee's assessment took account of two sets of problems -- some that were considered in its earlier review and continue to cause concern and those that have appeared during the engine tests since March 1978. In its first report the committee had concentrated on the engine for the first manned flight. In the subsequent review it gave more emphasis to longer range matters of the main engine system.

During December 1978, as the second report was nearing completion, the engine development program encountered two setbacks. On December 5, 1978, a fire occurred as a result of a leak in the heat exchanger of a test engine—a component the review committee had singled out for concern in its first report. On December 27, a fire originating in the main oxygen valve nearly destroyed another engine.

As a direct consequence of these incidents, the Senate Subcommittee called on the ad hoc Committee to review the latest problems and reexamine its previous findings and conclusions before submitting its second report. Thus, the review committee met again February 1-2, 1979, at the National Academy of Sciences in Washington, D.C., to hear the accounts of the origins and consequences of the incidents and to deliberate on their implications for the development of the shuttle's main engine.

This report contains the findings and recommendations of the review committee as a result of its meetings in October 1978 and February 1979.

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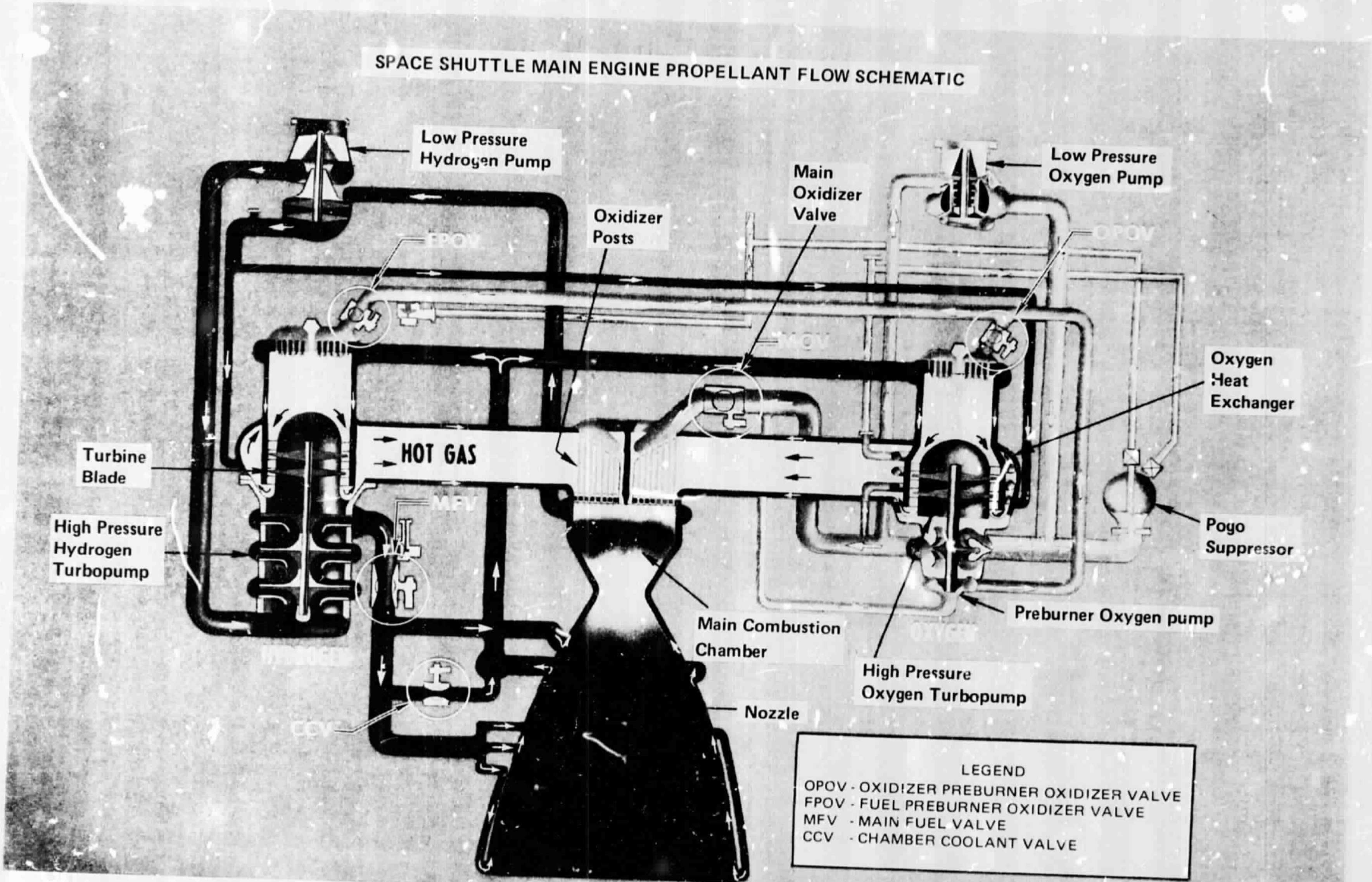
INTRODUCTION

The space shuttle, a winged spacecraft designed to carry a number of people and a large payload into space and to return to earth for subsequent reuse, is regarded as significant to America's future in space. During its development, even as late as 1978, the main engine for the space shuttle encountered a succession of problems -- many of them, however, typical of those usually experienced in the early stages of a major technological advance. The solutions to these problems have required the redesign of some components in the main engine and the modification of others.

Existing rocket engines are insufficient for the shuttle, and even new engines of conventional design cannot attain the performance level required. The shuttle is to be powered by three main engines, using a staged-combustion cycle for high efficiency and operating on hydrogen and oxygen at a chamber pressure of 3,000 pounds per square inch -- several times more than previous flight engines. Each engine must deliver up to 1,668,000 newtons (or 375,000 pounds) of thrust at sea level, with the highest combination of thrust-to-weight ratio and specific impulse ever required in a rocket unit (see Figure 1).

In its first report, the committee had observed:

> The development of such an operational engine requires a greater step forward in technology over the J-2 rocket, which was used in the two upper stages of the Saturn vehicle that launched the Apollo spacecraft to the moon, than the J-2 did over its predecessor, the RL-10 engine. However, any risk involved in making such an advance is reduced by the knowledge and experience gained through the development of the USAF Rocket Propulsion Laboratory - Pratt & Whitney experimental XLR-129 engine and the subsequent NASA Marshall Space Flight Center - Pratt & Whitney turbo-machinery program that produced turbopumps for an engine of 350,000 pounds of thrust. These two programs were experimental and, in fact, were not intended to reach the operational stage. Nevertheless, they clear-



Adapted from an Engine Diagram by Rocketdyne Division Rockwell International.

FIGURE 1

ly anticipated the successful development of the space shuttle main engine.[1]

The National Aeronautics and Space Administration (NASA) and the builder of the main engine, Rocketdyne Division of Rockwell International Corporation, decided to use a "success-dependent" strategy for developing the engine. This strategy is a departure from the traditional procedure of development stages in that component-development testing was foreshortened and the quantity of spare parts was severely limited. The success-dependent procedure was intended to offer potential savings in cost and time, by eliminating parallel and possibly redundant development and test hardware. However, as the committee noted in its earlier report, if or when malfunctions occur during the testing of the prototype of the operational engine, new hardware may need to be designed, constructed, and retrofitted, resulting in delays. That is what happened. The main engine program has been beset with technical problems related mainly to the rotating machinery. Although some of the problems were unresolved at the time of the earlier study, when the committee conducted its follow-up review in October 1978 both NASA and Rocketdyne reported that (in their opinion) solutions to the problems, adequate for the first manned orbital flight, had been identified and in most cases tested. In fact, significant progress had been made and the rate of testing had proceeded toward NASA's goal of 80,000 seconds of test time before the first manned flight (rescheduled from March 1979 to September 1979).

Since the committee's first report, the accumulated test time as of December 27 1978, has more than doubled to 34,810 seconds in 394 firings (see Figure 2). Of this total, a little more than 10,000 seconds has been at 100 percent rated power level, with seven tests run at 100 percent rated power for the full 520 seconds that the main engine operates during the launch. Furthermore, a test run at 102 percent rated power has been completed and an "abort and return-to-launch-site" test of 823 seconds has been made at approximately 97 percent rated power.

Because most of the long test runs have been on one particular engine (0005), it is not certain that all the problems have been solved. Not unexpectedly, some new problems have been encountered. These may constitute new obstacles to maintaining an orderly schedule for the shuttle. The committee's specific concerns are described and evaluated in later sections of this report. Here, the committee deals with previous concerns that have now been disposed of.

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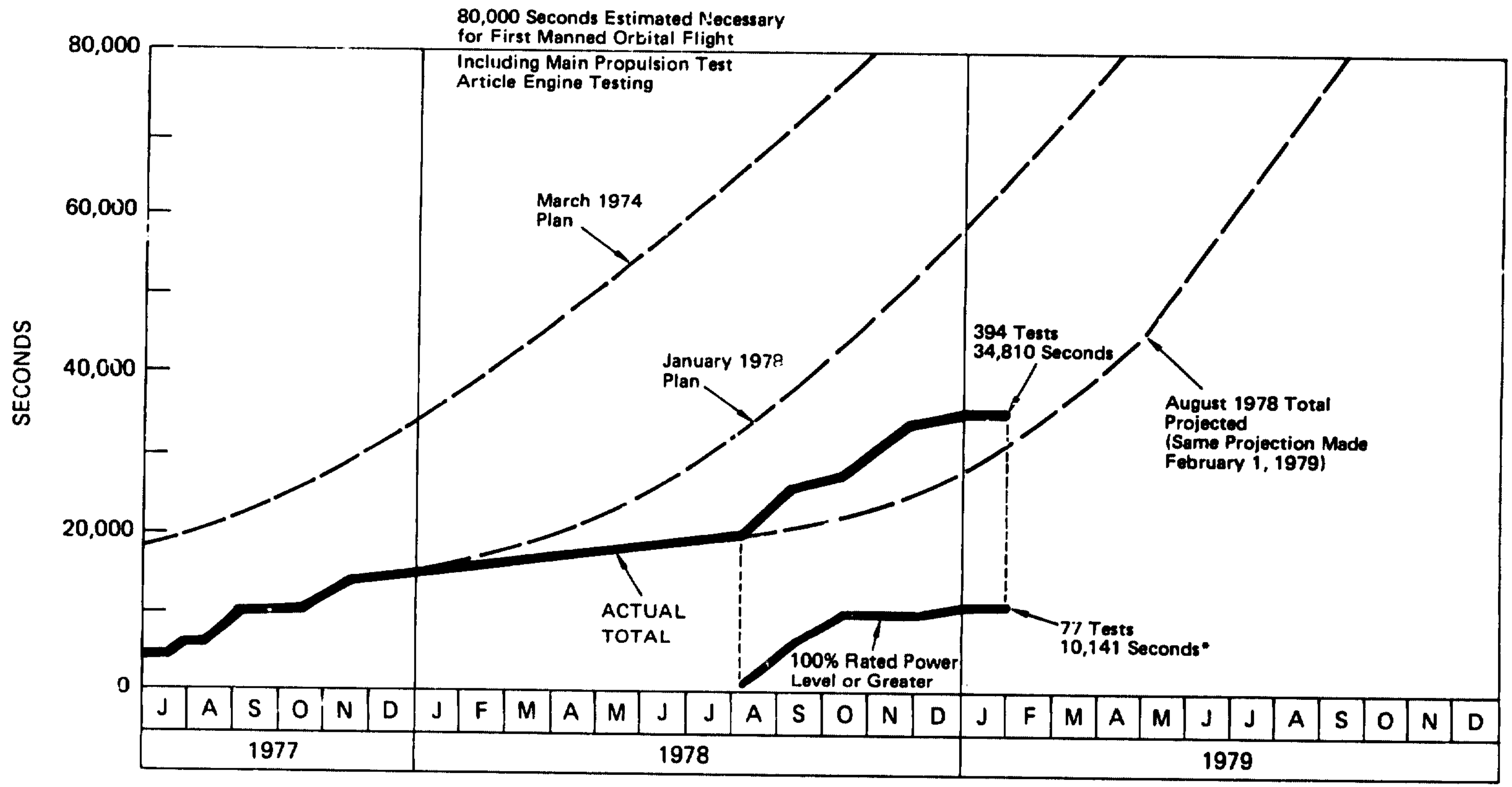
[1]National Research Council, Technical Status of the Space Shuttle Main Engine. A report by the ad hoc Committee for Review of the Space Shuttle Main Engine Development Program, Assembly of Engineering. National Academy of Sciences, Washington, D.C. March 1978, pp. 1-2.

ACCUMULATED ENGINE TEST DURATION



*Includes one test in November 1978 at 102% rated power level for 296 secs. This test and the other tests at 100% rated power are included in the total accumulation of 394 tests.

SOURCE: Based on NASA data.

FIGURE 2

In its first report, the committee had recommended the initiation of an alternative design for the shaft and housing of the high-pressure oxygen turbopump. NASA and Rocketdyne have responded fully to this recommendation with a preliminary redesign involving bearing relocation and housing redesign. In addition, they have made design changes to the present high-pressure oxygen turbopump. Such changes have the goal of achieving reliability for the early flight missions. Some of the design changes have not only been completed but the hardware is now being fabricated. The performance resulting from such changes will be evaluated in the near future. During its review, the committee has learned of a new design that has the potential for marked improvements in the performance of seals and the reliability of the high-pressure oxygen turbopump. If the space shuttle is to become a successful space transportation system, such improvements will be needed.

The first manned flight and the completion of the six orbital flight tests are major milestones in the development of the operational space transportation system for the 1980's. The later development of the operational engine includes increasing its thrust rating to at least 109 percent of rated power level, which is sometimes called full power level, and developing the capability for safe and reliable operation over a life of 55 missions, which means about 7-1/2 hours or 27,000 seconds of engine running time, with maintenance comparable to that of commercial transport aircraft engines.

The development of such a life span is not necessary for the first six orbital flights. In fact, to require such a lifetime capability by 1979 or 1980 would be unrealistic and would result in inordinate delays in the overall space shuttle program. Because high reliability, long engine life, and performance (in terms of power level) cannot be attained simultaneously within the schedule, the current approach is to emphasize reliability at the rated power level (100 percent) at the expense of engine life and full power level (109 percent rated power). The committee considers this order of priority appropriate. Thus, the successful completion of the first six orbital flight tests does not signify the end of the main engine development. Substantial further development must proceed to elevate the thrust level to 109 percent of rated power with high reliability and 7½ hours life.

CONTINUING CONCERNS

Tear-down Inspection After First Flight

In its earlier report, the committee recommended a complete tear-down inspection of the main engine after the first and sixth flights. In the view of some rocket engine experts, however, a tear-down inspection should be avoided unless visual inspection, including the use of a borescope,[1] indicates otherwise. This is based on the hypothesis that unless distress is visible or is indicated by a deterioration of performance, it is best not to disassemble a working engine. However valid this may be, some loading conditions are not encountered until the system is flown -- for example, consider the loads implied by the firing of solid rockets, maneuver loads, and acoustical vibrations. The committee considered three approaches: (i) a complete tear-down inspection of the three main engines after the first flight; (ii) a complete tear-down inspection after the third flight unless the visual inspection, borescoping, and data indicate that an engine is distressed after an earlier flight; and, (iii) a thorough inspection of one of the main engines after the first flight, with the tear down of only the two high-pressure turbopumps (and replacement of this engine with a spare).

On balance, the argument reduces to a simple point. In a closely coupled engine, with high thrust-to-weight ratio, where the performance could seriously deteriorate if some component fails to work to the required level, the difference in ground loads and flight loads could cause significant changes in the local deflection of walls, shafts, seals, or bearing retaining housings. Such deflections could cause wear and stress in locations that would not be detected by visual inspection and borescoping. Furthermore, if the Preliminary Flight Certification (firing tests of a single engine) and the results of the Main Propulsion Test Article (firing three engines simulating space flight operation) are accepted as valid, then there

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[1] A boroscope is an instrument, now utilizing fiber optics technology, used for illuminating and visually inspecting otherwise inacessible places.

should be no qualms about removing one engine for inspection and replacing it with a spare. After considering the three approaches, the committee still concludes that a tear-down inspection is essential and now recommends a complete tear-down inspection of one engine after the first flight and its replacement in the orbiter by a spare engine. Depending on the outcome of the tear-down inspection[1] and the results of borescoping and visual inspection after subsequent flights, the inspection procedure for the first six flights could be established.

Moreover, the committee also considers a complete disassembly and inspection of the engines to be essential after the sixth flight and supports the NASA proposal of a visual inspection, including borescoping the high-pressure turbopumps, after each of the orbital test flights. Much can be learned during the flight tests that will bear on the future development of the engine. NASA and Rocketdyne should allow for this in their planning, if they are not already doing so.

Component Test Stand

The committee, in its first report, had recommended that NASA and Rocketdyne explore means to acquire and operate a component-development test rig for the rotating machinery of the main engines. Instead, NASA and Rocketdyne have chosen to use a rocket engine itself for this purpose. To this end, test stand A-3 at Santa Suzanna, California, has been reactivated. The committee considers that this approach is far from ideal and could lead to long delays in the event of major mishap such as a failure in a high-pressure turbopump. Such a failure could result during tests to explore the functional limits of components, including the "red-line" limits for operational safety, because the engine is used as a test stand. Thus, if further failures occur, long delays will result unnecessarily.

An additional consideration is the possibility of an unexpected failure of a component during the operational life of the shuttle. The sustaining engineering program needed to support the shuttle may be more economically and more effectively carried out through the use of a component test stand. The committee is concerned that replacement hardware will not be available when components fail and, worse yet, spare engines will not be available for use as new test stands to replace those lost as a result of component failures.

The committee considers that it is not too late to develop a component test rig. A component test rig would be valuable not only in the testing process to extend the life of the engine to 7½ hours, but also for the sustaining engineering that is likely to prove necessary over the useful life of the shuttle. While recognizing that engines will have to be used for some time to test components, the committee urges NASA and Rocketdyne to take appropriate actions

[1]The committee understands that no contingency plan exists to cope with problems uncovered by this inspection. This is a consequence of a success-dependent program strategy.

to acquire a component-development test rig.

Oxygen Heat Exchanger

NASA and Rocketdyne have complied with the committee's recommendation to explore alternative designs to relocate or reconfigure the oxidizer heat exchanger. The heat exchanger is now in a hot, hydrogen-rich location (see Figure 1). Short of placing it in a less perilous location, there is no practical way to eliminate the threat to the total system in the event of a failure in the heat exchanger. Since March 1978, NASA and Rocketdyne have made a design study of a "line-replaceable" heat exchanger that can be more readily and thoroughly inspected in the field -- one that could be replaced and would be less subject to damage during fabrication. As designed, the new heat exchanger would be about 170 pounds heavier than the present 20-pound heat exchanger. The present program plan calls for completing the detailed design of the line-replaceable heat exchanger and holding it as a back-up until it may be needed.

While the committee concurs with the actions taken to date, it is still concerned with the present heat exchanger and reemphasizes the statement in its previous report that urges continued attention to the oxidizer heat exchanger by both NASA and Rocketdyne.

Evidence has been found that heat exchanger tubes have been rubbing against their supports during some of the engine tests. Such rubbing could lead to small holes in these tubes. With the oxygen pressure in the tubes relatively high, even a small hole will emit a jet of pure oxygen into the hydrogen-rich gas, which will result in combustion within the heat exchanger. In this event, potential is great for a disastrous explosion. It is of the utmost importance that the heat exchanger be readily accessible for routine inspections in the field. The committee recommends, therefore, that NASA and Rocketdyne move ahead with the construction and testing of the line-replaceable heat exchanger for installation in the shuttle main engine as early as practicable.

Integrity of High-Pressure Fuel Turbopump Turbine Blades

In its earlier report, the committee noted the three failures that had occurred in the high-pressure fuel turbopump turbine blades up to that time. Because such problems are common in turbine development, the committee assumes that the problems can be resolved before the Preliminary Flight Certification tests are completed. To that end, NASA and Rocketdyne have initiated an inspection program to detect and remove blades that contain cracks they consider harmful. For the longer term, however, the committee recommends that a more aggressive program be established to understand the cause of the turbine blade cracking in order to prevent it. The need exists for improved blades. This can be achieved by (i) an improved blade design, (ii) an improved alloy, (iii) a modified cast structure,

(iv) a more flaw-free material, (v) a more searching and stringent inspection system -- or some combination of these. The long range objective of improved turbine blades does not seem to have progressed in the main engine development program beyond today's state-of-the-art.

NEW CONCERNS

High-Pressure Fuel Turbopump Turbine Blades Platform Cracks

Since March 1978, no complete blade failures have occurred in the high-pressure fuel turbopump turbine. The committee is concerned, however, about the appearance of cracks in the blade platforms after very few operating cycles. The cracks may be caused by low-cycle thermal shock from the start-up and shut-down cycle. In addition, a few cracks have developed in the leading edge of some blades. When a crack is found in the leading edge of the blade, the blade is now replaced. By contrast, NASA and Rocketdyne regard platform cracks as tolerable unless these propagate into the blade. The difficulties involved in perceiving clearly how far a crack has progressed is a point of contention between the committee and NASA.

If blades with platform cracks are to be used at all, a decision to regard a crack as having grown to a dangerous size must be based on prior experience. Although such experience is not very extensive at this time, it is being accumulated. Experience in the test program to date has shown that the high-pressure fuel turbopump can be operated for at least 15 start-stop cycles of the engine without any failures in the turbine blades. After 15 start-stop cycles, the high-pressure fuel turbopump is disassembled, the turbine blades removed, the blade coatings stripped off, and any cracks carefully examined. Then a metallurgical examination is made, which includes cutting, etching, and microscopically inspecting the blades. The resulting data are being collected by Rocketdyne for a data base on all the high-pressure fuel turbopump turbines in the program. By the time of the first manned flight, it is expected that a substantial amount of data will have been acquired. The data are intended to provide confidence in the operational procedures yet to be established. The committee suggests that the data be displayed in an appropriate statistical distribution to justify with confidence the selected interval between inspections.

Still, no program now exists for the prevention of cracks in the turbine blade platforms of the high-pressure fuel turbopump. The present planning allows the use of blades with small cracks in their platforms for engines in the first manned orbital flight. Such a procedure is contrary to current, conventional practice. Thus, the results of future tests must prove that such platform cracks will not result in actual or incipient failures of the blades. Therefore, effective inspection measures must be used after each cycle of operation, definite limits to crack size must be defined, and limits on rate of growth must be established. Every effort must be made to establish a technical and statistical basis justifying the use of blades with platform cracks in early flights.

The committee understands that NASA's Marshall Space Flight Center has initiated a full-scale fracture mechanics program to determine the rate these cracks grow and the inspection interval needed to ensure that no crack-induced failure occurs between inspections. The Marshall program is intended to complement the Rocketdyne program. If this fracture mechanics program is fully successful, the committee deems the inspection intervals will be well defined prior to the first flight. In any event, the committee recommends that NASA prepare and document detailed procedures for determining crack growth rates and develop statistical data to justify its confidence in this matter.

High-Pressure Fuel Turbopump Turbine Blades Coating

Rocketdyne is conducting a relatively extensive program to find a satisfactory coating for the high-pressure fuel turbopump turbine blades. The program was undertaken initially to develop a reliable coating to enable the blades to tolerate thermal spikes, which are high gas temperatures for very short periods, that occurred during the early engine tests. Since then, thermal spikes have been greatly reduced. The stated justification for coating the blades was to suppress thermal shock stresses generated in start-stop operation. The committee considers that the need for coatings is questionable and that sometimes they are the cause of problems. For example, if the coating is not well bonded to the blade material, it will spall or peel, causing turbine wheel unbalance and vibration. If the coating is well bonded, cracks in the coating can propagate into the blade material.

Since the original need for coating the high-pressure fuel turbopump turbine blades seems to have been eliminated, any expected benefit from coating seems to be questionable. Therefore, the committee recommends that test runs with uncoated blades be included in the test program. If the results support the hypothesis that coating is not warranted, the use of a coating should be discontinued.

Low-Pressure Fuel Turbopump Turbine Bearing Fretting

During the course of tests, fretting of the turbine end-bearing has been observed in the low-pressure fuel turbopump. Fretting is usually indicative of inadequate bearing retention, which permits relative movement between the bearing and its journal or housing. Under such circumstances, fretting cannot be alleviated by dry lubrication. The relative motion needs to be reduced by proper bearing retention. This will involve a redesign of this part of the low-pressure fuel turbopump. The committee, therefore, recommends that the turbine bearing retention system on the low-pressure fuel turbopump be redesigned to reduce the relative motion between the bearing and its journal or housing.

Main Injector Oxidizer Post Shields

In early summer of 1978, a number of failures occurred in the oxidizer posts in the main injector of engines 0002 and 0005. Design modifications have been made to prevent such failures from recurring. The oxidizer posts (see Figure 1) carry oxygen internally through the main injector to the combustion chamber. An array of these posts separates the oxygen from the hot, hydrogen-rich gas, which flows around, and impinges on, the posts at high pressure and relatively high velocity. Thread-cracking in the posts has been attributed to vibration in bending. The cause of the failures is postulated to be fluid mechanical forces. These failures allow oxygen to leak and mix with the fuel, leading to premature burning. Once this happens, failures occur in adjacent posts.

To remedy this problem, steel shields have been installed on adjacent pairs of the oxidizer posts in the outer ring of posts -- i.e., those first encountered by the incoming hot gas. The function of the shields, according to NASA, is to protect the first row of posts from the incoming flow and to break up high-frequency oscillations in the wake of the posts -- thus reducing the vibratory loads and stresses in the threads. Subsequent tests have shown the shields to be effective in eliminating the pressure oscillations and reducing the loads in the posts. To date, tests have demonstrated a lifetime for the shields and posts in excess of 5,000 seconds. Calculations indicate that the shields will outlast the projected 7½-hour lifetime of the engine. The modification to the main injector has increased the weight of the engine about 13 pounds. A major part of the increase is due to the addition of 42 oxidizer post shields.

Of concern to the committee is the measured increase in the turbine inlet temperature of the high-pressure fuel turbopump at rated power level after the post shields were installed. The higher temperature is caused by the increased power required to overcome the pressure loss when the flow is restricted by the shields. Consequently, the committee recommends for the intermediate term that a study be undertaken to identify and eliminate the source of the unsteady flow at the first row of posts. Rocketdyne has proposed a new post design and material (Haynes-188) intended to resolve the problem of the injector post failures without the use of the shields, thereby eliminating the resulting temperature increase in the high-pressure fuel turbopump turbine inlet. This has not yet been tested.

Flight Certification

The engine development program includes a Preliminary Flight Certification that consists of a set of ground tests on a single engine. The purpose of these tests is to certify the engine configuration for use in the first six orbital flights.

In its initial report, the committee made certain recommendations with respect to the minimum test requirements for Preliminary Flight Certification that should be fulfilled in tests on a single "flight-configured engine" before the first manned orbital flight. NASA and Rocketdyne now propose Preliminary Flight Certification test requirements that are essentially in agreement with and, in some aspects, more stringent than the committee's recommendation. The proposed requirements call for an accumulation of 5,000 seconds of engine test time, including at least 3,000 seconds at rated power level and 425 seconds at 102 percent rated power level, as well as one aborted-flight simulation involving either abort-to-orbit (665 seconds at rated power level) or abort with return-to-launch-site (823 seconds at rated power level). The committee endorses this set of Preliminary Flight Certification requirements as an adequate demonstration of the engine's performance and reliability for the first manned orbital flight.

However, the committee is concerned that because of design changes, the engines to be used in the orbital flight tests are not exactly the same configuration as the engine to be tested in the Preliminary Flight Certification. The differences are significant. While the committee continues to recommend the use of a "flight-configured engine" for the Preliminary Flight Certification tests, it concludes that the Certification, as presently scheduled, is premature. The committee recommends that curren ly planned testing continue but that the formal Preliminary Flight Certification be delayed until the configuration of the engine to be certified is the same as the actual flight engines in all respects affecting safety.

The Preliminary Flight Certification should be viewed as a formal event. If there are any configuration differences, NASA, Rocketdyne, and in particular the Material Review Board and the NASA Aerospace Safety Advisory Panel should agree in advance on the acceptability of the configuration to be certified. Similarly, if any changes are made during Preliminary Flight Certification testing, the acceptability should be redetermined by the same groups.

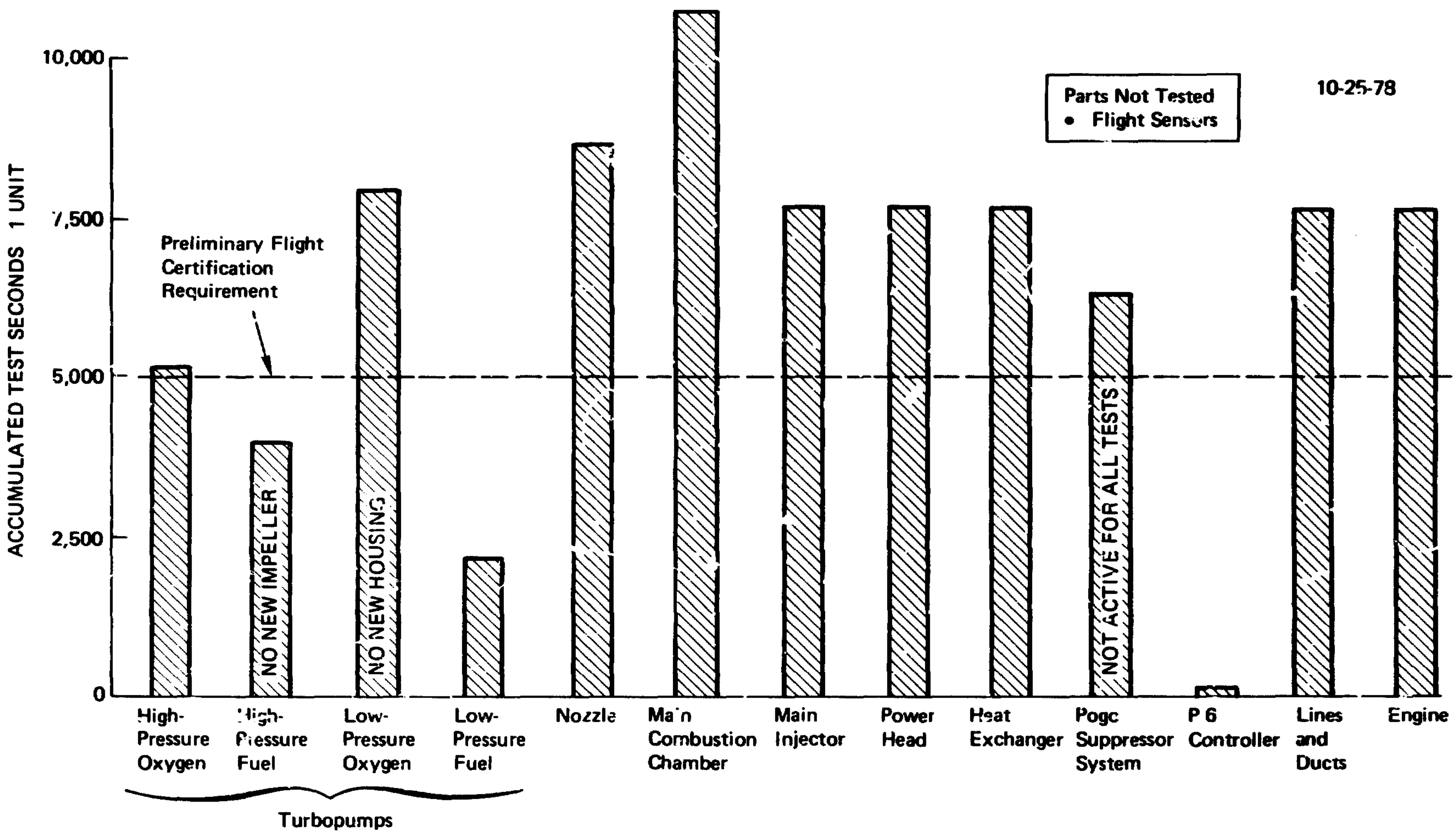
Component Test Requirements for Orbital Flight Tests

It has been standard practice for manned space flights using expendable launch vehicles that the engines be subjected to ground tests for at least ten times the duration of the actual flight. This testing protocol has provided an adequate margin to account for variations from engine to engine and for unforeseen events that might occur in flight. By contrast, the shuttle engine, unlike previous manned space propulsion systems, is designed to be reused in subsequent launches after inspection and, if necessary, repair and refurbishment. Therefore, the committee considers it unnecessarily stringent to require engine ground testing amounting to ten times the flight duration for the space shuttle main engine for flights after the first. In the committee's judgment, the performance and reliability of all components in the flight engine should be demonstrated by ground tests for a life of at least three times the use such a component will encounter in the six orbital flight tests.

Because the total engine-on flight time for the orbital flight test program is about 3,000 seconds (520 seconds per flight), the committee recommends that, insofar as practicable, all components of the engine be tested to the point where single components have each accumulated at least 10,000 seconds (see Figure 3). One way to accomplish this objective is to continue testing the engine used in the Preliminary Flight Certification tests toward the goal of 10,000 seconds. Alternatively, designated components could be run on research and development engines until the 10,000-second goal is attained for each component. Because it seems likely that some minor components, whose replacement is not a matter of concern, will not survive these tests, a list of components that could be replaced without risk to the program needs to be agreed upon in advance by appropriate NASA review groups and by Rocketdyne.

Should any engine component fail to attain the objective of 10,000 seconds, the committee recommends that it be replaced in the engine during the orbital flight test program but not to be flown for more than 30 percent of the successfully accomplished test time for the component. It is recommended that any exception to this procedure be approved at the highest level of NASA.

FIRST MANNED ORBITAL FLIGHT ENGINE CONFIGURATION TESTED (Single Unit)



SOURCE: Rocketdyne Division Rockwell International

FIGURE 3

RECENT ACCIDENTS

In December 1978, two main engines experienced damaging malfunctions while being tested at the National Space Technology Laboratories at Bay St. Louis, Mississippi. After NASA and Rocketdyne had examined the engines and evaluated the failures, they reported their findings to the committee.

Engine 0007

During the first checkout test for the preflight certification of engine 0007 on December 5, 1978, an explosion occurred in the heat exchanger at 3.5 seconds of the planned run of 50 seconds. The source of the failure was attributed to a leak in the coil tubing of the heat exchanger, which was caused, according to the explanation, by a weakness in the tubing that occurred during arc welding while an adjacent bracket was reworked with the heat exchanger still in the engine. The weakness went undetected because existing procedures did not call for a detailed inspection or proof-test of the reworked part. As a result, the heat exchanger and high-pressure oxygen turbopump, both integral to the engine, were damaged -- though these and other major components of the engine are considered reusable. Inspection procedures and pressure testing have now been established for similar repairs.

The committee recognizes the description of the cause of the explosion as a possible order of events but points out that there are two other ways the failure in the tubing could have occurred -- i.e., very high internal pressure caused by a restriction, such as debris, in the tubing or slow growth of a flaw in the tubing. In any event, the committee recommends that NASA and Rocketdyne establish inspections and proof testing or rebalance procedures as appropriate for all reworked parts. The paucity of development hardware in the program, coupled with the ambitious test schedule, makes the use of refurbished parts a certainty. While the practice of using reworked parts and subcomponents provides valuable experience in the development of an engine for a 7½-hour life cycle, it increases the chance for flaws or malfunctions, with the consequent risk of failures. Therefore, the committee considers it necessary for NASA and Rocketdyne to develop appropriate inspection procedures with a sense of urgency. Because the committee considers a failure in any part of the oxygen system to be potentially catastrophic, the accident in Engine 0007 reinforces the committee's concern, expressed in its first report, about a single-point failure in the heat exchanger.

Engine 2001

Engine 2001 had passed the acceptance test in January 1978 and completed four Main Propulsion Test Article runs between April and July 1978 -- accumulating a total of 287 seconds of test time. After this series of tests, the engine was returned to Rocketdyne for a turbopump retrofit. Then, during the third of a new series of acceptance tests, at 255.6 seconds of its test run, fire broke out in the main oxidizer valve, leading to extensive damage to the engine and the A-1 test stand. The failure was caused by a sequence of events: pressure oscillation in the oxygen flow led to vibrations in the main oxidizer valve inlet sleeve, which were sufficient to loosen one of eight retainer screws and allow fretting between metal parts; this resulted in enough friction to heat the metal to its ignition point in pure oxygen.

Actions to avoid fretting in the future include replacing the thin metal shims with ground shims, coating the surfaces with an oxygen-compatible dry lubricant,[1] and replacing the cap screws with screws with a conical shoulder, and providing conical seats incorporating a locking device. The committee supports the need for remedial changes.

In the design goals of compactness and lightness in the closely coupled main shuttle engine, vibrations of fluid-mechanical origin may occur. This provides considerable potential for rubbing or fretting. The committee recommends, therefore, that all fasteners should be examined for loosening and wherever feasible all means of eliminating such loosening should be incorporated.

Rocketdyne has initiated an investigation into the source of the vibrations in the main oxidizer valve and potential remedies. The committee considers further investigation into this problem to be important to pursue.

This episode underscores the earlier finding by the committee that parts and components need to be tested individually before they are assembled and tested as an engine system. If the main oxidizer valve had been mounted in a test stand so that its compliance could have been the same as in the engine assembly and tested, the vibration and fretting might have been identified early in the test program.

One of the effects of both incidents is to highlight the shortage of spare parts and components -- not only to ensure that the test and development program can be completed on a reasonably early schedule

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[1]During a discussion of dry lubricants, the committee concluded that more study is needed to make a convincing case that dry lubricants can be used safely.

but to provide enough hardware for the manned flight tests and later operational missions. The situation appears more critical now than at the time of the committee's last review.

In a previous section of this report, the committee has noted that replacement parts and additional engines to be used as test stands will be needed to advance the progress of the program in the event of malfunctions and accidents. To ignore this in a development program as highly complex as this one is to take inescapable risks. Therefore, the committee urges that a plan be drawn up and carried out as quickly as possible to provide additional replacement parts and engines for the space shuttle main engine program.

SCHEDULE CONCERNS

Some components or parts of the engine to be tested for Preliminary Flight Certification are new relative to the configurations used in the research and development engines previously tested. Incorporating previously untested components in an engine designated for certification is considered unusual and is disturbing to the committee. This procedure would reduce the probability of success of the Preliminary Flight Certification. The existence of any components with very little test time, such as the P-6 engine controller and the new impellor for the high-pressure fuel turbopump, leads the committee inexorably to the conclusion that an early Preliminary Flight Certification is unlikely. Any failure (not necessarily catastrophic) will lead to program delays. This is particularly true because of the existing shortage of development engines, spare parts, and test stands. These shortages undermine the expectation for an early manned orbital flight. In view of this, it appears unlikely that the first manned orbital flight will occur before April or May 1980. The first manned flight could be somewhat earlier only if the engine testing program encounters minimal or no difficulties--an improbability, considering the previous test history of the shuttle main engine.

Once the recommended tests are completed in a satisfactory way, the committee is confident the main engines will perform safely for the first manned orbital flight.

SUMMARY OF RECOMMENDATIONS

A. With respect to the first manned orbital flight, the committee recommends that:

- No significant differences should exist in the shuttle main engine that NASA intends to certify and the one it intends to fly. The formal Preliminary Flight Certification should be delayed until an engine of flight configuration is available for testing.

- NASA and Rocketdyne should prepare a detailed technical case for the method for determining platform crack growth rates, the intervals and procedures of inspection, and the criteria for the replacement of turbine blades in the high-pressure fuel turbopump. The case should explain the rationale and demonstrate that engine operation with some platform cracks is not harmful.

- One engine should be removed from the shuttle orbiter following the first flight and a complete tear down and inspection performed for signs of wear or stress.

B. For later in the manned orbital flight program, the committee recommends that:

- An agreed upon list of engine components should be tested to the point where individual components have each accumulated 10,000 seconds of test time before the sixth orbital flight. The test time is to be accumulated on a schedule that maintains about 3:1 ratio between total time in ground tests and total time in flight on any single component or assembly.

C. For the longer term in the shuttle flight program, the committee recommends that:

- o A plan to acquire additional engine test and development hardware should be prepared and implemented in the program as soon as possible.

- o Appropriate actions should be taken to acquire a component-development test rig as early as possible, not only for use in the engine development but for use in the sustaining engineering program when the shuttle becomes operational.

- o The turbine bearing retention system on the low-pressure fuel turbopump should be redesigned to reduce any relative motion or fretting between the bearing and its journal or housing, eliminating the need for dry film lubrication.

- o Tests of the high-pressure fuel turbopump should take place with uncoated turbine blades, and if test results indicate that a coating is not warranted, its use should be discontinued.

- o A program should be established to gain an understanding of the source of platform cracks in the high-pressure fuel turbopump turbine blades -- a program designed to lead to crack prevention.

- o An aggressive program should be undertaken to gain an understanding of the cracking of the high-pressure fuel turbopump turbine blades in order to prevent its occurrence.

- o A study should be undertaken to define the primary cause of the oxidizer injector post failure to provide a "fix" without the need for shields, thus eliminating the source of increased turbine inlet temperature in the high-pressure fuel turbopump.

- o The design, development, construction, and testing of an alternative high-pressure oxygen turbopump should continue in order to be ready to be installed in the engines by 1983 or 1984.

- o A line-replaceable heat exchanger should be constructed and tested for installation in the shuttle main engines as early as practicable.