NASA Technical Memorandum 86969

Advanced Research and Technology Programs for Advanced High-Pressure Oxygen-Hydrogen Rocket Propulsion

S.J. Marsik
Lewis Research Center
Cleveland, Ohio

and

S.F. Morea
Marshall Space Flight Center
Huntsville, Alabama

(NASA-TM-86969) ADVANCED RESEARCH AND TECHNOLOGY PROGRAMS FOR ADVANCED HIGH-PRESSURE OXYGEN-HYDROGEN ROCKET PROPULSION (NASA) 14 p HC A02/MF A01 CSCL 20H G3/15
N85-21231
Unclas
14532

Prepared for the
1985 JANNAF Propulsion Meeting
sponsored by the JANNAF Interagency Propulsion Committee
San Diego, California, April 9-12, 1985

NASA

④

ADVANCED RESEARCH AND TECHNOLOGY PROGRAM FOR ADVANCED HIGH PRESSURE OXYGEN-HYDROGEN ROCKET PROPULSION

S.J. Marsik
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

S.F. Morea
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

A research and technology program for advanced high pressure, oxygen-hydrogen rocket propulsion technology is presently being pursued by the National Aeronautics and Space Administration (NASA) to establish the basic discipline technologies, develop the analytical tools and establish the data base necessary for an orderly evolution of the staged combustion reusable rocket engine. The need for the program is based on the premise that the USA will depend on the Shuttle and its derivative versions as its principal earth-to-orbit transportation system for the next 20 to 30 yr.

The program is focused in three principal areas of enhancement: (a) life extension, (b) performance and (c) operations and diagnosis. Within the technological disciplines the efforts include: rotordynamics, structural dynamics, fluid and gas dynamics, materials fatigue/fracture/life, turbomachinery fluid mechanics, ignition/combustion processes, manufacturing/producibility/nondestructive evaluation methods and materials development/evaluation.

The paper presents an overview of the Advanced High Pressure Oxygen-Hydrogen Rocket Propulsion Technology Program Structure and Working Groups objectives with highlights of several significant achievements.

E-2495

INTRODUCTION

The Space Shuttle Main Engine (SSME) is operational and has been performing in an excellent manner. However, the SSME was designed for reusability and long life as well as high performance. It is in the reusability and life areas that technology work remains to be done. The design specifications of the engine are shown in Fig. 1.

The high performance of the engine is attained by the use of a staged combustion power cycle, coupled with high combustion chamber pressure. Referring to the SSME powerhead components (Fig. 2), the propellants are partially burned at a low mixture ratio high pressure and relatively low temperature in the preburners to produce hydrogen-rich gas (steam) which powers the high performance turbopumps. The hydrogen-rich gas is then directed to the main injector, where it is injected along with additional oxidizer and small amount of fuel, into the main combustion chamber at high mixture ratio. The propellant flow, temperatures and pressures in various sections of the engine are shown in Fig. 3. Details of the SSME operation can be obtained from Ref. 1.

The design of the SSME and its hardware were based on the state-of-the-art at the time of its development. It became evident from the operational experience that the expectations for the initial hardware were too optimistic. Improvements are needed in all sensitive areas and sections of the engine to bring its life expectancy to the design requirements. They are also needed to enhance the engine performance in order to increase operating margins at the upper end of the thrust range and to improve diagnostics in its operations/maintenance in an effort to reduce the turnaround time in the flight schedule. Most of the needed improvements in the SSME engine require an improved technological base. Therefore, NASA instituted a research and technology program for advanced high pressure, oxygen-hydrogen rocket propulsion.

This paper describes the technology program. It provides a brief description of the program structure and elaborates on the technical effort by providing specific objectives for each discipline within the program, by summarizing individual work elements within each discipline and by highlighting several significant achievements within the scope of effort of the program.

PROGRAM ORGANIZATION

Based on the premise that the U.S. will depend on the Shuttle and its derivative versions as its principal Earth-to-Orbit transportation system for the next several decades, NASA instituted, in

Approved for public release; distribution is unlimited.

1981, a new technology program. The overall objective of the program is to establish the basic discipline technology necessary for an orderly evolution of high pressure, oxygen/hydrogen staged combustion reusable rocket engines in general, and the SSME in particular. Thus, the work areas within the program deal with investigation, development and definition necessary to formulate improved designs and techniques to upgrade performance, extend life, reduce operations cost, lower weight and improve the functional capability of the main propulsion engines. The program is also directed to support the continued development and operation of the space transportation system and its derivative engines. To achieve the objective the technology program focuses on three principal areas: (a) Life Extension Enhancement, (b) Performance Enhancement and (c) Operations/Diagnostics Enhancements. The objectives of each focus are pursued within a series of disciplinary working groups. The working group structure is shown in Fig. 4. The responsibility of each working group is to formulate and maintain a long-range plan for the respective discipline, assure its implementation, monitor progress and initiate action as necessary to achieve the objectives. Each working group draws its members from both the technology users who establish needs and focus priorities, and technology developers who identify opportunities. Responsibility for the overall accomplishment of the program, under cognizance of the Propulsion, Power and Energy Division of the Office of Aeronautics and Space Technology has been assigned to the Marshall Space Flight Center, Huntsville, Alabama, with the assistance of the Lewis Research Center, Cleveland, Ohio. The overall functional relationship of the program is shown in Fig. 5.

WORKING GROUPS OBJECTIVES AND HIGHLIGHTS OF SIGNIFICANT ACHIEVEMENTS

The technical portion of the technology program is carried out in the working groups as indicated in Fig. 4. The working groups plans comprise some 130 Work Elements. These elements are approximately equally divided between the short-range direction of improving the cost per flight through components life enhancement and providing modest uprating capability, and the long-range direction of performance improvement and multiple applications. Both short-range and long-range elements can be found in each working group. General objective of each working group with a summary of work elements pursuing the objective are given below. Included in the description of the Working Groups effort are highlights of representative work elements which are in various stages of progress.

WORKING GROUP A - BEARINGS

The evolution of cryogenic turbopumps to support fully reusable chemical rocket propulsion has placed new demands on bearings. Experience with conventional rolling element bearings in the SSME turbopump confirms previous analytical predictions that the life of this type of bearing will fall far short of the reusability goals. While some improvements may come through the use of better materials, the major improvement in life requires methods which will reduce either bearing speed or the bearing load.

The objective of this working group is to advance the state-of-the-art in bearing technology, primarily cryogenic turbomachinery bearing technology, by exploring the life and performance effects of design changes, design concept changes, materials changes, manufacturing technique changes and lubrication system changes.

Major effort of the working group is focused on improved producibility of rolling element bearings through ion plating of materials, surface ion implantation, powder metallurgy techniques, as well as development of new design concepts such as magnetic bearings, hydrostatic bearings and hybrid bearings.

Hybrid Bearings for LH_2 and LO_2 Turbopumps. One of the work elements which promises a large benefit is the development of a hybrid bearing. This bearing consists of a combination of hydrostatic and ball bearings which can be combined to share either speed or load. The two concepts of a hybrid bearing (i.e., parallel speed and parallel load), can be seen in Fig. 6. Reduction of either the speed or the load on the ball bearing portion through the transfer of these parameters to the hydrostatic portion will dramatically improve the bearing life in rocket engine turbopump applications.[2,3]

WORKING GROUP B - STRUCTURAL DYNAMICS

Development of the current generation of the O_2/H_2 propulsion systems has been characterized by several structural failures, primarily due to higher cycle fatigue (HCF). A number of these failures have been solved by trial and error. However, as even higher performance systems are being planned, better knowledge of the system dynamic response is required.

The objective of this working group is to develop improved understanding of the operating dynamic characteristics of high-performance liquid rocket systems in order to: increase lifetime and performance, decrease weight, identify incipient failures, meet deflection requirements, predict effect of proposed changes, determine changes to meet specified requirements and decrease costs.

To achieve the objective, the majority of the effort in this working group is directed toward development of analytical tools and methodology that would allow accurate prediction of the structural response and accompanying local stresses caused by complex thermal and mechanical loads, leading to fatigue and failure in space propulsion structural components. The goal is to develop generic models of the composite load spectra formed in turbomachinery, probabilistic structural analysis formulations and statistical models of structures. The models will be based on the SSME environment and on data from nonreusable rocket engines.

WORKING GROUP C - ROTORDYNAMICS

Many SSME turbomachinery failures can be attributed to a lack of understanding of the dynamic behavior of the rotor and the forces acting upon it. Rotor instability, high bearing loads and excessive rotor deflections with rubbing have been some of the problems encountered in the early SSME operations.

The objective of this working group is to define the way in which high bearing loads and rotor deflections occur in high pressure, cryogenic turbomachinery, to describe more accurately and completely the forces which interact with the rotor and surroundings, and to define design requirements for turbomachinery components which influence rotordynamics loads, deflections and stability.

To achieve the objective, a portion of the effort is devoted to the development of analytical and simulation techniques for better understanding of rotordynamic forces and their effects on bearings, turbine/case interactions and rubbing in turbopumps. Other work elements in this working group pursue investigation of: (1) configuration modifications which reduce relative rotor assembly movement and dynamic balancing, (2) verification of dynamic characteristics of damping seals, (3) derivation of whirl parameters of internal rotor friction caused by press fits and splines, and (4) application of eddy current damping technology in cryogenic turbopumps.

Eddy Current Damping Technology. A unique method of dissipating vibrational energy caused by rotor instability is by means of eddy current generation in a nonferrous conductor caused to vibrate in a magnetic flux field. Eddy current damping can be effective in controlling both the synchronous and nonsynchronous whirl, thus reducing dependence on ultra precision balancing or the need for frequent rebalancing. Furthermore, if properly located and with properly designed bearing support, it can reduce the magnitude of forces transmitted through the bearings to the casing, resulting in bearing life extension. A successful attenuation of synchronous vibration of a stiff unbalanced rotor shaft using passive eddy current damping has been demonstrated.[4]

WORKING GROUP D - TURBOMACHINERY FLUID MECHANICS

Many SSME turbomachinery problems can be attributed to designs resulting from lack of understanding of the fluid flow environment in critical areas such as seals, pump impellers, turbine blades, etc.

The objective of this working group is to advance technology in turbomachinery fluid mechanics and provide sufficient analytical tool for future advanced designs. Therefore, the major portion of the effort is focused on investigation of turbopump characteristics from low blade speed to steady state conditions. This investigation will provide better understanding of transient as well as steady state modeling. The rest of the effort is devoted to defining of fluid forces on impellers, dynamic characteristics of bushing, labyrinth and floating-ring seals and the investigation of rubbing tolerances.

Compressible Fluid Dynamic Seal Test Facility. At the threshold of major accomplishment in the Turbomachinery Fluid Mechanics Working Group is the establishment of a Computer-Integrated Compressible Fluid Dynamic Seal Test Facility located on the campus of the Texas A&M University. This facility is uniquely equipped to analyze and evaluate seal dynamics (i.e., axial pressure distribution, leakage, direct and cross-coupled stiffness and damping) of existing seals as well as to predict the dynamics of future designs, thus aiding in optimization of these designs.

Currently the facility is operational at 8,000 rpm; flow rate of 950 cfm; and 100 psig pressure in air. Four seal configurations (constant clearance, tapered, honeycomb, labyrinth) have been tested and data for seal stiffness, damping and cross-coupling have been obtained. Existing modeling appears good for constant clearance seal but is only marginal for tapered seal. Honeycomb and labyrinth seal models require significant modification.

WORKING GROUP F - FATIGUE/FRACTURE/LIFE

The Space Shuttle Program requires a safe and durable reusable propulsion system with extremely high performance. Present analytical procedures used for life prediction which utilize the flow growth concept, either do not consider conditions required by the SSME or are too simplistic in their approach to yield the desired accuracy.

The objective of this working group is to improve the life predictions of various fracture-critical parts by improving existing, or developing new, analytical tools which will be verified by testing, and also to extend life by material enhancement techniques.

The majority of the effort in this working group is directed toward understanding and developing analytical models of low cycle fatigue/high cycle fatigue interactions and their effects on fracture mechanism, creep-fatigue conditions and interactions, environmental contributions to fatigue, and resultant cumulative fatigue damage. Effort is also devoted to the development of a method for fatigue life extension through periodic restoration of a fatigue-damaged surface to its original condition.

WORKING GROUP G - IGNITION/COMBUSTION PROCESSES

Development experience has indicated areas of potential advancement in combustion dynamic prediction codes and experimental evaluation techniques aimed at improving life and increasing operational limits.

The objective of this working group is to extend the state-of-the-art of main combustion chambers/injectors and turbine drive combustor with emphasis on operational and service life problem areas exposed during SSME development. To achieve the objective, the effort of this group is focused on improvements and verification of combustion codes, enhancement in main chamber combustion and cooling technology, development of analytical tools for reliable thrust chamber life prediction and extension of current dual throat technology to advanced SSME applications.

Thrust Chamber Life Prediction and Life Enhanced Design. The main combustion chamber (MCC) of the SSME is exposed to an environment that produces high heat fluxes in the life-limited throat region. To accommodate these fluxes, the copper base MCC liner is regeneratively cooled through integral rectangular cooling channels. During operation, large transient thermal gradients subject the MCC liner to large thermoplastic cyclic strains which in turn influence the fatigue life of the liner hot gas wall.

Life predictions based on the low cycle thermal fatigue failure mechanism were generally unsuccessful when subjected to test verfications. During hot-fire testing of channel wall combustors at NASA Lewis Research Center and at Rocketdyne (Rockwell International Corp.), it was determined that cyclic operation results in a permanent mid-channel deformation and wall thinning. This thinning phenomenon is termed cyclic material creep and appears to be significantly accelerated at elevated temperatures. Based on these results, it was decided that an improved analytical method, which models the observed cyclic creep, was needed for life prediction capability. Such a method in which the chamber finite element geometry is updated periodically to account for accrued wall thinning and distortion was developed.[5]

WORKING GROUP H - FLUID AND GAS DYNAMICS

SSME development results point to a lack of data for the gas dynamic environment. Premature nozzle tube splits, injector tube bending and cracks, bellows shield cracks and face plate cracking are evidence of this lack of definition.

The objective of this working group is to obtain clearer understanding of the interaction of the thermal behavior, flow behavior and material behavior in the hot gas duct systems and thrust chamber nozzle, for the purpose of finding ways to increase the life and the performance of these systems.

To achieve the objective, the major portion of the effort in this group is devoted to the development and verification of analytical models for reliable predictions in fluid/structural interactions, pressure fluctuations in nonhomogenous flows, multifluid mixing and turbulence, thermal and chemistry effects in rocket engine subsystems, high and low frequency unsteady aerodynamic environments and three-dimensional viscous flow field through turbine stages. A substantial amount of effort is devoted to understanding the distribution of flow parameters in parallel multiple transfer ducts under varying upstream and downstream conditions, and to understanding of the fluctuating pressure field in the discharge of turbines and pumps under varying boundary conditions. Effort is also devoted to experimental determination of boundary layer behavior on turbine vanes and blades and the determination of temperatures and pressures on rotating turbine blades.

Duct Flow Nonuniformity Study. The hydrogen-rich gas from both SSME turbopumps is routed through five hot-gas transfer ducts into the main injector. Three ducts are on the fuel side and two on the oxidizer side. During the steady state operation of the engine, about 70 percent of the hot-gas flow is routed through the fuel side and remaining 30 percent is passed through the oxidizer side.

It became apparent early in the development that the distribution at the exit of the Hot Gas Manifold (HGM) fuel side duct was nonuniform with large flow separation in the lower half of the center transfer duct and smaller separation regions at the inner walls of the outer transfer ducts. These nonuniformities at the exit of the fuel side of the HGM produce local high velocity flow regions resulting in high aerodynamic forces on the main injector liquid oxygen (LOX) posts. Nonuniformities in the back pressure sensed by the high-pressure fuel turbine resulted in oscillatory loads on the turbine blades.

An evaluation of the fuel-side portion of the system, through analytical as well as experimental effort was undertaken and directed toward improving the overall flow distribution in the SSME HGM. The effort resulted in a proposal to change the design from the current three-duct transfer to a two-duct transfer along with accompanying modifications in the geometry of the system. The three-dimensional viscous flow numerical analysis showing a significant improvement in flow distribution in a two-duct system was subsequently verified experimentally.[6,7]

Similar effort was devoted to an evaluation of the fuel turbopump exhaust and the turnaround duct (TAD) at the exit of the turbine. The analytical results of the flow in the TAD indicated three regions with potential separation. Also the study of the geometry effects has shown that by optimizing wall curvature and flow diffusion in the turnaround, improved duct performance can be achieved.[8]

WORKING GROUP J - INSTRUMENTATION

The service life and performance requirements of the SSME are severely testing some of the state-of-the-art diagnostic and monitoring equipment.

The objective of the Instrumentation Technology Program is to advance the state-of-the-art of instrumentation associated with the SSME to improve service life and performance by providing increased measurement capability and to reduce operational costs by eliminating unnecessary inspection and premature replacement of components.

There are two broad categories of instrumentation being investigated in this program. One category focuses on development of sensors and systems intended to become an integral part of the engine during operations and/or maintenance. The purpose of these instruments is to provide information necessary for engine control and/or diagnostics throughout the life of the engine. The other category focuses on instrumentation systems and techniques whose application is primarily intended for engine component test stands and/or the test bed engine. The main purpose of these instruments is to provide reliable detailed information for verification of analytical models being developed under this technology program.

Research of Pressure Instrumentation. Improved performance of the SSME engine control and analysis depends on more reliable and accurate pressure sensing in a wide range of temperatures, pressures and vibration.

The performance and survivability of a solid state (silicon) piezoresistive pressure transducer have been successfully demonstrated at liquid nitrogen temperature and at high pressure. The transducer design concept for the SSME application utilizes packaging materials with similar thermal coefficients of expansion and maintains the transducer seals primarily in compression.[9] Successful completion of this effort will provide the technology base for the development of space qualified advanced pressure transducer hardware for the current Space Shuttle as well as future space vehicles.

Reusable Engine Maintenance and Instrumentation. The ever-increasing demands placed on rocket engine performance and life expectancy establish the need to develop and incorporate a condition monitoring system (CMS) into the engine. Such a system will result in significant reductions in maintenance costs and turnaround times. A large number of in-flight and between flight measurements and analyses will be required for a full scale CMS.

It has been established that turbopump rotor bearings and turbine blades are the most critical elements in limiting turbopump life. Therefore, in the current effort three technologies were selected to be developed to monitor the bearings and turbine blades: (a) isotope wear detector, (b) fiberoptic deflectometer, (c) fiberoptic pyrometer.[10] In addition, design modifications to current configuration SSME high pressure turbopumps are being developed for incorporation of the sensors. Signal processing algorithms were evaluated and ranked for their utility in providing useful component health data.

WORKING GROUP L - MANUFACTURING/PRODUCIBILITY/INSPECTION

The objective of this working group is to develop and evaluate manufacturing techniques for advanced propulsion hardware and selected materials, to optimize producibility of SSME components and assemblies and to improve production and in-service nondestructive inspection and testing.

The work elements in this group include: vacuum plasma coating process for turbopump components (i.e., blades, discs, heat shields, etc.) and combustion chamber walls; advanced welding techniques (i.e., plasma arc, variable polarity plasma process, laser welding, inertia welding, etc.); evaluation of ceramic materials for high temperature LOX/H_2 engine components; advanced nondestructive evaluation and inspection techniques.

Vacuum Plasma Coating Process. Improved thermal barrier coatings offer significant potential to increase service life by reducing leading edge erosion, protecting the substrate from temperature spiking, minimizing spalling and lowering the incidence of radial airfoil cracks. These thermal barrier coatings also offer improvements in operating performance by providing protection from hydrogen embrittlement or improved thermal resistance to elevated engine temperatures.

An application of a low pressure plasma coating of a 50/50 blend of Cr_2O_3 and NiCrAlY on SSME high pressure fuel turbopump turbine blades provided a significant improvement in durability and thermal protection when tested in a simulated service environment.[11]

WORKING GROUP M - MATERIALS DEVELOPMENT/EVALUATION

Historically, rocket engine materials have been drawn from a pool of alloys developed for use in air-breathing engines. Years of successful operations using a disposable rocket engine justified such a practice. However, the requirement for reusability and the service life corresponding to the Space Shuttle requirement requires re-examination of the selection of materials. Several comparisons of operating characteristics between representative rocket engine and aircraft gas turbine are shown in Table 1.

Since the development and evaluation of materials appears to be the fundamental building block in the development of advanced engine, the objective of this working group is rather board; - to develop and evaluate candidate materials for application in advanced high pressure O_2/H_2 propulsion systems. Therefore, work elements within this working group encompass: compatibility of materials with SSMElike environment for hydrogen embrittlement and ignition of materials in oxygen by rubbing contact, etc.; advanced materials for turbopump components, i.e., blades, vanes, turbine disk, bearings, etc.; evaluation of ceramics materials for rocket engine.

Better Materials for Rocket Engine Turbine Blades. A study was conducted by Rocketdyne (Rockwell International) to evaluate six classes of candidate materials for turbine blade life enhancement and/or evolutionary performance enhancement of the SSME turbopumps. The material classes evaluated were: (a) single crystal and advanced single crystal alloys; (b) directionally solidified eutectic superalloys; (c) oxide dispersion-strengthened superalloys; (d) rapid solidification processed superalloys; (e) fiber reinforced superalloy composites; and (f) structural ceramics. The effort focused on the three key material properties indicative of the operational life for an SSME turbine blade: (1) stress-rupture strength; (2) mean stress high-cycle fatigue strength; (3) thermal strain low-cycle fatigue strength.

The study identified advanced single crystal alloys, i.e., high thermal gradient directionally solidified or post solidification hot isostatic pressing of conventionally processed single crystal alloy, as a class of materials which would enhance the SSME turbine blade durability by tenfold with the current turbine design (i.e., retrofit) and current operating conditions. The study also identified fiber reinforced superalloys (FRS) as a blade material which could produce higher engine performance by allowing the turbine to operate at a 400 °F increased temperature, while still providing an increase in durability of approximately twentyfold (Fig. 7).[12] However, the use of FRS materials would require a modification in the design of the turbine wheel to accommodate the blade mounting.

Both the advanced single crystal and the fiber reinforced superalloys approach are being pursued in the development of new turbine blades. It appears that the advanced single crystal blades could be retrofitted into the current design of the SSME turbopump in the late 1980's. Blade fabricated from FRS materials could be available for use in the early 1990's.

CONCLUDING REMARKS

The Advanced Research and Technology Program for Advanced High Pressure Oxygen-Hydrogen Rocket Propulsion, was instituted by the National Aeronautics and Space Administration, to develop new technology which would enable enhancement in both the life and performance of the existing system as well as provide a basis for improved future designs. The program is developing hardware and generic analytical tools in each disciplinary working group within the program.

The following examples are representative of working group efforts:

(1) Cryogenic hybrid bearings (i.e., combination of hydrostatic and rolling elements).
(2) Improved methods in rotordynamic balancing and damping in turbomachinery.

(3) Optimization in design of compressible fluid seals (a facility for evaluation of dynamic seal characteristics in now available).
(4) Improved analytical tools for fatigue/fracture/life and structural dynamics evaluation and prediction.
(5) Improved analytical tools for aerothermal loads for turbomachinery, transfer ducts and fuel injector evaluation and prediction.
(6) Improved life for main combustion chambers.
(7) Improved turbine blades and vanes using thermal barrier coatings.
(8) Single crystal and advanced single crystal turbine blades for life enhancement.
(9) Fiber reinforced superalloy rocket engine components for life and performance enhancement.
(10) Advanced instrumentation, control, health monitoring for enhanced performance and improved economy.

REFERENCES

1. Space Transportation System Technical Manual - Space Shuttle Main Engine. RSS-8559-1-1-1, Rocketdyne Division, Rockwell International Corp., Sept. 1983.

2. Hannum, N.P.; and Nelson, C.E.: The Performance and Application of High Speed Long Life LH_2 Hybrid Bearings for Reusable Rocket Engine Turbomachinery: NASA TM-83417, 1983.

3. Butner, M.F.; and Lee, F.C.: Hybrid Bearings for LH_2 and LO_2 Turbopumps. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 119-131.

4. Cunningham, Robert E.: Preliminary Results of Passive Eddy Current Damper Technology for SSME Turbomachinery. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 194-198.

5. Kasper, Harold J.: Thrust Chamber Life Prediction. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 27-30.

6. Pelaccio, D.G., et al.: Experimental Evaluation of an Advanced Space Shuttle Main Engine Hot-Gas Manifold Design Concept. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 264-281.

7. Thoenes, J., et al.: Numerical Analysis of Flow Non-Uniformity in the Hot Gas Manifold of the Space Shuttle Main Engine. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 282-287.

8. McLallin, Kerry L.: Analytical Study of Flow Phenomena in SSME Turnaround Duct Geometries. Proceeding of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 298-308.

9. Johnson, R.L., and Wamstad, D.B.: An Advanced Solid State Pressure Transducer for High Reliability SSME Application. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 320-331.

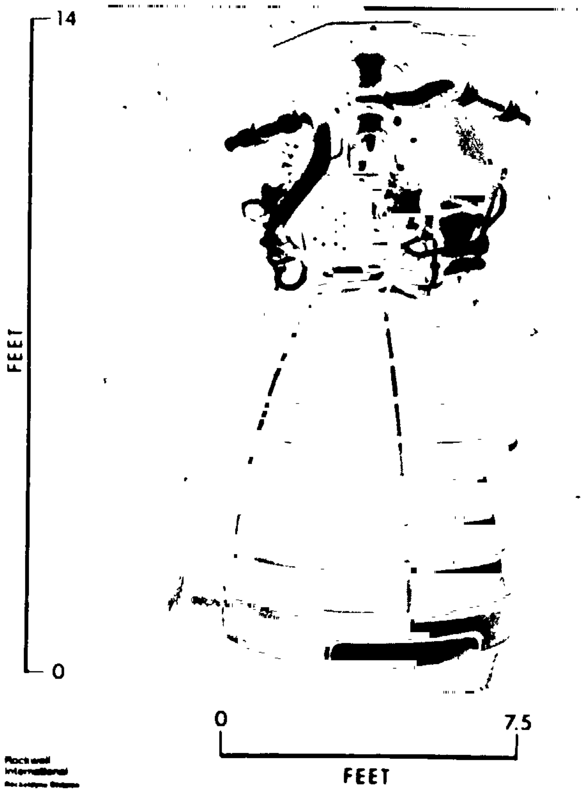
10. Hampson, M.E.; and Barkhoudarian, S.: Reusable Rocket Engine Turbopump Condition Monitoring. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 339-348.

11. Holmes, Richard R.: Vacuum Plasma Coatings for Turbine Blades. Proceedings of MSFC Advanced High Pressure O_2/H_2 Technology Conference, S.F. Morea and S.T. Wu, eds., Univ. of Alabama, 1984, pp. 46-54.

12. Chandler, W.T.: Materials for Advanced Rocket Engine Turbopump Turbine BLades. (RI/RD83-207, Rocketdyne; NASA Contract NAS3-23536.) NASA CR-174729, 1983.

TABLE I. - COMPARISON OF OPERATING CHARACTERISTICS BETWEEN ROCKET ENGINE TURBINES AND AIRCRAFT GAS TURBINES

Item	Rocket engine turbines	Aircraft gas turbines
Fuel	Hydrogen or CH_4	Petroleum distillate
Oxidizer	Oxygen	Air
Operating speed, rpm	up to 110 000	15 000
Blade tip speed, ft/sec	1 850	1 850
Horsepower/blade	700	200 - 470
Turbine inlet temp, R	up to 2 160 R (uncooled)	2 600 (uncooled)
Heat transfer coefficient, Btu/ft^2-hr-F	54 000	500
Thermal spike-transients, °F/sec	up to 30 000	100
Engine starts	55 - 300	2 400
Operational life, hrs	7.5 - 100	8 000

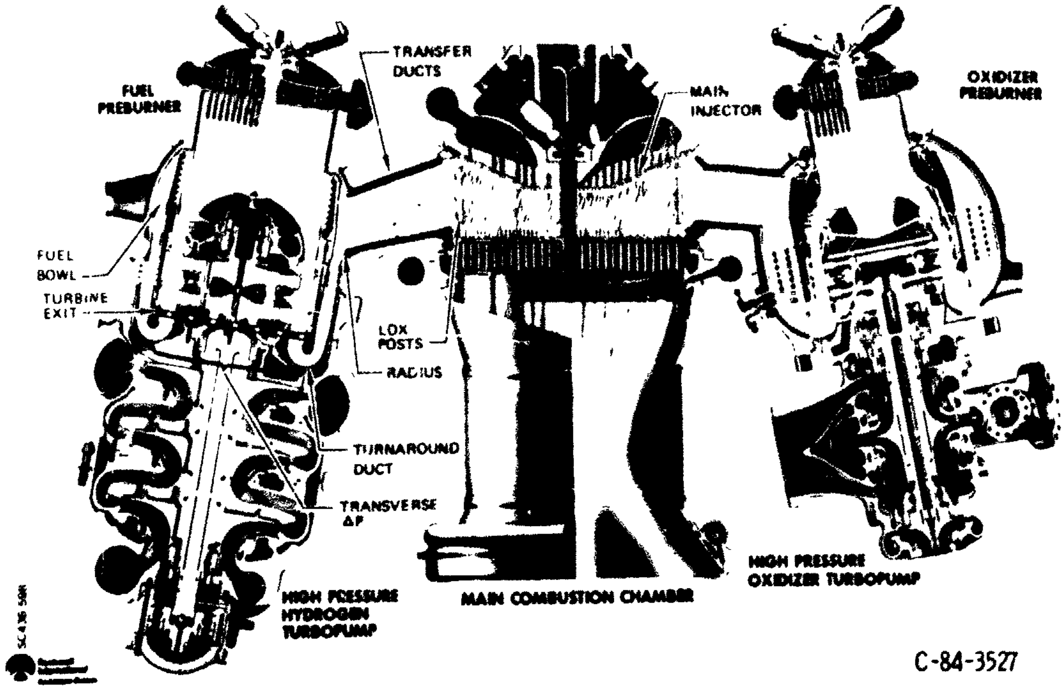


▪ THRUST, RATED	
SEA LEVEL	375,000 lbf
VACUUM	470,000 lbf
▪ FULL POWER LEVEL	109%
▪ CHAMBER PRESSURE	2970 PSIA
▪ AREA RATIO	77.5
▪ SPECIFIC IMPULSE (NOM)	
SEA LEVEL	363.2
VACUUM	455.2
▪ MIXTURE RATIO	6.0
▪ LENGTH	167"
▪ DIAMETER	
POWERHEAD	105" x 94.5"
NOZZLE EXIT	94"
▪ LIFE	7.5 HRS 55 STARTS
▪ SPECIFICATION DRY WEIGHT	6668 LB

C-84-3524

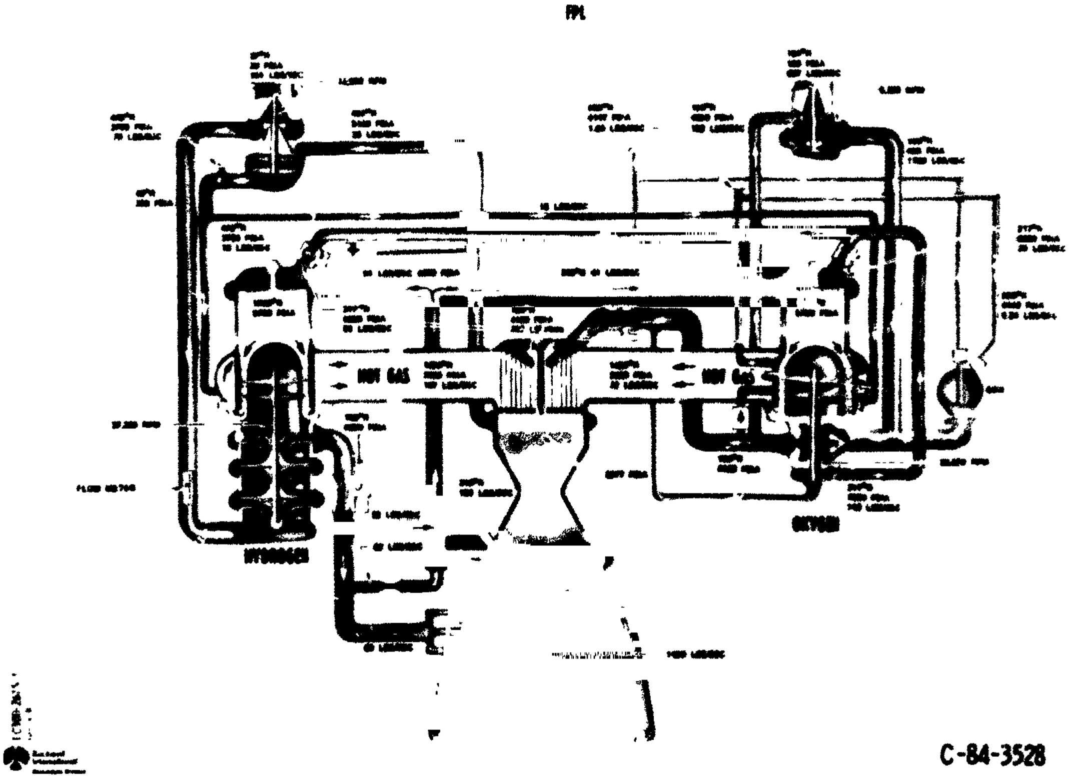
Figure 1. - Space shuttle main engine, main design specifications.

ORIGINAL PAGE IS
OF POOR QUALITY



C-84-3527

Figure 2. - SSME powerhead component arrangement.



C-84-3528

Figure 3. - SSME propellant flow schematic with temperatures and pressures at full power level; MR 6:1.

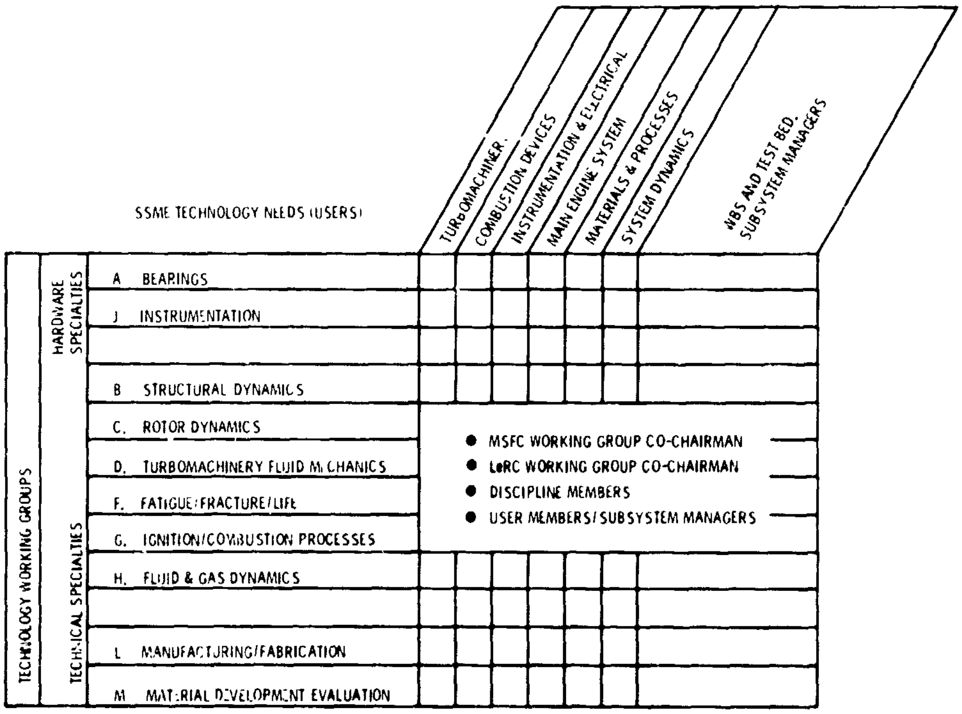


Figure 4. - Advanced high pressure O_2/H_2 propulsion technology working group structure

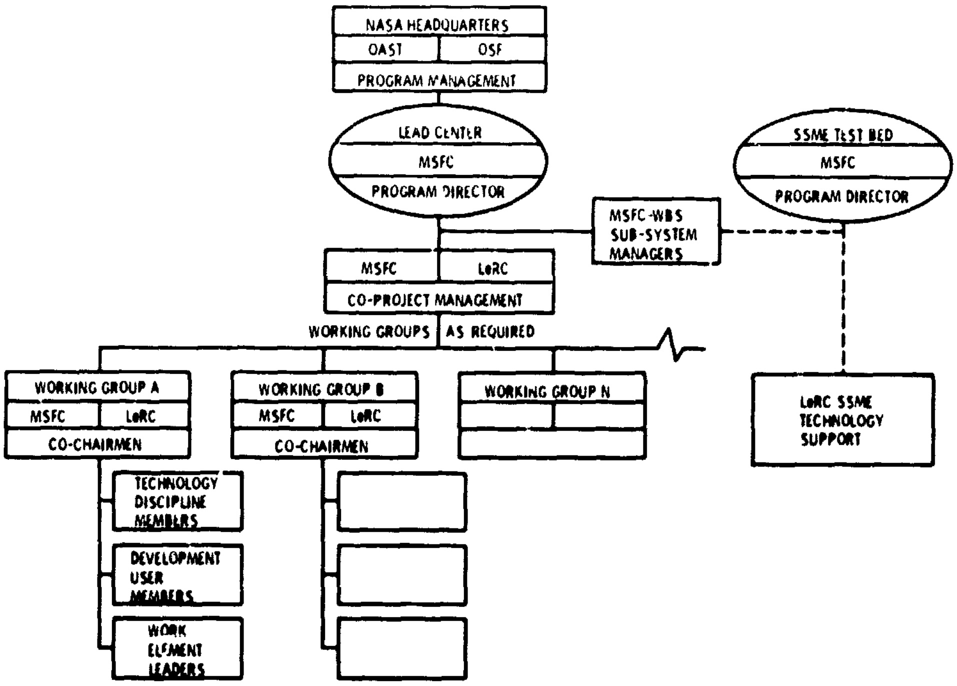
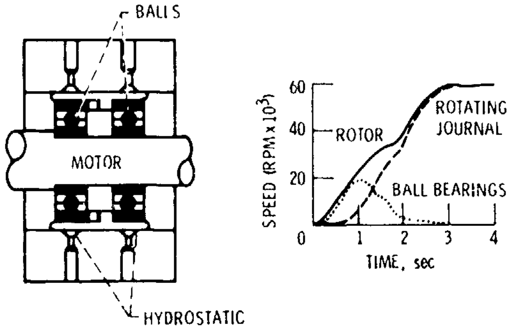
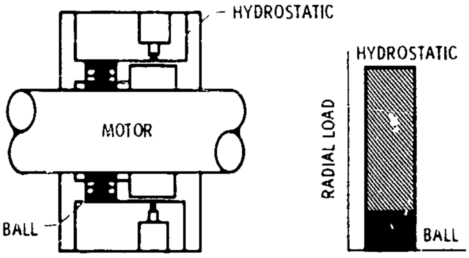


Figure 5. - Advanced high pressure O_2/H_2 propulsion technology functional relationship.



(a) Parallel-speed hybrid bearing.



(b) Parallel-load hybrid bearing.

Figure 6. - Hybrid bearing concepts.

MATERIALS	BENEFITS		AVAILABLE	
	PERFORMANCE	LIFE	NEAR TERM	LONG TERM
ADVANCED SINGLE CRYSTAL SUPERALLOY		▨	▨	
FIBER REINFORCED SUPERALLOY COMPOSITE	▧	▩		▧

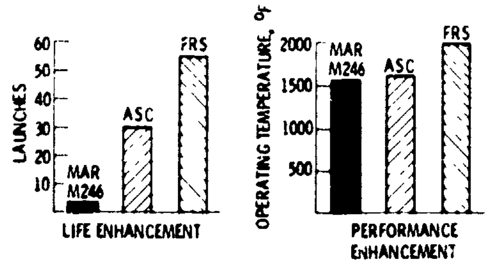


Figure 7. - Advanced materials for rocket engine turbine blades compared to currently used materials in SSME-MAR M246.