Technical Status of the Space Shuttle Main Engine

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

Assembly of Engineering

11763

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

NOTICE

Copies of this publication are available from:

Assembly of Engineering
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

AD HOC COMMITTEE FOR REVIEW OF THE
SPACE SHUTTLE MAIN ENGINE DEVELOPMENT PROGRAM

Eugene E. Covert, CHAIRMAN
Professor of Aeronautics & Astronautics
Massachusetts Institute of Technology

David Altman
Vice President & Technical Director
Chemical Systems Division
United Technologies Corporation

Allen F. Donovan
Senior Vice President, Technical
The Aerospace Corporation

Don A. Hart
Deputy Director
Rocket Propulsion Laboratory
U.S. Air Force

Maynard L. Pennell
Vice President - Product Development (Retired)
The Boeing Company

William Rostoker
Professor of Metallurgy
University of Illinois at Chicago Circle

Lee F. Webster
Manager, Test Products
Engine Test Facility
Arnold Engineering Development Center
U.S. Air Force

Robert B. Young
Vice President
Aerojet-General Corporation

Richard C. Mulready, Special Adviser
Director, Technical Planning
Pratt & Whitney Aircraft Group
United Technologies Corporation

Albert J. Evans, Project Officer
Aeronautics and Space Engineering Board
Assembly of Engineering

Laura D'Sa, Administrative Secretary

ABBREVIATIONS USED IN FIGURES

CCV	Chamber Coolant Valve
FFC	Final Flight Certification
FMOF	First Manned Orbital Flight
FPL	Full Power Level (109 percent RPL)
FPOV	Fuel Pre-burner Oxidizer Valve
FRF	Flight Readiness Firing
HPFP	High Pressure Fuel Pump
HPFT	High Pressure Fuel Turbine
HPFTP	High Pressure Fuel Turbopump
HPOT	High Pressure Oxygen Turbine
HPOTP	High Pressure Oxygen Turbopump
LPFTP	Low Pressure Fuel Turbopump
LPOTP	Low Pressure Oxygen Turbopump
MCC	Main Combustion Chamber
MFV	Main Fuel Valve
MOV	Main Oxidizer Valve
MPTA	Main Propulsion Test Article
OPOV	Oxidizer Pre-burner Oxidizer Valve
P. A.	Pressure Actuated
PFC	Preliminary Flight Certification
RPL	Rated Power Level
SSME	Space Shuttle Main Engine

Almost from the start of the program, a succession of both technical and administrative problems has caused delays in the development of the main engines for the nation's space shuttle, the principal transportation system for both civilian and military operations in space in the 1980's.

As the time approaches for determining the readiness of the space shuttle for its first manned orbital flight, scheduled for March 1979, the Subcommittee on Science, Technology, and Space of the U.S. Senate Committee on Commerce, Science, and Transportation has sought assurance that the engines will perform safely and reliably. While the Subcommittee recognizes that the National Aeronautics and Space Administration conducts extensive reviews of the space shuttle program and, in addition, receives separate, continuous evaluations from NASA's Aerospace Safety Advisory Panel and specific ad hoc reviews by special groups, the Senate has called upon NASA to initiate on behalf of the Subcommittee an independent assessment of the engine system to be conducted by the National Research Council's Assembly of Engineering.

In a letter to the NASA administrator, Robert A. Frosch, dated December 14, 1977, Senators Adlai E. Stevenson and Harrison L. Schmidt observed:

> Recognizing...that the main engine represents a major technology advance and...that the engine development continues to experience difficulties, we are concerned whether everything possible is being done to assure development of a safe and reliable engine system...We would ask the [National Research Council] committee to give particular attention to questions of safety of the main engine during both the orbital flight test and operational phases of the shuttle program...We ask that this independent review...be completed prior to the end of February 1978 so that it can be considered during the FY 1979 authorization hearings.

Accordingly, the National Research Council's Assembly of Engineering organized the ad hoc Committee for the Review of the Space Shuttle Main Engine Development Program to conduct the study.

The shuttle main engine requires high-speed and high-pressure turbopumps. Because this technology is relatively new, there are few experts with the relevant background and experience in such rocket propulsion systems. The members of the committee have broad competence and experience in dealing with such advanced systems.

One such advance is the XLR-129, an experimental engine that was tested but never made fully operational. Its development led the committee to draw upon the knowledge of Richard Mulready of Pratt & Whitney Aircraft, a Division of United Technologies Corporation, which designed and developed the XLR-129 under Air Force sponsorship. Mr. Mulready assisted the committee as a special adviser.

The committee met first January 30-31, 1978, and twice since, on February 16-17 and February 23-24, including a site visit to the Rocketdyne Division of the Rockwell International Corporation in California to witness the work in progress on the main engine. Clearly, the committee's study has been conducted with great speed and intensity in order to meet the deadline set for it by the Senate Subcommittee.

The committee is grateful for the cooperation and documentation provided by NASA and Rocketdyne to enable the members to become quickly familiar with the problems and prospects of the shuttle main engine program. Moreover, the committee acknowledges the assistance of members of earlier technical review groups who described the findings of their studies at its first meeting -- in particular, H.E. Grier, EG&G Co., Chairman of NASA's Aerospace Safety Advisory Panel, and G. Elverum, TRW, Chairman of the Space Shuttle Main Engine Panel of the Space Shuttle Review Team, who are neither NASA nor contractor employees.

Finally, the committee expresses its thanks to Alexander H. Flax, President of the Institute of Defense Analysis, who, although unable to participate fully as a member of the committee, attended the committee's first meeting and participated in its initial deliberations.

INTRODUCTION AND SUMMARY

The space shuttle, a hybrid of spacecraft and airplane engineering, is the nation's most significant undertaking in manned space flight since the Apollo program. The shuttle consists of a manned orbital vehicle, launched by three identical liquid-propellant main rocket engines and two strap-on solid-propellant motors, or boosters. The main engines are built into the vehicle. The solid-fuel boosters are to be jettisoned about 2 minutes after the launch, when the shuttle reaches an altitude of some 25 miles; the boosters are intended to be recovered and reused. When fully developed, the shuttle will be a reusable, versatile vehicle transporting people, materials, experiments, and objects such as communications satellites into orbit and returning to earth to land like a conventional airplane. Each operational shuttle is designed to make at least 55 round trips into space, returning to an airport strip.

Flight tests of the shuttle orbiter, involving approach and landing without any of the rocket engines, have taken place after it was launched from a modified Boeing 747 aircraft. The next major milestone of the program is a manned orbital test flight. The committee considers it appropriate and wholly consistent with all previous aircraft experience to have a test pilot aboard the machine on its first flight. This increases the operational flexibility and, thus, the likelihood of success for the first manned orbital flight.

The successful operation of the shuttle is based on advances in the operational state-of-the-art of its main engine, particularly with respect to its reusability and to increased performance levels of its components in terms of power per pound. 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 sub-

1

sequent 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
clearly anticipate the successful development of the space shuttle main
engine.

.   Major developments of new flight vehicles have traditionally
proceeded by stages, with provision made for alternative approaches
along the way in the design and construction of components.*
Customarily, the overall system is separated into clusters and sub-
clusters representing different components and functioning assemblies.
These are designed and tested separately under simulated operational
conditions, then redesigned to correct any problems or malfunctions,
and ultimately qualified first for peak performance and then long-term
service. Often, when major innovations are required, more than one
approach to a design is initiated in parallel and constructed and
tested separately. Later, the best design, possibly with modifications,
is chosen and the others are discarded. When component performances
have been validated, entire assemblies are then tested for coordinated
functions. Finally, the complete engine is put through a series of
tests under full power to assess proof-of-flight capability. Such a
step-by-step, conservative approach provides opportunities to test
each piece under conditions that exceed the demands of operational
performance. In this way, it becomes possible to anticipate unexpected
events and to plan for contingencies that may arise in flight testing.

This is clearly a careful, costly, and lengthy approach. NASA's
past successes in major developments of flight vehicles have led the
agency and its contractor for the shuttle development to rely more
heavily on computer computations to reduce the need to evaluate new
designs by testing and, consequently, to reduce the need for redesign
work. Thus, unlike such previous programs as Apollo, the development
strategy for the shuttle program, including its main engine develop-
ment, has been described as "fully concurrent, success-oriented" -- a
strategy based on the assumption that each piece of development
hardware and its subsequent verification test will succeed on the first
attempt. For the most part, the development tests employ an engine
configuration assumed to be the same as the operational hardware to be
used for the manned orbital flights. Further, the parts are manufac-
tured on production tooling. Such a strategy offers potential savings
in costs by eliminating parallel and possibly redundant development and
test hardware.

It may be that this strategy already has saved time and money,
inasmuch as the quantity of hardware and spare parts have been reduced
significantly. However, if or when malfunctions occur during the
testing of the operational engine, new hardware may need to be designed,
constructed, and retrofitted, causing delays in the program.

---
*See Appendix A for a detailed discussion.

Indeed, such an eventuality has befallen the shuttle main engine. As often happens in the course of developing a complex, high-performance system, NASA and Rocketdyne have encountered some technical problems related mainly to the rotating machinery and the high-pressure turbopumps which have led to engine test malfunctions and delays of test sequences. At the time the committee conducted its study in February 1978, some of the problems were unresolved. Solutions have been proposed but are yet to be proved correct through testing.

The committee understands that NASA is considering conducting the first six manned orbital flights of the space shuttle at 100 percent power of the "rated power level" of the main engines. Later flights will require a thrust level that is 9 percent greater than rated power or "full power level" in order to launch the full shuttle payloads into orbit. The requirements for safety and reliability of the engine operating at full power place more stringent demands on the various components of the engine than when it operates at the lower, rated power, level. Thus, even after the engine is qualified for the first manned orbital flight, additional development may be necessary to qualify the engine at full power. The development plan under consideration calls for the certification of the engine at 100 percent power as a prerequisite for the first manned orbital flight and a subsequent certification of the engine at 109 percent power. This two-stage certification strategy represents a change of philosophy reached by NASA during the period of the committee's review.

It is especially important to understand that while the program has been underway for nearly six years and is now within one year of the first scheduled manned orbital flight, the development of the engine is not as far along as the timetable may suggest. The initiation of engine development was delayed 9 months for nontechnical reason. Thus, in terms of accumulated test experience, the current state of development of the space shuttle main engine is relatively immature.* The committee finds that the problems now being encountered are not alarming but rather typify the early stage of any similar new technological development.

The solution to the problems encountered in the shuttle main engine involves the redesign or modification of parts in the rotating machinery, with each change affecting the performance of this closely coupled engine. While many elements of the engine development point to the ultimate success of the program, incorporation of the changes and the tests to assure their effectiveness could result in delays. The ambitious timetable may have to be extended to avoid a first manned orbital flight with a high risk factor.

---

*In the development of such a complex system, experience is gained slowly at first, but as work proceeds experience accelerates rapidly.

In the final analysis, the amount and results of testing performed on the ultimate flight-configured engine will determine the timing and safety and reliability of the engine for the first manned orbital flight. The committee expects that, at the completion of the planned testing, adequate data should be available by late summer or early fall 1978 to enable NASA to develop a realistic schedule. The committee concludes that the appropriate time for NASA to review the shuttle flight schedule is when these data are available. The data may suggest that a delay is desirable to allow for a more realistic rate of testing, to provide leeway for as yet unforseeable changes, to incorporate proof-tested parts in the main propulsion test article (MPTA) and flight engines and, perhaps most important, to allow adequate time to analyze root problems and seek out their solutions rather than attempt to cure symptoms.

In addition to these conclusions, the committee also makes a number of recommendations. Some address the need to adhere to currently established testing criteria and standards in spite of the pressures imposed by an ambitious schedule. The committee recommends testing the engine at an added safety margin above the power level of the first manned orbital flight and tearing down the engines for inspection following at least the first and sixth flight. Additional recommendations concerning the need for future design work and component testing are also made in this report.

The balance of this report provides a brief description of the shuttle main engine and how it operates, its present status, the committee's perception of the critical issues and their consequences, and, finally, the conclusions and recommendations. In making this assessment of the shuttle main engine program, the committee always recognized two basic requirements: First, the need to develop main engines with performance levels that will enable the first manned orbital flight to be as reliable and safe as America's earlier manned space flights, and then to achieve full power for later flights. Second, the need to maintain full power performance in the same engines for at least 55 missions of each shuttle.

Based on the experience of the program so far, the committee sees no reason to suggest that a safe and reliable main engine cannot be developed ultimately for the manned orbital flight tests and the later operational flights.

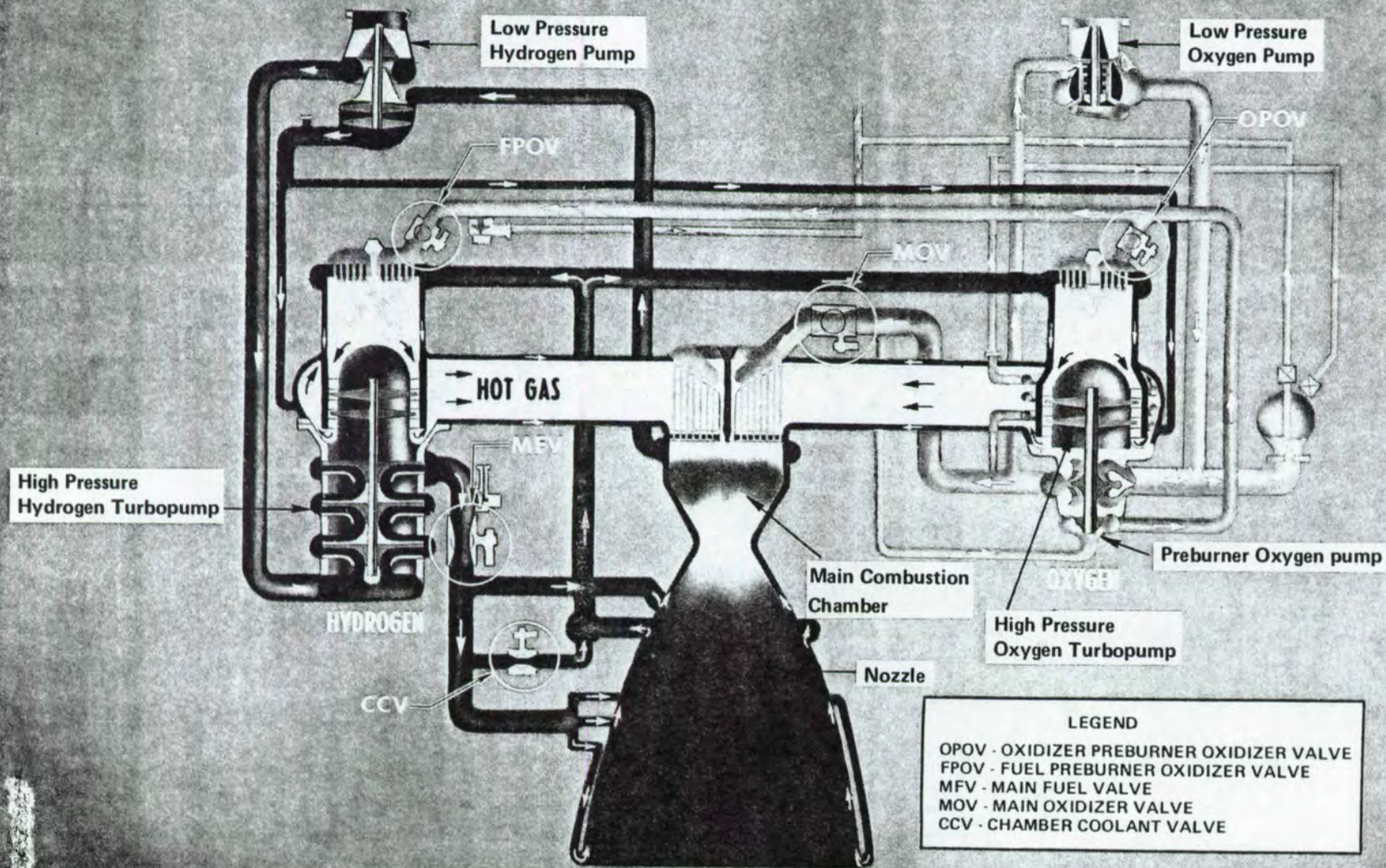# SPACE SHUTTLE MAIN ENGINE - A BRIEF DESCRIPTION

The main engine is a machine for producing the thrust necessary to
launch the space shuttle into a low orbit around the earth.

The shuttle has three main engines that operate on cryogenic
liquid propellants -- liquid hydrogen, the fuel, and liquid oxygen to
burn the hydrogen. Each propellant is pumped to a very high pressure
by two pumps. One is a low-pressure pump that increases the pressure
several hundred pounds per square inch. Then a high-pressure pump
increases the hydrogen pressure to 6,200 pounds per square inch and the
oxygen to 4,600 pounds per square inch. Such pressures are greater
than those of any previous operational hydrogen/oxygen engines, e.g.,
the RL-10 and J-2, though such pressures have been developed in two
experimental programs.

Each of the four pumps (low- and high-pressure hydrogen, low- and
high-pressure oxygen) is driven by a power source from within the
engine. The two high-pressure pumps are each powered by a turbine
mounted on the pump shaft (Figure 1). The turbine is driven by a hot,
fuel-rich gas. The gas is produced in a pre-burner where a relatively
large amount of hydrogen reacts with a small amount of oxygen. The
product of this combustion is a mixture of hot hydrogen and superheated
steam. The two low-pressure pumps also are driven by turbines. The
low-pressure hydrogen pump turbine uses hydrogen gas tapped from else-
where in the cycle which is described later. The low-pressure oxidizer
pump, also described later, is driven hydraulically by liquid oxygen
that is tapped from elsewhere in the cycle.

The hydrogen flowing from the high-pressure fuel turbopump is an
effective coolant as well as a source of a high energy. In this engine
it follows several paths to cool the critical parts where combustion
occurs or hot gases flow. In its cooling function, the liquid hydrogen
is heated and vaporized. Most of the gaseous hydrogen is routed to the
two pre-burners, which serve as gas generators for the turbines that
drive the high-pressure pumps. A smaller amount of the gaseous
hydrogen is piped to the turbine that drives the low-pressure hydrogen
pump. Most of the liquid oxygen is channeled directly to the main

SSME PROPELLANT FLOW SCHEMATIC

Low Pressure Hydrogen Pump

Low Pressure Oxygen Pump

FPOV

OPOV

MOV

HOT GAS

High Pressure Hydrogen Turbopump

MFV

Preburner Oxygen pump

Main Combustion Chamber

High Pressure Oxygen Turbopump

HYDROGEN

OXYGEN

Nozzle

CCV

LEGEND

OPOV - OXIDIZER PREBURNER OXIDIZER VALVE
FPOV - FUEL PREBURNER OXIDIZER VALVE
MFV - MAIN FUEL VALVE
MOV - MAIN OXIDIZER VALVE
CCV - CHAMBER COOLANT VALVE

Figure 1

combustion chamber. A small amount of the liquid oxygen enters a special very high-pressure pump stage mounted on the end of the shaft of the high-pressure oxidizer pump. The oxygen flowing at this stage is under pressure of 7,650 pounds per square inch, the highest pressure in the entire engine. Then the pressurized liquid oxygen is fed to the two pre-burners, where part of the hydrogen is burned. The pre-burner exhaust is used to drive the high-pressure pump turbines.

The main event now takes place. The pre-burner exhaust, consisting of hydrogen and superheated steam, mixes with the primary high-pressure liquid oxygen in the main combustion chamber, where combustion takes place at high pressure. The products of combustion, consisting mostly of superheated steam, pass through a constriction, the nozzle throat, and expand rapidly to a high velocity. Over 1,000 pounds per second of combustion products moving at high velocity is the action that produces the reaction or thrust for the vehicle.

While the basic concept is simple -- cold liquid hydrogen and oxygen coming in and superheated steam propelled out -- the various flow paths need meticulous control. Such control is provided by valves at critical points in the engine. The valves are activated by a special purpose digital computer called the engine controller, which converts such data as pressure and temperature into position signals. For this operation, the controller is a closed loop device, i.e., it is self-correcting. The controller also monitors signals from sensors mounted in the engine, so that it can quickly shut down the engine when a malfunction is detected.

Another function of the controller is to control carefully the engine start-up and shut-down. Without careful control, parts of the engine may overheat and even melt. Destructive fires may take place by oxygen washing over hot metal surfaces. Prior to start-up all four pumps are pre-chilled by liquid propellant circulating through them. Sparkplug-like igniters in both pre-burners and the main combustion chamber are energized. The main hydrogen valve opens first. As the cold hydrogen comes in contact with the engine parts it is gasified. The warm hydrogen gas begins to turn the turbines. The oxidizer control valves then open in a precise sequence: the igniters initiate combustion first in the pre-burners and then in the main combustion chamber. The shut-down is essentially the reverse of this process: the oxidizer flow is turned off, then the hydrogen flow. The control-ler is designed to ensure that all the oxygen is purged from the lines downstream of the valves before the hydrogen flow is shut off. This is necessary to reduce the possibility of a "hot spike" or high tempera-ture surge at shut-down.

The space shuttle engine has severe requirements of light weight, compactness, high absolute thrust, and high thrust per pound of fuel burned. Much of the reduction in weight of the main engine is achieved by two basic design philosophies. One integrates the system as fully as possible. This implies, in part, an exceedingly compact, inter-

active arrangement. Compactness provides economies in size and weight. It also implies extremely high power densities in the fuel and oxidizer pumps. The small separation of hot and cold gases, of fuel gases and oxidizer gases, and of liquids and gases gives rise to potential hazards that impose extremely stringent demands for reliable construction.

The other basic design philosophy is to weld as much of the assembly as possible. This eliminates heavy flanges and bolts, thus saving substantial weight and reducing the size of the assembly. Because welds are sometimes a source of incipient cracks, standards of quality control and inspection must be very high. Both NASA and Rocketdyne appreciate this need and are working to ensure that high standards are met in production.

This brief description marks the shuttle main engine as a complicated, high-performance machine made up of a number of interacting components and, like its predecessors, designed to provide a high thrust per unit of weight. Unlike its predecessors, it is designed to be reusable for many flights to orbit. Accordingly, the successful development of the shuttle engine is a prodigious engineering challenge.

CURRENT STATUS

On April 4, 1972, Rocketdyne was authorized to proceed in developing
the space shuttle main engine — 9 months after it was selected as
the contractor to develop the engines. Engine system testing began in
June 1975, nearly 15 months later than the original schedule. Operation
of the engine at rated power level was first achieved in March 1977.

In the course of the development NASA expects to accumulate about
80,000 seconds (1,333 minutes) of operating experience on the main
engines. By February 25, 1978, a total of only 11 minutes of operation
at rated power level had been accomplished, with no operating time at
full power level. A typical flight will require about 8 minutes of
engine operation, most of it at close to rated power level for the
early flight tests and at full power level for the later operational
missions. The engine's ability to run in demonstration tests at flight
power level for a total duration of at least five flights (40 minutes)
without significant malfunctions is one of NASA's essential pre-
requisites to its use in actual flight.

Based on the test time accumulated through February 1978 at rated
power, the engine is still relatively early in its development. It is
at a point at which running time is accumulating slowly. Development
programs are designed to uncover problems as rapidly as possible early
on, and to demonstrate performance and reliability later. As the
problems are resolved, the rate at which running time is accumulated
increases rapidly to enable performance and reliability to be demon-
strated relatively quickly.

In tests, there have been a number of engine test malfunctions,
some requiring substantial reconstruction and, therefore, causing
delays. This is a practical consequence of component proof testing.
The types of malfunctions have included cracks, fractures, leaks, and
lack of rigidity. It will not be a simple matter to correct such
problems, but neither do they involve major redesigns.

As the testing proceeds and more is learned about the engine, a
series of changes or modifications will have to be developed to achieve
the required performance and durability. Many of these changes, but

not all, will have to be fully incorporated before the engine can be
qualified for first flight. Thereafter, a second program of qualifica-
tion will be required to achieve an engine capable of operating at full
power, i.e., 109 percent of the rated power level. At present, some
changes are likely to be required to raise the power level and
simultaneously increase the life of the engines to the original objec-
tive of 7½ hours. This may upset the overall process of developing the
engine in view of the extent of the changes that might be necessary.

TECHNICAL CONCERNS

Operation at rated power level has revealed a number of problems. Most of these difficulties are found in the rotating machinery, i.e., the four, high-speed, turbine-driven centrifugal pumps that deliver the liquid hydrogen and oxygen propellants to the combustion chamber under high pressure.

Examples of the difficulties are high vibration-induced stresses in the high-pressure fuel pump turbine blades, major leakages through shaft seals in the high-pressure oxygen pumps, inability of the fuel pump to operate at the inlet propellant pressures for which it was designed, and low efficiencies. These low efficiencies result in increased power requirements and thus increased turbine inlet temperatures to ensure adequate pump delivery. This occurs because a specified engine thrust requires a specified rate of propellant flow.

The committee notes a significant dichotomy in the state of subassembly development testing. Such engine components as the combustion chamber, the nozzle, the pre-burner, the valves, and the computer-controller were tested as components and are performing relatively satisfactorily in general. The testing of the high-pressure turbopumps as components also had been planned, and a facility had been built at Rocketdyne for the purpose. Testing on this rig was initiated on May 1, 1975, and concluded on September 12, 1977, with only 161 seconds on the oxygen pump system and 111 seconds on the hydrogen pump system. Some of the difficulties encountered with the test rig were caused by the very high system pressures that required heavy hardware that was hard to manage. Thus, long delays resulted when changes were made. Rocketdyne and NASA concluded that component testing of the high-pressure turbopumps could not be carried out at a rate that would be useful in the development program. As a result, NASA and Rocketdyne decided to conduct turbopump development tests by running the pumps as part of the total engine system. The committee considers this decision has great bearing on any examination of the problems in the turbopumps. For instance, it precludes testing the high-pressure turbopumps at conditions other than the normal operating conditions. The decision

also has the effect of preempting the use of hardware for turbopump development that could otherwise be used for engine performance development testing.

The lack of an adequate test rig to conduct component tests expeditiously outside the engine appears to be the primary reason that the turbopump problems were not discovered before last summer, during the initial engine tests at the rated power level.

NASA and Rocketdyne hold that the engine tests at rated power level have provided the data necessary to identify any deficiencies in the engine and the high-pressure turbopumps, and the data necessary to formulate corrective actions. Insofar as the committee is aware, however, no rocket engine using turbopumps has ever been produced without extensive development testing of the turbopumps first as components.

In this connection, a facility for component testing of high-pressure turbopump systems was developed for the XLR-129 program. While an adequate turbopump test rig cannot be made available to contribute to the development of the main engine for the first flight, past experience suggests that such a test rig could be very useful in the long run for identifying and solving problems associated with durability and reliability. Accordingly, NASA and Rocketdyne may want to explore the most effective way to acquire an operating component test rig for the rotating machinery.

The committee considers the following to be of primary technical concern:

o The high-pressure oxidizer turbopump is critical to the performance and safety of the main engine. While the committee recognizes the design changes being made, it notes a considerable number of these are yet to be verified. Nevertheless, the complexity of the design, the relative flexibility of the shaft and housing, the complicated load paths, the extremely high performance demands, and the planned multiple reuse suggest that a back-up shaft and housing design be initiated. While a long lead-time is involved, a parallel development seems to be in order for this key assembly.

o The heat exchanger downstream from the oxidizer turbo-pump pre-burner is an extremely complicated welded assembly. It is located in a position where inspection is difficult. While no recent incidents have been attributed to heat exchanger failures, the committee is concerned that a failure of the heat exchanger could be catastrophic. Therefore, this item warrants continued management attention.

o   The preliminary flight certification of the engine re-
    quires the development of a specific set of hardware that
    will meet the test requirements. Because the main engine
    is a closed cycle machine in which the performance of
    each individual component such as a valve, say, or a
    turbine-driven pump or a heat exchanger affects all the
    other components, it is essential that the number of
    changes between successive tests be kept as low as
    possible, particularly when the performance of the
    component is involved.

o   Three failures in the high-pressure fuel turbopumps have
    been attributed to high cycle fatigue in the turbine
    blades. The first two incidents (which occurred at
    accumulated times of 313 seconds and 2,973 seconds) were
    confirmed by fractographic analysis. The third failure
    is inferred because the turbine was destroyed by fire
    during testing. While there is general agreement among
    the experts that the material used for fabricating the
    blades is suitable, the committee considers that a more
    complete characterization of the material is needed.
    The problem of high cycle fatigue is common in turbine
    development, and the committee is confident this
    problem will be solved. While the turbine blade
    problem* has received considerable attention and
    although it may require a year or so to provide a
    permanent solution, the committee finds the difficulties
    to be characteristic of the kinds of problems encoun-
    tered in the development of any new turbine system.

Not unexpectedly, many components are being redesigned or modi-
fied to a greater or lesser extent. For instance, all four turbopumps
(low-pressure and high-pressure, fuel, and oxidizer) are being altered,
sometimes by several changes simultaneously. One indication of the
present state of the engine development is that the turbine inlet
temperature of the high-pressure fuel turbopump is running some 450° F
above the design value of 1,271° F at 100 percent power level. The
program developed to reduce the temperature is outlined in Figure 2.
It is not now certain that each of the changes will produce the
predicted temperature reduction. It is certain, however, that each of
these changes will affect the performance of the rest of the engine.
In effect, a whole succession of configuration changes is under-
going tests. Because changes are being made in several other parts of
the engine as well, it appears likely that the development will take
more time than planned. This, too, is to be expected in any major new
development. In fact, the more advanced the design, the longer the

---

*See Appendix B for more details

HPFTP TURBINE TEMPERATURE REDUCTION

		TEMP REDUCTION	MPTA 90% RPL	MPTA RPL	MPTA FPL	FIRST FLIGHT SET	SECOND FLIGHT SET
SHORT RANGE DESIGN CHANGES	1) OPEN CCV TO 100% AT RPL	130°	1830°R				
	2) REBALANCE PREBURNER INJECTORS	70°		1815°R	DECREASE FPB FUEL INJ. 10% INCREASE OPB FUEL INJ. 10%		
	3) REDUCE HPFT BRG COOLING	45°			1890°R	1900°R REDUCE 3 LB/SEC	
LONG RANGE DESIGN CHANGES	4) ADD HPFP INDUCER	45°					
	5) REDESIGN HPFT NOZZLE AREA	60°					REDUCES TURBINE INLET TEMPERATURE TO 1630°R FPL OPERATION
	6) REDESIGN HPOT NOZZLE AREA	60°					
	7) INCREASE MCC THROAT 10%	105°					

Source: Rocketdyne Division Rockwell International

14

Figure 2

development process is likely to take. The time required to correct test-induced failures ranges from a few weeks for simple modifications to over a year for more complicated redesigns. Note that some of these redesigned parts may not be needed for the first manned orbital flight. Full power operations, however, require such modifications.

Fortunately, many elements of the engine program give evidence that the desired performance, durability, and safety can be achieved. Thus the committee has no doubt about the successful final outcome.

SCHEDULE CONCERNS

To bring together all the necessary components for a safe, reliable, and reusable engine without undue and costly delays to the scheduled first manned orbital flight requires managerial skills of the first order. Such skills are particularly necessary for a program in which decisions are made seven or eight years before the main event. In this case, the schedule needs to possess some flexibility. Slippages of a month or two in a program of 100 months, involving the development of a new, technically challenging system, do not represent a serious defect. Indeed, a 10 percent to 12 percent extension in schedule should be regarded as normal and not an anomaly.

However, as critical milestones approach, intense pressures to meet the schedule are apt to develop. Frequently, this involves considerable parallel effort and overtime work. So long as everything goes reasonably well, this causes no untoward problems. But when troubles arise, the potential increases for new, unforeseen difficulties, both technical and managerial. The temptation exists to cut corners, omitting tests of components for instance, to keep to the schedule. Moreover, human fatigue or stress can lead to mistakes in judgment.

In such circumstances, increased demands are placed on management to know when to hold to the original schedule and when to allow a slippage. Indeed, a first flight may be delayed and, yet, because of the greater reliability attained through improvements and modifications, the overall program can be benefitted, and the early delay can be made up so that later flights are on schedule.

In the case of the space shuttle main engine, the authorization was delayed by 9 months. This imposed great pressure on the schedule. To deal with this, NASA and Rocketdyne have laid out an ambitious timetable for incorporating and testing newly designed parts. The rate of accumulation of engine operating time shown in Figure 3 is clearly based on meeting it. Notwithstanding, the committee considers such an optimistic schedule is not likely to be realized in practice because

ACCUMULATED ENGINE
TEST DURATION
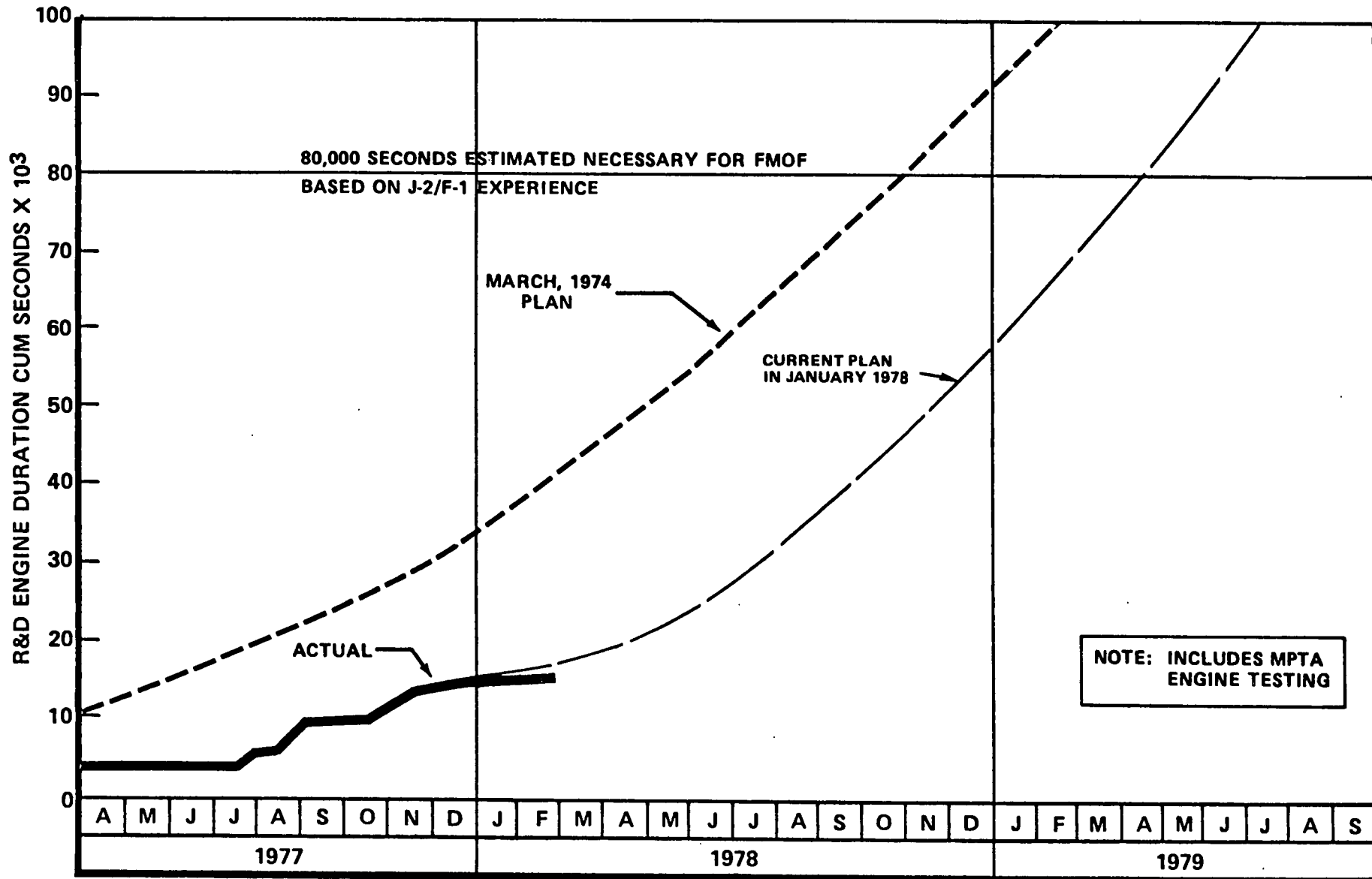
Figure 3

of the small likelihood of success of all the modifications currently
in progress.

The completion of tests and evaluation of performance of modified
components during the next 5 to 7 months should help substantially in
determining the time that will be required to obtain a flight-
certified engine. While the committee recognizes that a successful
engine can be developed without component testing of the high-pressure
turbopumps, in the absence of any past experience with such a program
there is inadequate data to make a reliable prediction of the time
required to accomplish the development.

The committee suggests that NASA will need to examine the status
of the engine development in late summer, early fall, or whenever data
sufficient to assess the engine status becomes available, in order to
prepare a precise schedule. The data may show, for example, that the
first manned orbital flight is possible within the current schedule.
On the other hand, it may show that the optimism is not warranted.
Moreover, the data may suggest that a delay is desirable to allow
for a realistic rate of testing, provide leeway for further changes,
incorporate proof-tested parts in the main propulsion test article and
flight engines and, most importantly, allow time to analyze problems
and proposed solutions adequately. In the last respect, the committee
is concerned that the current schedule is so compressed it generates
an atmosphere that seems to inhibit realistic evaluations of the
problems encountered so far.

SAFETY AND RELIABILITY

Safety must always take precedence over scheduling concerns. Because no flight test of the space shuttle main engine is planned prior to the first manned orbital flight, confidence in the safety and reliability of the engines in manned flight must be based upon:

o Safety and reliability designed into the engine

o Testing of flight-configured engines

o Quality control and testing of the three engines
   when mounted in the orbiter for the first flight.

It is important that the term "flight-configured engine" be well understood. "Configuration" means identification of all the parts making up an engine. As in any engine development, design changes are made in response to problems as they are uncovered. Thus, early in the development program, the configuration is in a state of change. While total test time in the overall program is an important measure of the maturity of its development, the amount of testing performed on the flight configuration is the single most important parameter in considering the safety and reliability of the first flight. Figure 4 shows the improvement in the operating conditions expected from incorporation of improved hardware. When this chart was prepared, the contractor had assumed all changes would be fully effective.

Evaluating the "testing of flight-configured engines," therefore, involves a verification of the extent of engine maturity. Rocketdyne plans to achieve approximately 40,000 seconds (11 hours) of firing time on the flight-configured engine (Figure 5) before the first manned orbital flight (FMOF). To accomplish this, the committee suggests that additional hardware will be required. What is more, additional technical problems are likely to arise in the course of testing.

NASA has divided the preliminary flight certification into two phases. The first phase, labelled PFC-FMOF (Preliminary Flight
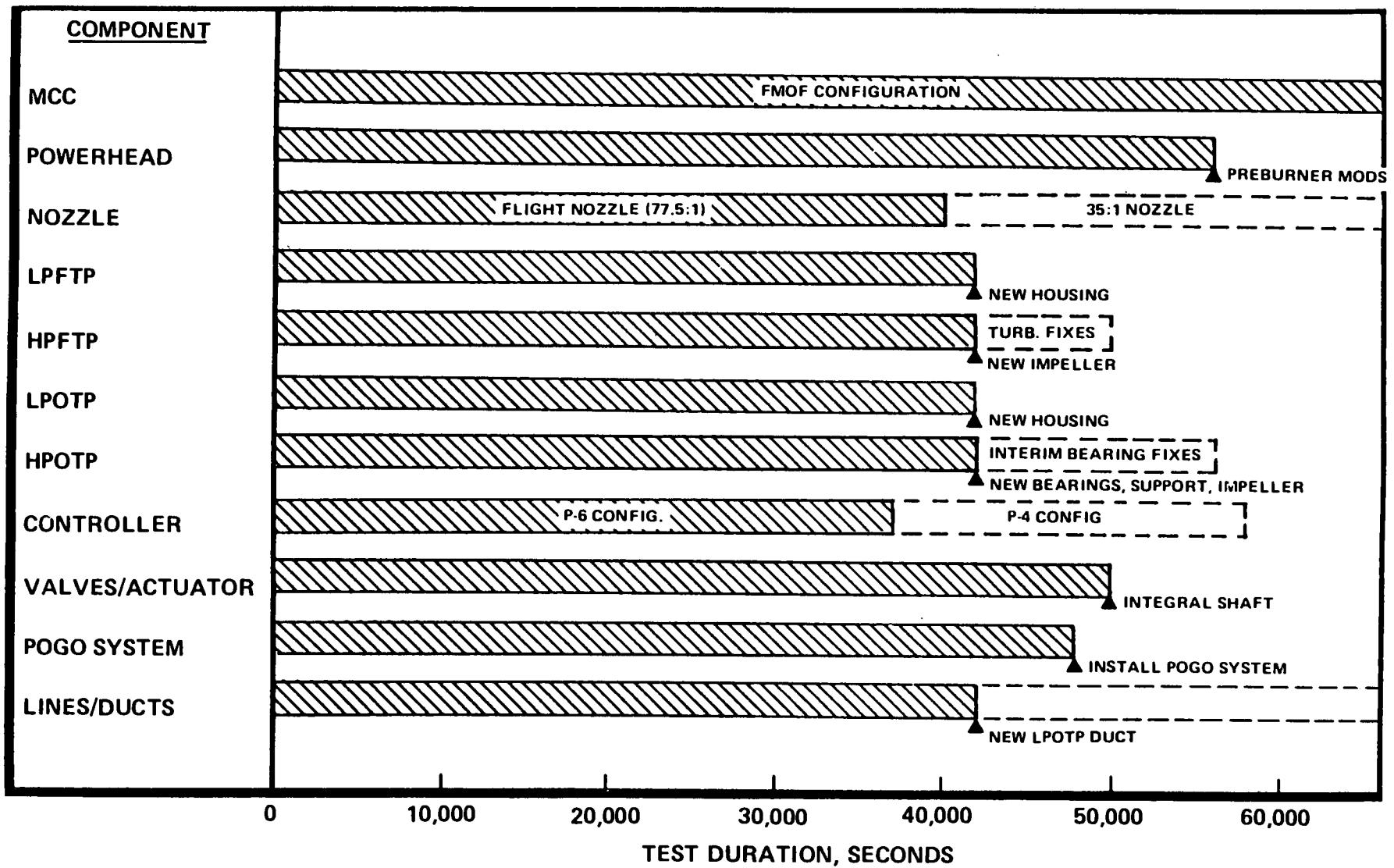
SSME CONFIGURATION VERIFICATION

	PFC-FMOF ▽	PFC ▽		FFC ▽
	1977	**1978**	**1979**	**1980**
	4	1 | 2 | 3 | 4	1 | 2 | 3 | 4	1 | 2

R&D PROGRAM: 1-4 │ 5-7 │ 8-13 /FIRST FLIGHT │ LONG TERM

MPTA PROGRAM: 1-4 │ 5-7 │ 8-13

FLIGHT PROGRAM: FIRST FLIGHT SET ▽

OPERATING COND.

• PERCENT RPL, %	90	90-100	109	109
• HPFT INLET TEMP, R	1830	1815	1900	1735
• HPOT INLET TEMP, R	1400	1525	1585	1500
• HPFT SPEED, RPM	32,700	34,900	37,200	37,600
• HPOT SPEED, RPM	25,500	27,300	29,400	29,900
• PROP. INLET COND.	MPTA	MPTA	FLIGHT	FLIGHT

CAPABILITY

• POGO SYSTEM	NONE	YES	YES	YES
• GIMBAL	NONE	FULL	FULL	FULL
• LIFE, SECONDS	700	4500	4500	12,600
• COMPONENT LIMITING	HPFT TURBINE	LOW PR. LOX DUCT	LOW PR. LOX DUCT	DEMONSTRATION

Source: Rocketdyne Division Rockwell International

20

Figure 4

TEST SECONDS ON FMOF CONFIGURATION

COMPONENT	
MCC	FMOF CONFIGURATION
POWERHEAD	PREBURNER MODS
NOZZLE	FLIGHT NOZZLE (77.5:1) 35:1 NOZZLE
LPFTP	NEW HOUSING
HPFTP	TURB. FIXES / NEW IMPELLER
LPOTP	NEW HOUSING
HPOTP	INTERIM BEARING FIXES / NEW BEARINGS, SUPPORT, IMPELLER
CONTROLLER	P-6 CONFIG. P-4 CONFIG
VALVES/ACTUATOR	INTEGRAL SHAFT
POGO SYSTEM	INSTALL POGO SYSTEM
LINES/DUCTS	NEW LPOTP DUCT

TEST DURATION, SECONDS

0   10,000   20,000   30,000   40,000   50,000   60,000

☐ test time accomplished

▨ test time not yet accomplished

Figure 5

21

Certification-First Manned Orbital Flight), will achieve the following milestones on a single, flight-configured engine:

o 1 hour total time

o 10 starts

o 50 percent of the firing time at the 109 percent
   rated-power level with inlet conditions the
   same as expected in first manned orbital flight.
   (NASA is considering reducing this power level
   to 100 percent.)

The current NASA scheduling for the shuttle main engine calls for complete preliminary flight certification (PFC in Figure 4) to be completed before first flight. This complete preliminary flight certification is to be performed on the same engine used in the first phase, or PFC-FMOF, described above. In the second phase, total duration is to be extended to 9,000 seconds (2.5 hours), and the number of starts extended to 25. This test duration is more than 12 times a single flight duration, which is an appropriate margin from high-cycle fatigue considerations.

The committee was informed that NASA is giving serious consideration to limiting engine power to 100 percent rated power level for the first manned orbital flight. Data were presented indicating that the mission objectives for this flight, including abort modes, can be achieved at 100 percent rated power level or less. The committee considers this reasonable, but finds it important to demonstrate engine operation at a power level in excess of the mission requirement. The committee suggests that such a safety margin be set at 2 percent (102 percent of whatever power level is selected for the mission).

In addition to the development testing and the preliminary flight certification of the single engine, NASA plans call for tests of the main propulsion test article (MPTA), i.e., the cluster of three flight-configured engines fed from a flight-configured main tank. These tests are indicated in Figure 4 as tests 8 through 13. The committee is concerned that the planned testing may be reduced to maintain the schedule.

The last important confidence factor, quality control and testing of the actual flight engines, involves management procedures to ensure that the actual flight engines are identical in every essential respect to those successfully tested during the development, the preliminary flight certification for first manned orbital flight, and the tests of the main propulsion test article. NASA and Rocketdyne have such procedures,which appear adequate to the committee. Acceptance testing on the actual flight engines involves three starts — two at short duration and one at full flight duration. In addition, the actual flight engines for the first manned orbital flight will be tested for 20 seconds on the launch pad in a "hold-down" test.

If the three safety and reliability considerations are handled successfully, as described above, the committee is confident that the main engines will perform safely in the first manned orbital flight. By this, the committee means that the engine must perform not only without failure, but also without indication of incipient failure, appearance of distress abnormal wear conditions, or borderline values of measured parameters, and so forth. This confidence is also based upon the assumption that the ground testing of flight-configured engines will provide for a reasonable test time at a power (thrust) level 2 percent greater than the power level to be used in first manned orbital flight.

With respect to subsequent flights in the shuttle program, NASA plans to use the first set of three engines on the first six manned orbital flights. No disassembly of the engines after flight is currently planned, only boroscope and visual inspection. The committee recommends that this inspection be expanded to include engine "teardown" and inspection after the first and sixth flights. If the inspection following first flight reveals no signs of distress and if the engines are performing properly, boroscope and visual inspection after the next four flights are considered adequate.

The committee did not address in detail the approach and schedule for final flight certification, i.e., assurance of the safety and reliability of the engines throughout their 55 missions. Improvements in pump efficiency and in main combustion chamber cooling are planned to reduce the fuel turbine inlet temperature to the design level. Most of these changes, listed in Figure 2, are still in the design or fabrication stage, leaving proof of capability still to be demonstrated. Reduction of the inlet temperature is essential to the attainment of satisfactory turbine life over the course of the manned missions. Each actual improvement realized in the turbine inlet temperature should be closely monitored and alternative approaches should be developed for any change that falls short of the expected temperature reduction. Only when the engine performance level has stabilized can the final assessment of engine life be completely meaningful. Additional time and additional test hardware are likely to be required to reach final flight certification.

RECOMMENDATIONS

o It is too early to predict the exact timing of the first manned orbital flight. The committee expects adequate data will be available by late summer or early fall of 1978 to plan the first flight schedule more realistically. Because of the number of critical milestones yet to be achieved, the committee recommends that the schedule be reviewed at that time.

o The committee recommends that Rocketdyne acquire an additional engine and critical parts to accomplish the required testing in this period. This hardware can be diverted from the production program into the R&D program, and replaced in the production program at a later date.

o The committee recommends the initiation of an alternate design of a new high-pressure oxygen turbopump shaft and housing.

o The committee recommends a review of the decision to perform turbopump development tests by running the pumps as part of the engine system to examine alternative options for the long term. NASA and Rocketdyne should explore means of acquiring and operating a component-development test rig for the rotating machinery. Among the options are: modification of Rocketdyne's existing test rig for the shuttle main engine; use of the component-development test rig for the XLR-129 experimental program if it is intact and available; design and construction of a new test rig utilizing the engineering experience involved in the development and use of the XLR-129 facility. This kind of equipment is likely to prove invaluable throughout the life of the space shuttle transportation system.

o To minimize future delays in the schedule, NASA and the contractor should allow adequate time to analyze root problems and seek out their solutions rather than selecting technical "fixes" to cure symptoms.

o The minimum preliminary flight certification requirement before first flight,as currently planned by NASA should not be compromised and should be strengthened by a requirement for tests at a power level in excess of that required for flight, as follows:

1. Successful completion of the main propulsion test article program on flight configuration engines with at least two uninterrupted full duration runs at 102 percent of first manned orbital flight power level.

2. Successful completion of at least 10 starts and 3,000 seconds of operation on a single engine of flight configuration. At least 25 percent of this time should be at 102 percent of first manned orbital flight power.

o A complete tear-down inspection of the main engine should be conducted after the first and sixth flights. If there are no signs of distress and if the engines are performing properly after the first flight, a boroscope and visual inspection should be sufficient after each of the next four flights.

o While the heat exchanger has encountered no problems recently, the committee urges that it should continue to receive management's attention. The heat exchanger system poses a potential threat to the total shuttle system. However, the changes required for a redundant heat exchanger to eliminate this single point threat of failure seem to be so extensive that provision for redundancy is impractical. Nevertheless, the committee recommends that an alternate design and development should be explored to relocate or reconfigure the heat exchanger system.

o The next step in the engine development should be to increase the power level to a full 109 percent.

APPENDIX A

TURBO MACHINERY DEVELOPMENT CONCEPTS

by
Lee F. Webster

Past Approach

In the past, the U.S. rocket industry has employed component test facil-
ities for the development of rocket engine pumps and turbines. Such
facilities are designed to subject the applicable hardware to the total
range of operating conditions required to prove that these components
have achieved the design performance and reasonable operability before
risking testing of the complete engine system. Use of such facilities
allowed detailed measurement of performance, stresses and temperatures
without restrictions imposed by the limitations of other engine system
components. Thus the testing could be designed to define the strong and
weak characteristics of the component, as well as to assess the margin
for error available when the component was integrated into the system.
Generally, this approach minimized costs incurred from damage to other
engine system parts if failure occurred.

With the growing complexity of rocket systems, component test
facilities have also become more complex and more expensive, often be-
coming developmental efforts in themselves. Lead times required to
design, procure and "debug" such facilities are often measured in years
and thus become a major item in planning for the acquisition of a rocket
engine.

Space Shuttle Main Engine Approach

Early Space Shuttle Main Engine program planning was predicated on
the construction and use of a component test facility. However, efforts
to use the facility proved to be difficult, expensive and not very fruit-
ful in terms of acquiring useful turbo machinery information. Figure
A-1 summarizes the accomplishments in terms of the test and running time
over a 27-month time. Normally, such testing for past rocket develop-
ments would have accumulated at least 10 times more testing. Late in
the past year, this approach was abandoned. Future turbo machinery
testing is to be accomplished only on engine test stands using the in-
tegrated engine assembly as the test fixture.

SUMMARY OF TESTING AT COCA-1 FACILITY

Initiated May 1, 1975 · Concluded Sept. 12, 1977

	Tests	Sec	Assemblies Tested
COCA 1A			
LPOTP	15	706	4
LPOTP-HPOTP	24	161	3
COCA 1B			
LPFTP	47	2192	6
LPFTP-HPFTP	27	111	6

Source: Rocketdyne Division Rockwell International

Figure A-1

Results

Because of the lack of a successful turbo machinery test facility, characterization and verification of the high pressure pump designs is a pacing item in the development schedule. Some problems have been identified during engine testing and efforts for their solution are now underway, as shown in Figures A-2 and A-3. Some of these problems must be solved before the hardware to be used for the first manned orbital flight can be tested on the engine. Because of the interaction of the various components of the engine and the multiplicity of modified designs yet to be proven, the committee judges that development testing could take longer than the current schedule allows. Further no apparent adjustment to work plans on the test stands or provision of additional hardware to accommodate the shift of turbo machinery development testing to the complete engine was detected.

Analysis

With current developmental testing behind schedule and many redesigns still to be added to the system and proven, it is prudent to focus on the acquisition of an engine configuration suitable for early flights, thus minimizing potential shuttle program delays. It is time to consider the establishment of an interim engine developmental goal (see Figure A-4) (Block I design) with performance and life limited to that adequate for safe early flights. Planning for the acquisition of a final (Block II) design to attain the final performance and life characteristics should begin immediately. Such thinking fits into current schedule projections by NASA and the contractor as shown by Figure A-4 on which the committee has added possible Block I and Block II breakpoints.

SSME CONFIGURATION BASELINE

MPTA (1-4)

- **HPOTP (HIGH PRESSURE OXYGEN TURBOPUMP)**
  - Improved Balance—Reduced Synchronous Radial Loads
  - Increased Bearing Preload
  - Improved Turbine Bearing Coolant Flow

- **HPFTP (HIGH PRESSURE FUEL TURBOPUMP)**
  - Existing Heavy Turbine Blade Dampers
  - Existing Turbine Platform Seals
  - Turbine Blade Damper Side Platform Coating
  - Bradelloy Turbine Tip Seal

- **LOW PRESSURE LIQUID OXYGEN DUCT**
  - Existing Design
    - Life Limited—2780 Seconds
    - Limited—$2°$ Gimballing @ 90%

Source: Rocketdyne Division Rockwell International

Figure A-2

SSME CONFIGURATION CHANGES—STEP 1

MPTA (5-7)

- HPFTP

  - Machined Damper Precision Fit-Up

  - Faired Turbine Struts

  - Six Segment Rene'/Nickel Turbine Tip Seal

  - Modified Leading Edge Turbine Platform Seals

  - Damper Contact Platform Coating Removed

- LOX PRESSURE LOX DUCT

  - Interim Design Flex Joints

    - Life Limited—4500 Seconds

    - Full Gimballing

- FUEL TURBINE TEMPERATURE REDUCTION

  - Rebalance Preburner Injector Resistances—70°

Source: Rocketdyne Division Rockwell International

Figure A-3

SSME CONFIGURATION VERIFICATION

Timeline markers: PFC-FMOF ▽ | PFC ▽ | FFC ▽

	1977	1978				1979				1980	
	4	1	2	3	4	1	2	3	4	1	2

R&D PROGRAM: 1-4 | 5-7 | 8-13 / FIRST FLIGHT | LONG TERM

MPTA PROGRAM: 1-4 | 5-7 | 8-13
FIRST FLIGHT SET ▽

FLIGHT PROGRAM: BLOCK I → ← BLOCK II →

OPERATING COND.				
• PERCENT RPL, %	90	90-100	109	109
• HPFT INLET TEMP, R	1830	1815	1900	1735
• HPOT INLET TEMP, R	1400	1525	1585	1500
• HPFT SPEED, RPM	32,700	34,900	37,200	37,600
• HPOT SPEED, RPM	25,500	27,300	29,400	29,900
• PROP. INLET COND.	MPTA	MPTA	FLIGHT	FLIGHT
CAPABILITY				
• POGO SYSTEM	NONE	YES	YES	YES
• GIMBAL	NONE	FULL	FULL	FULL
• LIFE, SECONDS	700	4500	4500	12,600
• COMPONENT LIMITING	HPFT TURBINE	LOW PR. LOX DUCT	LOW PR. LOX DUCT	DEMONSTRATION

Source: Rocketdyne Division Rockwell International

Figure A-4

31

APPENDIX   B

NOTES ON
HIGH-PRESSURE FUEL TURBOPUMP TURBINE BLADE FAILURES

By

William Rostoker

During operation at rated power level of the space shuttle main engine
a problem in the high-pressure fuel turbopump (HPFTP) became apparent.
Two pump failures are clearly due to failure of one or two turbine
blades. A third failure is attributed to a blade failure, but no
direct evidence is available. Rather, the evidence is a loss of
turbine power. The status of each blade failure incident is tabulated
below.

1.	T/P	0202 R1	8 starts & stops	330 sec	original design
2.	TEST	95	38 " "	2,976 sec	coated blades
3.	T/P	0202 R4	21	4,325 (A)	coated
			11	2,356 (B)	"

    NOTE: A   47 blades with this usage
                B   16   "   "   "   "

In the first case the failure was attributed to damper lock-up. Calcu-
lation suggests the mean stress to be in the neighborhood of 55,000
pounds per square inch in this condition. Two blades were cracked; no
separation occurred.

        In the second case damper lock-up was also alleged to be the cause.
The physical reason for the second failure is different from the first.

        In the third case the pump was destroyed so no detailed evidence
existed.

        Blade material: MAR-M-246, hafnium modified, directionally
solidified (DS). Operating temperature: 1600-1700° F gas temperature
with temperature spikes over 2000° F.

        Environment: hydrogen and steam, with blades subject to steady
stress (centrifugal) plus vibratory stresses due to turbulence
associated with struts supporting the main shaft bearing and the inlet
guide vanes. The vibratory component of stress is to be reduced by a
damper device between the turbine blades. The blades are subject to
high-frequency fluctuating stresses superimposed on a large static
stress level leading to a high cycle fatigue possibility. Blades also

32

are subject to a hydrogen quench at the end of a burn leading to
thermal fatigue crack possibilities

Three sets of turbine blade failures:

1. T/P 0202 R1
   uncoated blades, original turbine design, 330 sec. total
   run involving 8 starts and stops. Blade platform and
   tree root gold-plated to reduce H_2 absorption. Damper
   surfaces Ni plated.

   Two blades discovered with cracks but no severence - one
   crack started at the leading edge, near the base of air-
   foil. Another crack started at the trailing edge,
   higher up from the base. Cracks ran across the grain.

   Reputed reason for cracking: damping eliminated because
   Au-Ni fused the blades together.

2. Test 95

   Coated blades (NiCrAlY (0.003") + ZrO_2 (0.004")
   No Au coating. Ni coating on damper surfaces. 2976 sec.
   total run - 38 starts and stops.

   One fractured blade - crack started at leading edge near
   base of airfoil.

   One cracked blade (3 blades away) at same location.

   Reputed reason for cracking: temperature spike over
   2100° F - 1 sec allowed softened Ni coat to extrude up
   into space between damper and blade causing seizing and
   elimination of damper action.

3. T/P 0202 R4

   Test 147, coated blades, no Au, no Ni coatings
   Mix of blades: 47 - with 4,325 sec life (21 starts & stops)
                   16 - with 2,356 sec life (11 starts & stops)
   The replacement of 16 blades because of thermal fatigue
   cracks in the platform although no failures had occurred
   there. Pump lost power, ceased to pump H_2 although O_2 flow
   continued. Hot turbine + O_2 led to catastrophic oxidation
   and melting. Blade evidences obliterated. No way of
   knowing if a blade fracture began the events.

Fracture and Crack Appearances

Initiation (Stage I) flat, cleavage like, transgranular basically
same appearance as in laboratory high cycle fatigue tests. Hence

deduced as high cycle fatigue fracture. Thermal fatigue does not seem to be an initiating factor. Fatigue cracks do appear on the platform but not on the leading or trailing edges.

Fatigue cracks progress nearly halfway across the blade before fast fracture takes over.

Crack or Fracture Frequency

1. T/P 0202 R1
   2 cracked blades. 61 uncracked blades in first stage
   100% inspection showed no visible cracks in the 61.

2. Test 95

   2 cracked blades, 61 uncracked blades in first stage (100% inspection) at 639 sec (13 starts and stops) full inspection showed no cracks in any blade.

3. T/P 0202 R4

   At 2,000 sec (2,356 sec before failure) all 63 blades in the first stage were crack-free in airfoil, although there were thermal fatigue cracks in the platform.

Discussion

There have never been more than 2 cracked blades among the 63 in the first stage. There are two possible interpretations that can be inferred:

a. Two blades out of 63 contained microscopic crack-like flaws that escaped detection. Quality control by the supplier requires flaw detection by dye penetrant (0.010 in resolution), X-ray radiographic and visual. These are not likely to detect microscopic, especially sub-surface, flaws.

b. Two blades failed out of 63 represent the normal low probability of early failure in a distribution of failure lives that spans over a ten-fold range.

Actually a. and b. are the same. The random occurrence of microscopic flaws not detectable by present art provides for the wide range of fatigue levels of normally identical products. At the time of early failure, possible cracks in the remainder could still be too small to be resolvable.

Rocketdyne staff are inclined to accept the range of high cycle fatigue resistance as state-of-the-art for turbine blades. Elimination of such microscopic flaws as shrinkage porosity, non-metallic inclusions and carbide networks are not expected to be feasible or necessary. They expect to eliminate early fractures by reducing the

fluctuating stress component by redesigning the struts in the hot gas inlet and by redesigning the dampers between blades to more efficiently reduce fluctuating stresses.

Note that no blade failures (fracture or cracking) have been observed in the second stage although the static (centrifugal) stresses are the same. However, the gas temperature is lower but the primary reputed difference is that the dynamic stress components are much less than in the first stage.

An important but lost study opportunity would have been to analyze, experimentally, the reduced fatigue life of the surviving, uncracked blades. This would have demonstrated whether sub-microscopic cracks had developed but were beyond resolution or that the blades were not of reduced fatigue life -- in which case the two failed blades (in each case) must have been flawed.

Conclusions

1. Coatings are not an issue in blade cracking.

2. Thermal fatigue is not an issue in blade cracking.

3. The DS MAR-M-246 hafnium-modified material is probably as good a blade alloy as laboratory testing will indicate.

4. The quality of casting and the sensitivity of quality control is limited so that high cycle fatigue performance has a large range, i.e., fatigue life at a given stress fluctuation can vary from shortest to longest by a factor of ten. This statement represents the state-of-the-art.

5. The turbulence-generated fluctuating stress component should be reduced by modified strut design, if possible.

6. Re-designing the damper will probably reduce the fluctuating stress component on the leading edge as well as the trailing edge of the airfoil, but this cannot be verified until full testing of a single engine is completed.

7. Unless there is a new approach to screening and rejecting potentially low performance blades (high cycle fatigue) and unless the cycle service stresses can be reduced, the expectation of reducing fatigue failures to zero for the life of the turbine is not optimistic. The evidence is not adequate to determine any metallurgical hypothesis for failure. It could be due to a non-detectable flaw that is to be expected in the tail of the distributor functions or it could be due to a flaw that is a result of lack of procedural control. The characterizations

of the material, particularly the spread in the fatigue behavior, are incomplete and should be completed.

8. The blades are less likely to be a problem if the temperature is reduced 350-500° F., as proposed by the contractor.