Advanced Technology for Future Space Propulsion Systems

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SUMMARY

The NASA Project Pathfinder contains programs to provide technologies for future transfer vehicles including those powered by both advanced chemical and electric propulsion rockets. This paper discusses the Chemical Transfer Propulsion and Cargo Vehicle Propulsion elements of Pathfinder. The program requirements and goals for both elements are discussed, and technical activities which are planned or underway are summarized. Recent progress in programs which support or proceed the Pathfinder activities is detailed. In particular, the NASA Program for Advanced Orbital Transfer Vehicle Propulsion, which acted as the precursor for the Chemical Transfer Propulsion element of Pathfinder is summarized.

INTRODUCTION

The Presidential Space Policy (ref. 1) announced in February 1988, directed NASA to pursue a long range goal to establish human presence and activity beyond Earth orbit. The direction acknowledged that an intelligent goal selection among the many alternatives being considered required a broader science and technology base. To lay a foundation for deciding advanced goals, the President's directive created Project Pathfinder, a major new program for research and development of technologies to enable a wide range of manned and unmanned missions beyond Earth orbit (refs. 2 and 3).

Pathfinder is intended to build upon the ongoing Civil Space Technology Initiative (CSTI). While CSTI aims to develop technologies related to space operation in low Earth orbit, Pathfinder will focus on emerging, innovative technologies that would make possible lunar/interplanetary missions, robotic exploration of the solar system, an outpost on the Moon or a manned expedition to Mars. The vision of possible future missions to study Earth, return to the Moon, piloted missions to Mars or the continuing robotic exploration of the Solar System are contained in the report of the President's National Commission on Space (ref. 4). The role and requirements for technology development to enable these missions are enumerated in the report of the Sally Ride Committee to the NASA Administrator (ref. 5).

Project Pathfinder is organized around four major thrusts: Exploration, Transfer Vehicles, Humans in Space, and Operations. Each of these thrusts is concerned with a set of key technology elements to support critical mission capabilities. Of interest to this paper is the Transfer Vehicle Thrust which will provide for transportation to and from the Moon, Mars, and other planets, and for transfer between different Earth orbits, for example, movement of people or cargo between low Earth orbit and geosynchronous orbit. This thrust

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contains a technology element for chemical propulsion, the Chemical Transfer Propulsion element, and an element for high power electric propulsion, the Cargo Vehicle Propulsion element.

The Pathfinder Chemical Transfer Propulsion Program was initiated in late 1988 and is intended to establish the technology base that will enable the development of space-baseable, high performance chemical transfer propulsion systems, as well as lander propulsion systems, that can provide the needed performance over a wide throttle range. The LOX/hydrogen expander cycle engine has been identified as the primary candidate to satisfy these requirements.

The very challenging missions that are now being considered and the availability of high-power levels in space had led to a renewed interest in high-power electric propulsion for interplanetary cargo vehicles, large Earth-orbital systems, and other nontime critical applications where the high specific impulse of these systems may be enabling. The status of high power electric propulsion and its application to various missions has been reviewed with respect to recent developments. The major thruster and system technology issues which must be addressed have been included in the Pathfinder Cargo Vehicle Propulsion Program. This activity will concentrate on ion and magnetoplasmadynamic (MPD) propulsion and its initial phase will concentrate on establishing the feasibility and practicality of these two systems.

Both the Pathfinder Chemical Transfer Propulsion and Cargo Vehicle Propulsion Programs have been preceded by research programs relevant to them. In particular, the NASA Orbital Transfer Vehicle Propulsion Program (ref. 6) is a precursor to the new Chemical Transfer Propulsion Program. Relevant research in ion propulsion and MPD propulsion (ref. 7) has been underway for two decades and has existed within NASA, the DOD, industry and academe.

This paper will briefly review the recent developments in transfer propulsion and high power electric propulsion which are relevant to these new Project Pathfinder activities. The goals and planned activities associated with Chemical Transfer Propulsion and Cargo Vehicle Propulsion will also be summarized.

CHEMICAL TRANSFER PROPULSION PROGRAM

The Pathfinder Chemical Transfer Propulsion Program has been established to provide the technology base that will enable the development of space-baseable, high performance chemical transfer propulsion systems, as well as lander propulsion systems that can provide the needed high performance over a wide throttle range. The LOX/hydrogen expander cycle engine has been identified as the primary candidate to meet these stringent mission requirements. Such advanced chemical rocket engines would enable transportation to, and return from, the Moon, the Martian Moon Phobos, Mars, and other planets in the Solar System as well as reliable and cost-effective Earth-orbit operations.

Design Goals/Characteristics

The NASA Office of Exploration (OEXP) is currently studying a variety of mission scenarios such as those noted above to provide recommendations and

activities so that a national decision for human exploration of the Solar System can be made. A preliminary set of propulsion technology requirements resulting from these studies is shown in table I. Propulsion requirements identified in these studies include: (1) fault tolerant and reliable engine operation, (2) space basing, long life and space maintenance capability, (3) man rating, (4) reusability, restart capability, and automated preflight operations, (5) integrated controls and health monitoring for self diagnosis, and (6) the ability to perform some level of on-orbit assembly.

Based on requirements such as these, a set of desirable characteristics for an advanced space-based engine has been established. These goals are listed in table II. Certain characteristics of the engine have been left undefined pending further definition of the mission of choice. Thrust is dependent on mission, whether a multistage vehicle is required and the number of engines required to achieve man rating and reliability requirements. Engine length can be driven by aerobrake compatibility. High chamber pressure is desirable to minimize size, but needs to be evaluated versus reliability and space maintenance/space assembly considerations. It is likely that chamber pressure will be in excess of 1000 psia to satisfy all requirements. Previous studies of Orbital Transfer Vehicle propulsion systems with very similar characteristics resulted in chamber pressures which were in the 1200 to 2000 psia range. These characteristics represent a set of highly ambitious goals and the degree to which all of these can be met concurrently has yet to be established.

The vacuum specific impulse goal of 490 sec (lbf-sec/lbm) is ambitious, but appears approachable, if not achievable, based on the work in previous activities. The selection of a 20:1 throttling ratio (with minimum performance loss) reflects not only the requirement for lander application, but also the versatility to perform low acceleration orbit transfer missions as well as to provide thrust variability for aeromaneuvering.

Reusable engines will require periodic maintenance. If the engine is space-based, the maintenance must be performed in space. Goals for service free life and time between overhauls will help to minimize maintenance time and cost for a space-based engine. In addition, the engine shall be of a modular design to facilitate maintenance. Space-basing will also require that engine operating characteristics, design techniques and diagnostic systems be employed to facilitate long-term storage in space.

The engine will be required to tolerate a number of failures without creating a hazard ("fail operational/fail safe" fault tolerance). In addition, the system shall tolerate off-design operation of some combinations of components in a way that can maintain overall system durability and allow completion of the mission.

For a man-rated vehicle, high reliability is required. Proven design standards for operational safety shall be employed. Redundant systems shall be employed as practical.

To achieve these goals/characteristics, critical technologies will have to be advanced in several areas. Technology development will be pursued in the areas of high performance variable flow components, high expansion ratio nozzle flow characterization, design for in-space maintainability and integrated

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health monitoring/control systems that will provide automated preflight operations, as well as fault tolerant engine flight operations.

Program Objectives

The objective of the program to validate high performance expander cycle concepts will be accomplished by completing the following:

(1) Proof-of-concept demonstration of a high performance, liquid oxygen/liquid hydrogen expander cycle will be undertaken in a test bed engine system, including

    (a) Validation of high pressure, high performance expander cycles

    (b) Investigation of engine system interactions, transients, dynamics, control functions, and preliminary health monitoring techniques

(2) Design and analysis methodologies will be validated to support the development of future, high performance liquid oxygen/liquid hydrogen expander cycle engines including

    (a) Assembly and validation of analytical methodologies for the design of advanced liquid oxygen/liquid hydrogen expander cycle engine components and systems

    (b) Validation of design concepts for high performance, space-based throttleable liquid oxygen/liquid hydrogen expander cycle engines

(3) Mission-focused components will be integrated into a focused-technology test bed engine to demonstrate the high performance, liquid oxygen/liquid hydrogen expander cycle engine system technology that is to be the basis for future space engine development.

(4) Propulsion studies will be conducted to define firm propulsion requirements and to trade propulsion system performance, configuration, operating characteristics, and the attributes that are key to long-term space transportation infrastructures (space-basing, reuse, man-rating, fault tolerance).

Technical Approach

The overall technical approach to be used in the chemical transfer propulsion program is shown in figure 1. The program consists of propulsion studies, focused advanced components technology efforts and systems technology activities. Utilizing the technology developed in the Orbital Transfer Vehicle Propulsion Program, advanced liquid oxygen/liquid hydrogen expander cycle engine components will be designed, fabricated and tested in component test stands. The testing shall be undertaken to validate the design methodologies and approaches that were used. The data base thus generated will be useful not only to validate component and subsystem performance, life, and operating characteristics but also the analytical methodologies used in design as well.

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The components will then be assembled into a test bed engine. The test bed engine will be used to conduct component interaction and system level verification testing and to establish a system level data base. High pressure expander cycle operation will be validated and engine models for predicting transient, steady state and throttling performance will be tested, refined and verified. In parallel with these activities, propulsion studies will be conducted to define propulsion system requirements which will guide the selection of focused advanced component technologies to be pursued in the program. These advanced components will have the necessary features, design characteristics, diagnostics, and scale to demonstrate the mission specific requirements of future Mars/Lunar transfer, lander, ascent and Earth return vehicle requirements. Focused advanced engine components emerging from component tests will be integrated into a focused-technology test bed engine. This engine will be capable of validating the mission specific requirements at the systems level. The projected completion date is in 1997.

ORBITAL TRANSFER VEHICLE PROPULSION TECHNOLOGY PROGRAM

In 1981, NASA initiated an Advanced Orbital Transfer Vehicle (OTV) Propulsion Technology Program. The objective of this program was to establish by the early 1990's the technology base for a high performance, multiple restart, variable thrust, orbital transfer propulsion system which could be man rated, space or ground based, and compatible with aeroassisted maneuver concepts. Uncertainties of the missions in the OTV mission models and the continual evaluation in OTV operation, technology and supporting infrastructure necessitated a broad statement of the program requirements and goals and lead to the redefinition of the engine size during the course of the program.

Studies to define propulsion concepts based on the requirements were completed in 1983 by Aerojet TechSystems Company, Pratt and Whitney, and Rocketdyne. The three engine concepts identified by each of these studies were baselined and a comprehensive program of technology development for each concept was begun. Later in the program, funding constraints allowed only the pursuit of the Aerojet and Rocketdyne concepts. In addition to the contractor specific technology development, a parallel effort of generic research and technology applicable to all concepts was also undertaken. Program definition and status have been reported previously (refs. 6, 8, and 9). Recent progress in defining engine concepts at the 7500 lbf level and in selected technology areas is given below.

OTV Engine Concepts

The dual propellant expander cycle engine concept flow schematic proposed by Aerojet is shown in figure 2. The key feature of the dual propellant expander cycle is that both hydrogen and oxygen are used to drive their respective turbopumps. This approach results in a higher ultimate chamber pressure than a conventional expander cycle and eliminates the need for interpropellant seals in the oxidizer turbopump. The concept would feature the use of burn resistant materials in oxygen, a high heat load baffled chamber and a dual spool hydrogen turbopump. The updated engine's specific impulse is predicted to be in excess of 480 sec at a mixture ratio of 6.0 by utilizing a chamber pressure of 2000 psia and a nozzle area ratio of 1000:1.

A hydrogen expander cycle with hydrogen regeneration and oxygen preheating at low thrust levels was proposed by Rocketdyne. The propellant flow cycle for this engine is shown in figure 3. The concept has a predicted specific impulse in excess of 480 sec with a chamber pressure of 1740 psia and an area ratio of 1080:1. The hydrogen pump is a four-stage centrifugal design preceded by an inducer and driven by a two stage partial admission turbine. The pump operates at 192 000 rpm and delivers an outlet pressure of 5600 psia. The oxygen turbo-pump is a single-stage centrifugal design and is driven by a single-stage partial admission turbine. The pump has an outlet pressure of 3000 psia and operates at 64 000 rpm.

The Pratt and Whitney baseline concept was a hydrogen expander cycle with hydrogen regeneration and oxygen preheating at low thrust. At a mixture ratio of 6.0 predicted specific impulse was slightly less than 480 sec with a chamber pressure of 1210 psia and nozzle area ratio of 600:1. The propellant flow schematic for the Pratt and Whitney concept is shown in figure 4.

OTV Propulsion Technologies

Based upon the engine concepts and identified technology needs a comprehensive effort was initiated in 1983 to develop the technology required for a 1990's engine development program. Highlights of selected achievements in the last two years are summarized below.

Turbomachinery technology. - The design of multi-stage low flow, high pressure pumps requires the efficient turning of the high velocity fluid from the impeller to the inlet of the next stage. A series of tests have been completed in a water tester to provide the data base for the design of high velocity ratio diffusing crossovers. Figure 5 shows the Rocketdyne Mark 49 turbopump and the general construct of the high velocity crossovers. The crossover was designed to provide a high diffusion (V_1/V_2) of 6.23. This is more than twice the diffusion obtained in the Space Shuttle Main Engine. Figure 6 shows the ceramic mandrel used in casting the crossover and gives a better indication of the shape and complexity of the crossover design. Early problems with casting/fabricating the crossover appear to be solved. Use of a high velocity ratio crossover produces benefits in terms of increased turbopump performance and improved pump stall margin.

Bearing life in existing reusable rocket engines is not sufficient to satisfy the goals of this program. Figure 7 shows predicted ball bearing fatigue life limits. For example the use of a 25 mm bearing in a hydrogen turbopump at 200 000 rpm would produce a bearing DN of $5x10^6$. To satisfy these requirements, both Rocketdyne and Aerojet have decided to use hydrostatic bearings. In laboratory tests, hydrostatic bearings have been demonstrated to achieve virtually unlimited life when metal on metal contact is eliminated. Aerojet will include hydrostatic bearings as part of its high speed liquid pump and gaseous oxygen drive turbine evaluation program. The Aerojet turbopump is shown in figure 8. Rocketdyne has fabricated a tester to evaluate high speed bearings in a liquid hydrogen environment. Both programs are scheduled to be under test early in calendar year 1989.

In order to maintain high turbopump performance with long operational life, Rocketdyne is considering using turbopump seals manufactured from plastic

materials. These seals would allow small, high speed turbopumps to use small seal clearances necessary to provide high efficiency without seal failures resulting from rubs which would be encountered with currently-used materials. Polyurethane materials are candidates for liquid hydrogen service and poly-imides for liquid oxygen and warm hydrogen. Initial screening of materials for oxygen service was completed several years ago. Typical results are shown in figure 9. Data from these tests were incorporated into a model of seal and energy dissipation in the rotor/static system. The model is capable of providing a ranking of seal materials based on the turbopump environmental conditions and the material characteristics of the seals, rotor and stator. Both static friction and wear and running friction and wear tests are currently underway in the tester shown in figure 10. Friction and wear test material combinations are shown in table III.

The Aerojet engine concept utilized a gaseous oxygen driven turbine for the oxygen pump. Rubs in high pressure gaseous oxygen can result in catastrophic failure. A ranking methodology for the tendency of materials to ignite in oxygen was developed early in the program (ref. 10). Results from the rubbing of dissimilar materials shows that the combination exhibits the characteristics of the most ignitable material. More recent tests have evaluated the rubbing and wear characteristics of materials which have undergone surface modification by ion implantation or electrodeposition. Monel K-500 (a material previously found difficult to ignite) both with and without surface modifications consisting of ion implanted chromium, silver, and lead, and electro-deposited chromium has been evaluated. As shown in Figure 11, several modifications lowered friction at low loads and for short periods of time. The desirable surface temperature characteristics of Monel were not significantly affected by the modification. These modified materials could be of benefit during the hardware start-up phase.

High area ratio nozzle technology. - Accurate calculation of engine specific impulse requires knowledge of boundary layer losses and energy extraction in very high area ratio nozzles. Until just recently, such data has been available for area ratios only up to 400:1.

Initial tests of a 1030:1 nozzle in the Lewis Research Center Rocket Engine Test Facility indicated that at the nominal chamber pressure of 350 psia the flow within the nozzle was laminar (ref. 11). Calculation of the flow condition within the nozzle indicated that even if the boundary layer flow was inclined to transition to turbulent, the acceleration conditions within the nozzle would tend to suppress turbulence and keep the flow laminarlike. More recent tests have extended the range of investigation from 350 to 1000 psia chamber pressure (ref. 12). These conditions correspond to a throat diameter Reynolds number range of $3x10^5$ to $10x10^5$. The heat flux distribution within the nozzle is shown in figure 12. As the chamber pressure is increased, and, correspondingly, the throat Reynolds increases, the flow becomes more transitional. Near the nozzle exit at 1004 psia, the flow appears to be nearly fully developed turbulent flow. Extrapolation of the heat flux data indicate that the relaminarization region will extend to a throat diameter Reynold's number of $22x10^5$ or 2600 psia. Relaminarization based on calculation of the acceleration parameter agree with these results. Additional tests are planned at higher chamber pressure to obtain data in the region of fully developed turbulent flow. Knowledge of the nozzle flow characteristics is extremely important in determining the nozzle and engine performance. Based on the results of

tests at 350 psia chamber pressure with a 1000:1 area ratio nozzle, a fully developed turbulent flow within the nozzle would result in a performance loss of 15 sec of vacuum specific impulse (ref. 13).

CARGO VEHICLE PROPULSION PROGRAM

If chemical propulsion is used, the challenging future space missions, such as those to the Moon and Mars, will require that propellant be a significant percentage of the total vehicle mass. For example, in the case of the Galileo mission, propellant accounts for 43 percent of the total mass of the spacecraft in Low Earth Orbit (LEO). For the more challenging Comet Rendezvous/Asteroid Flyby (CRAF) mission, chemical propellant makes up 76 percent of the LEO mass of the spacecraft. Several electric propulsion devices deliver a specific impulse significantly higher than chemical systems. Such devices, therefore, offer the promise of reduced propellant mass to perform a given mission. This gain can be reduced if the mass requirements for the power system become too large. Also, electric propulsion devices tend to produce low levels of thrust which, for many missions, results in long trip times. There are, however, many missions where increased trip time can be tolerated and the reduced propellant mass required becomes a program driver. One example of such a mission is an unmanned cargo vehicle.

Studies have shown that for a "cargo vehicle" supporting a piloted mission to Mars, high performance electric propulsion with a specific impulse over 4000 sec at multi-megawatt power levels can offer major reductions in total propellant mass requirements. This can be accomplished while still providing acceptable transit time performance. Compared with a chemically-propelled (cryogenic hydrogen/oxygen) cargo vehicle, using aerocapture at Mars, a non-aerobraking, high performance electric propulsion vehicle could reduce total mission mass required in LEO by an amount equivalent to at least three heavy lift launch vehicles (HLLV's). The reduction in launched mass is obviously even greater for a nonaerobraking, completely propulsive chemically propellant cargo vehicle.

At the present time, the Cargo Vehicle Propulsion Program element of project Pathfinder is not funded. The earliest prospects for initiating activity in this element of the program appear to be fiscal year 1991 (October 1990). In the meantime, maintenance-level research in promising electric propulsion technologies is being supported by the NASA Base Research and Technology Program.

Design Goals/Objectives

The design goals established for candidate electric propulsion systems are shown in table IV. The specific impulse goal is approximately 1 order of magnitude higher than chemical propulsion systems. High specific impulse clearly offers propellant mass savings. However, in order to exploit that benefit practically, it is essential that the overall vehicle exhibit acceleration levels, and resultant transit times, which are sufficient to meet acceptable overall mission time frames. This requirement necessitates low specific mass and high efficiency propulsion in order to keep low power system mass. High total

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impulse and high power capability per engine is also needed in order to accomplish mission propulsion system performance requirements with an acceptably low number of individual engines. Durability requirements are also an important consideration.

At the present time, the only operational uses of electric propulsion have been low power systems used to perform satellite stationkeeping functions. Since specific impulse over 4000 sec are of interest for Pathfinder, electrothermal systems such as arcjets are not adequate even with hydrogen propellant ($I_{sp} < 1500$ sec). Advanced concepts, such as electrodeless thruster systems, may ultimately provide the desired characteristics, but do not have sufficient technical maturity to be considered during the initial years of Pathfinder.

Ion engines have demonstrated specific impulses from less than 2000 sec to more than 10 000 sec, thrust efficiencies to over 75 percent, and total thrust impulses as high at 10^6 N·s for 10 kW class thrusters. Key issues are scale-up of ion acceleration subsystems for high power operation, increasing the power density to reduce the number of engines required, and thrust or life.

Magnetoplasmadynamic (MPD) propulsion technology is generally less advanced than ion systems. Power levels of 5 MW have been demonstrated in a pulsed power mode, but levels of only about 250 kW have been demonstrated for steady power. Most of the efficiency data fall into the 15 to 30 percent range, although some data for hydrogen and lithium propellants approach 50 percent efficiency at very low power levels. Higher efficiencies and specific impulses are generally obtained with applied magnetic fields, but a fundamental theoretical understanding of this mode of operation is lacking. The highest total impulse demonstrated is 10^6 N·s, at about 25 kW. Key technology issues are thruster efficiency and life.

Facility background composition and pressure have been shown in some cases to have a very significant (factor greater than two) impact on measured performance. The impact of facility effects and the availability of enough high fidelity ground test facilities are serious issues in the further development of high power, high performance electric propulsion systems.

Technical Approach

The Pathfinder Cargo Vehicle Propulsion Program will establish the practicality and feasibility of electric propulsion for a variety of missions. A three-phase program as shown in figure 13 is planned. Phase I would last approximately 5 years and will be devoted to establishing the feasibility and practicality of competing concepts. The phase I activity will culminate in the selection of the most promising candidate electric propulsion concept for further development.

Phase II will be a 5 year focused technology program that will demonstrate power and life requirements at high power levels. This phase would also define requirements for a technology flight demonstration. If required, a phase III flight validation experiment of high power electric propulsion technology would be undertaken. An overall program schedule for the first phase of the program is shown in figure 14.

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The phase I program will concentrate on performance and critical feasibility issues for the candidate thrusters. The first step will be to assess facility impacts on high fidelity performance and durability data. Reliable short term, in-situ methods of evaluating life issues will be developed along with the required facility capabilities, so that performance limits can be established for each thruster. Parallel thruster technology efforts will be performed for both self-field and applied-field MPD thrusters as well as ion engines. It is necessary to devote most of the resources early in the program to MPD development, because of its much greater technical uncertainties. Power processor technology will be directed to provide laboratory-class hardware. Supporting thermal and systems analyses will be included in the program, while mission studies will be provided from outside sources.

HIGH-POWER ELECTRIC PROPULSION TECHNOLOGY PROGRAM

Interest in very challenging missions and the prospects for available high-power levels in space has spurred renewed interest in high-power electric propulsion (ref. 14). Candidate systems include ion (refs. 15 to 18) and magnetoplasmadynamic engines (refs. 19 to 22). Electrodeless thrusters (ref. 23) represent more far-term possibilities. There are also potential applications for high I_{sp} electric propulsion in the range of tens of kilowatts that may be available from solar arrays (ref. 24).

Ion Propulsion

Ion propulsion is capable of delivering very high specific impulse and, based on a long history of research, can be considered sufficiently mature to be a candidate for near-term applications. In recent tests, a 30-cm diameter, divergent-field ion thruster operating with xenon propellant was operated for 567 hr (ref. 25). Primary wear mechanisms associated with long-life, high-power engines have been identified. Wear mechanisms identified included: (1) nonuniform erosion on the upstream side of the baffle, (2) oxidation, deformation and cracking of the tantalum cathode tube which is probably related to cold startup but may be due to the high partial pressure of water in residual facility gases, and (3) charge exchange ion erosion of the accelerator grid. Previous difficulties with screen grid erosion which was the life limiting mechanism in 3 kW mercury ion thrusters was greatly reduced. Based on these results, screen grid life in the 10 kW xenon thruster is projected to be in excess of 7000 hr.

As previously noted, scaling of ion engines to larger size is desirable. Both laboratory and engineering model 30-cm diameter xenon propellant thrusters have been operated over a power range of 2 to 20 kW. Preliminary performance results have also been obtained for laboratory model 50-cm diameter cusp and divergent field thrusters using 30-cm and 50-cm diameter ion optics over the 10-kW range. These results represent the first output of a program aimed at developing scaling technology and are an important precursor to the Pathfinder activities.

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Magnetoplasmadynamics

Both self-field and applied-field (fig. 15) MPD thruster research is underway. Self-field thruster research has been conducted primarily in the pulsed mode rather than continuous mode operation. High thermal efficiencies at megawatt power levels in pulsed operation with low electrode erosion rates have been observed. This indicates promise for future development of the MPD concept. Promising results with hydrogen and lithium propellants have shown 0.43 and 0.69 efficiency. Other propellants show efficiencies in the 0.1 to 0.35 range delivering specific impulse of 1000 to 4500 sec. Recent tests at NASA Lewis have demonstrated continuous operation of an MPD arc thruster at over 100 kW in both the self- and applied-field modes. Figure 16 shows the thruster in operation.

CONCLUDING REMARKS

The NASA Project Pathfinder Program has been established to provide technologies for future space exploration. The Chemical Transfer Propulsion element has only recently been initiated and the Cargo Vehicle Propulsion element has been planned but is not yet underway. Together these two elements provide technologies for future transfer vehicles propelled by advanced chemical or electric propulsion devices. Much research needs to be accomplished to enable bold new missions being envisioned for the 21st century, but NASA programs to accomplish that research are now being put in place.

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TABLE I. - CHEMICAL TRANSFER PROPULSION TECHNOLOGY REQUIREMENTS

Mission	Thrust, K	Fuel	I_{sp}, sec	Burn time, min	Reuse	Throttleable	Space exposure
Mars transfer (1st and 2nd stage)	75-100	LOX/LH$_2$	>460	<30	Yes (10)	No	Months
Lunar transfer Mars transfer (3rd stage) Mars/Lunar return	20-40	LOX/LH$_2$	>480	45-90	Yes (10)	No	Years
Mars and Moon descent	20-40	LOX/LH$_2$	>450	10-20	Mars-No Moon-Yes	Yes	Years
Mars and Moon ascent	20-40	(a)	Max	<20	Mars-No Moon-Yes (10)	No	Years

aMust be compatible with surface heat loads and stay times and capability to reduce losses to mission acceptable levels.

TABLE II. - TECHNOLOGY GOALS FOR SPACE TRANSFER ENGINE

Parameter	Reference engine system, RL-10A-3-3A	Space transfer vehicle engine goals/requirements
Propellants - Fuel	Hydrogen	Hydrogen
Oxidizer	Oxygen	Oxygen
Power cycle	Expander	Expander
Vacuum thrust (design point), lbf	16 500	TBD
Vacuum thrust throttling ratio (continuous and stable)	No throttling	20:1 (rated thrust to 5 percent with minimum performance loss)
Vacuum specific impulse, lbf-sec/lbm	444.4	490
Engine mixture ratio, O/F (design point)	5.0	6.0
Engine mixture ratio range	4.4 to 5.6	5.0 to 7.0
Combustion pressure (design point), psia	465	TBD
Nozzle area ratio	61:1	1000:1
Gimbal, deg	±4.0	±20 pitch and yaw
Weight, lb	310	TBD
Length, in.	70.1	TBD
Life - Operational	3 starts, 4000 sec	500 starts, 20 hr
Service free	Not specified	100 starts, 4 hr
Basing	Earth	Space
Human rating	No	Yes
Design criteria - Operational	Not specified	Fault tolerance (fail operational/fail safe)
Aerobrake	None	Compatible with aeroassist transfer
Maintenance (during operational life)	None	In-space maintenance (components easily replaceable)
Diagnostic instrumentation	None	Integrated controls and health monitoring

TABLE III. – FRICTION AND WEAR TEST MATERIAL COMBINATIONS

Fluid	Seal rotor	Seal ring
LOX	K-Monel INCO 718	KEL-F (baseline) Vespel Polybon M
Warm GH_2 (500 °F)	A-286	Vespel Polybon M
Cold GH_2 (-300 °F)	Titanium INCO 718	Hexcel 3124 Hexcel 3125 KEL-F (baseline)

TABLE IV. – CARGO VEHICLE PROPULSION GOALS

Characteristic	Goal
Specific impulse Efficiency Specific mass Scalability Durability	>4000 sec >0.60 <10 kg/kW To multi-megawatt Total impulse $>10^8$ N·s per engine
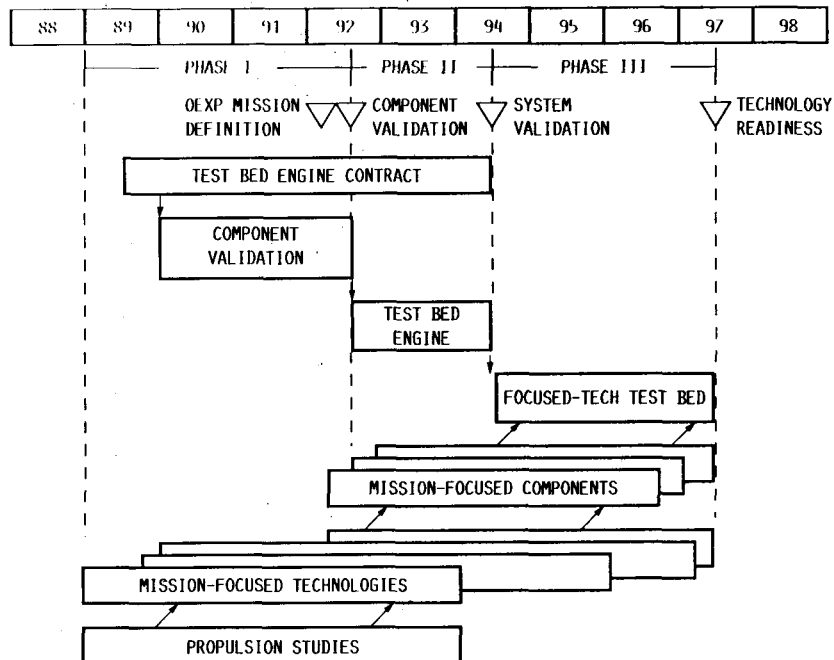
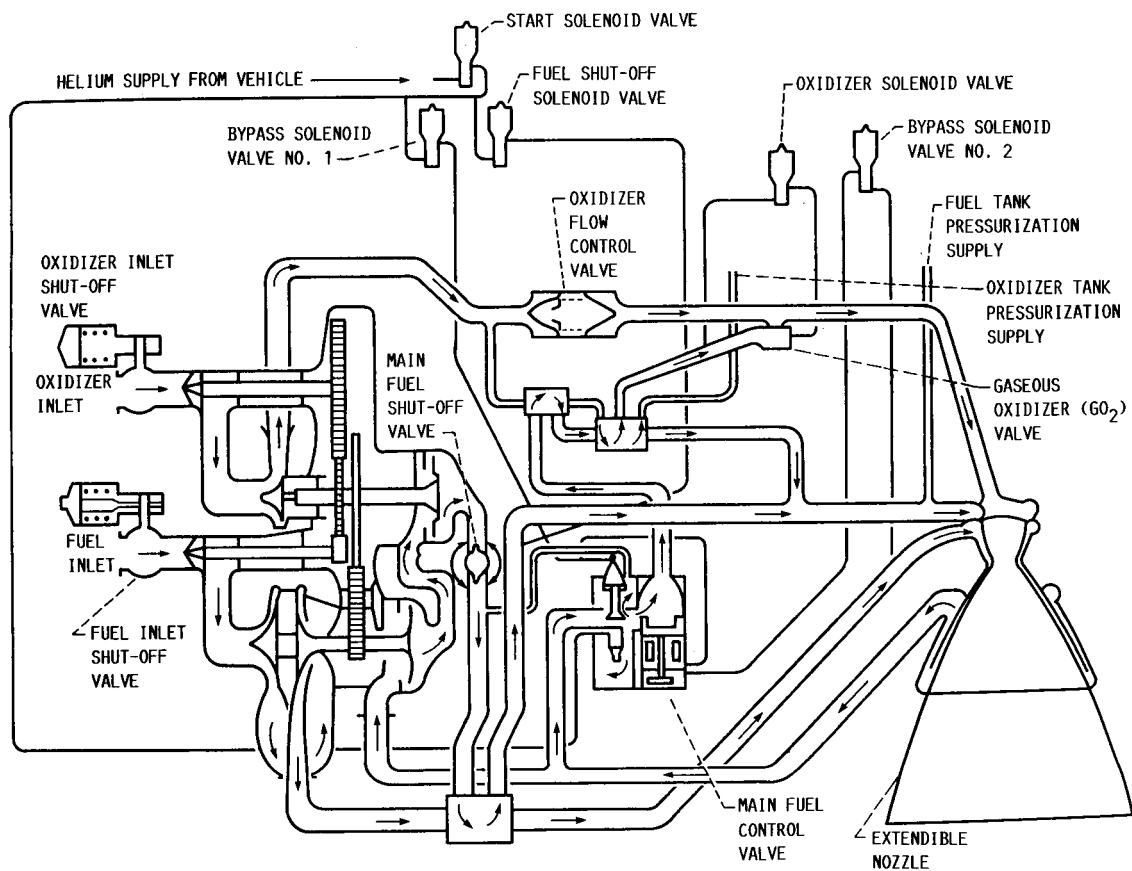FIGURE 1. – CHEMICAL TRANSFER PROPULSION PROGRAM SCHEDULE.

FUEL
START-UP
MAIN VALVE

OX START-UP
MAIN VALVE

FUEL TURBINE
BYPASS VALVE

O_2/H_2
HEX

OX
TURBINE
BYPASS
VALVE

HEAT
EXCHANGER
BYPASS VALVE

FUEL BACK-
PRESSURE
VALVE

FUEL IDLE
VALVE

H_2/H_2
HEX

H_2 REGEN
BYPASS
VALVE

TO BAFFLES

OX BACK-
PRESSURE
VALVE

OX COOLED NOZZLE

V   SHUTOFF

V   TWO POSITION

V   THROTTLING

———————— LIQUID HYDROGEN
------------------ GASEOUS HYDROGEN
——·——·—— LIQUID OXYGEN
— — — — GASEOUS OXYGEN

FIGURE 2. - FLOW SCHEMATIC; AEROJET ADVANCED OTV PROPULSION CONCEPT.

FUEL
INLET
VALVE

OXIDIZER
INLET
VALVE

FUEL
BOOST
TPA

OXIDIZER
TURBINE
BYPASS
VALVE

OXIDIZER
BOOST
TPA

FUEL
HIGH-
PRESSURE
TPA

OXIDIZER
HIGH-
PRESSURE
TPA

TURBINE
SHUTOFF
VALVE

O_2/H_2
HEX

TURBINE
BYPASS
VALVE

MAIN
FUEL
VALVE

GASEOUS
OXIDIZER
VALVE

MAIN
OXIDIZER
VALVE

THRUST
CHAMBER
ASSEMBLY

SHUTOFF

THROTTLING

———————— LIQUID HYDROGEN
------------------ GASEOUS HYDROGEN
———————— LIQUID OXYGEN

FIGURE 3. - FLOW SCHEMATIC; ROCKETDYNE ADVANCED OTV PROPULSION CONCEPT.

15

FIGURE 4. - FLOW SCHEMATIC; PRATT & WHITNEY ADVANCED OTV PROPULSION CONCEPT.

VIEW IN DIRECTION "A" SHOWING TWO OF
SEVENTEEN CROSSOVER PASSAGES

SECTIONAL VIEW OF CROSSOVER
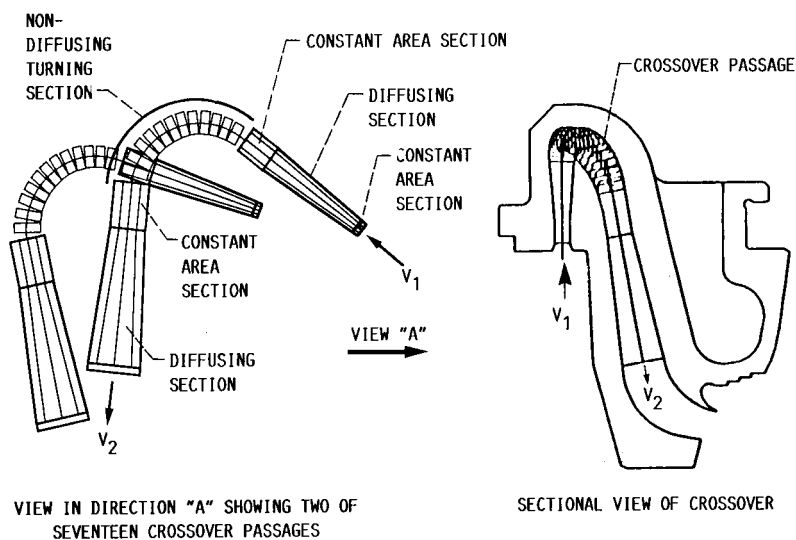
FIGURE 5. - SCHEMATIC OF HIGH-VELOCITY RATIO DIFFUSING CROSSOVER.
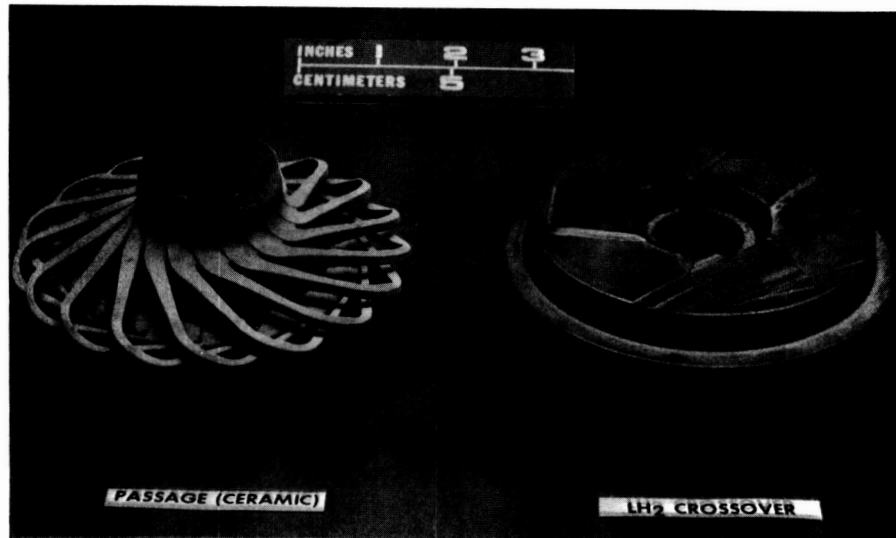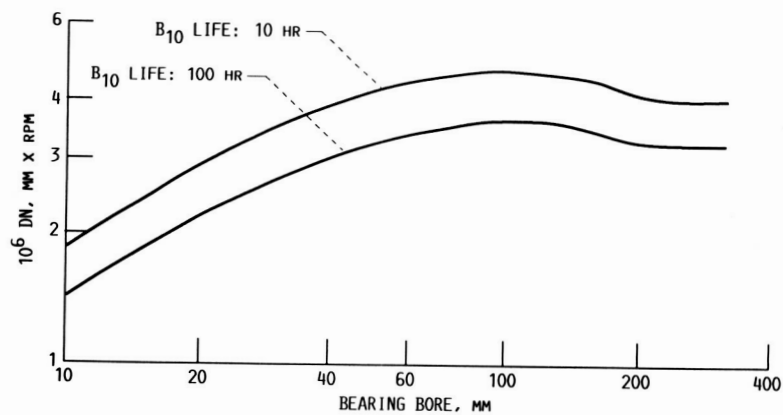
FIGURE 6. - HIGH VELOCITY RATIO DIFFUSER CASTING.
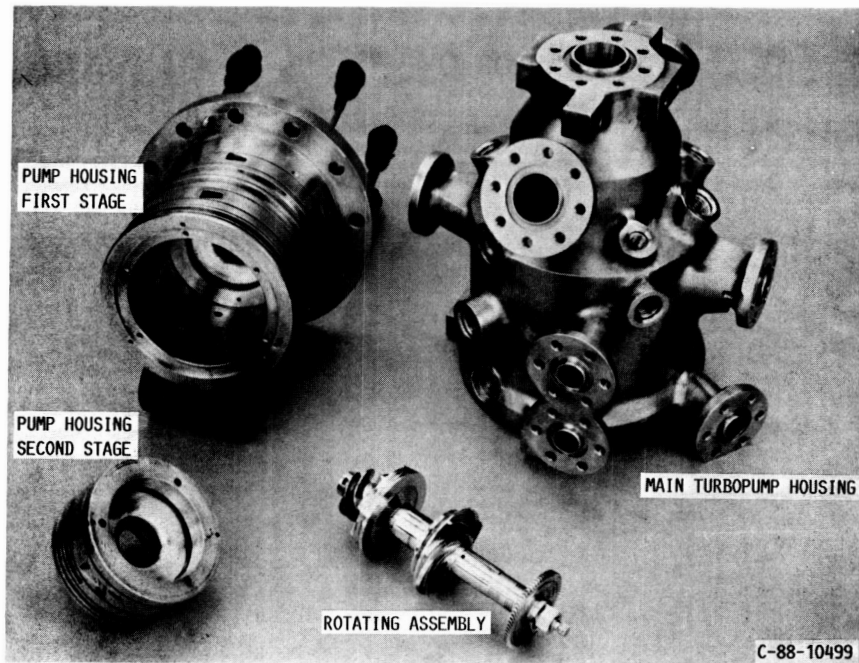

FIGURE 7. - BALL BEARING FATIGUE LIFE LIMIT.

FIGURE 8. - OXYGEN TURBUPUMP COMPONENTS.

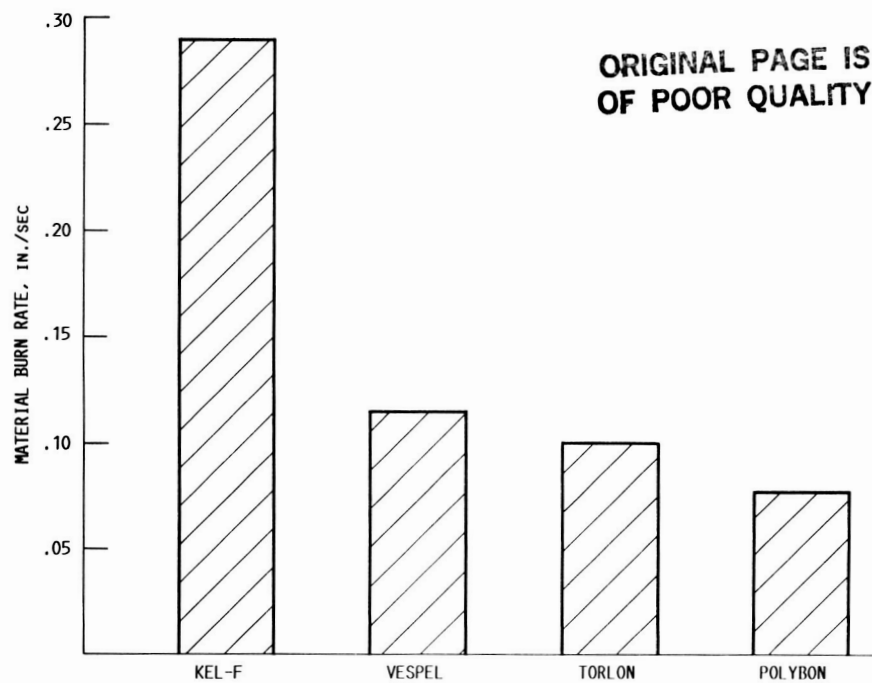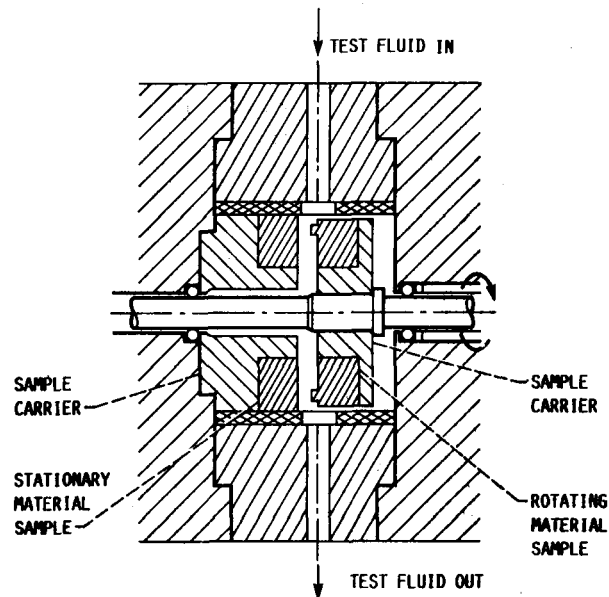FIGURE 9. - PROMOTED IGNITION BURN RATE FOR CANDIDATE SOFT SEAL MATERIALS.

TEST FLUID IN

SAMPLE CARRIER

SAMPLE CARRIER

STATIONARY MATERIAL SAMPLE

ROTATING MATERIAL SAMPLE

TEST FLUID OUT

FIGURE 10. - SOFT WEAR RING SEAL FRICTION AND WEAR TESTER.
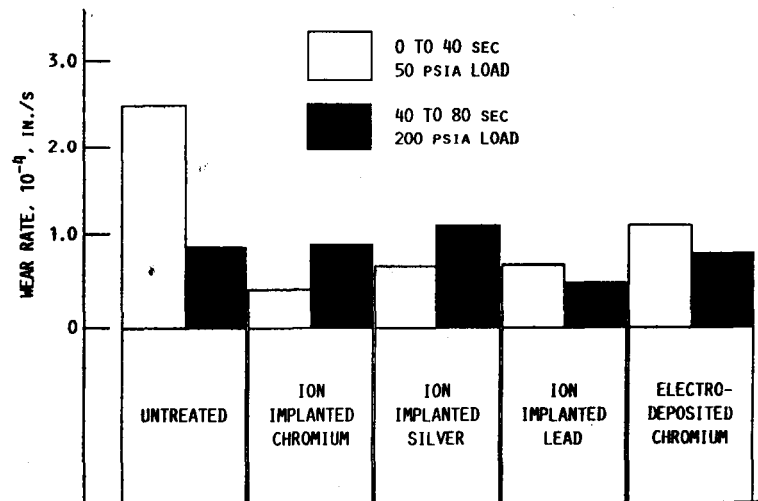
FIGURE 11. - COMPARISON OF WEAR RATES IN OXYGEN FOR MONEL K-500 WITH/
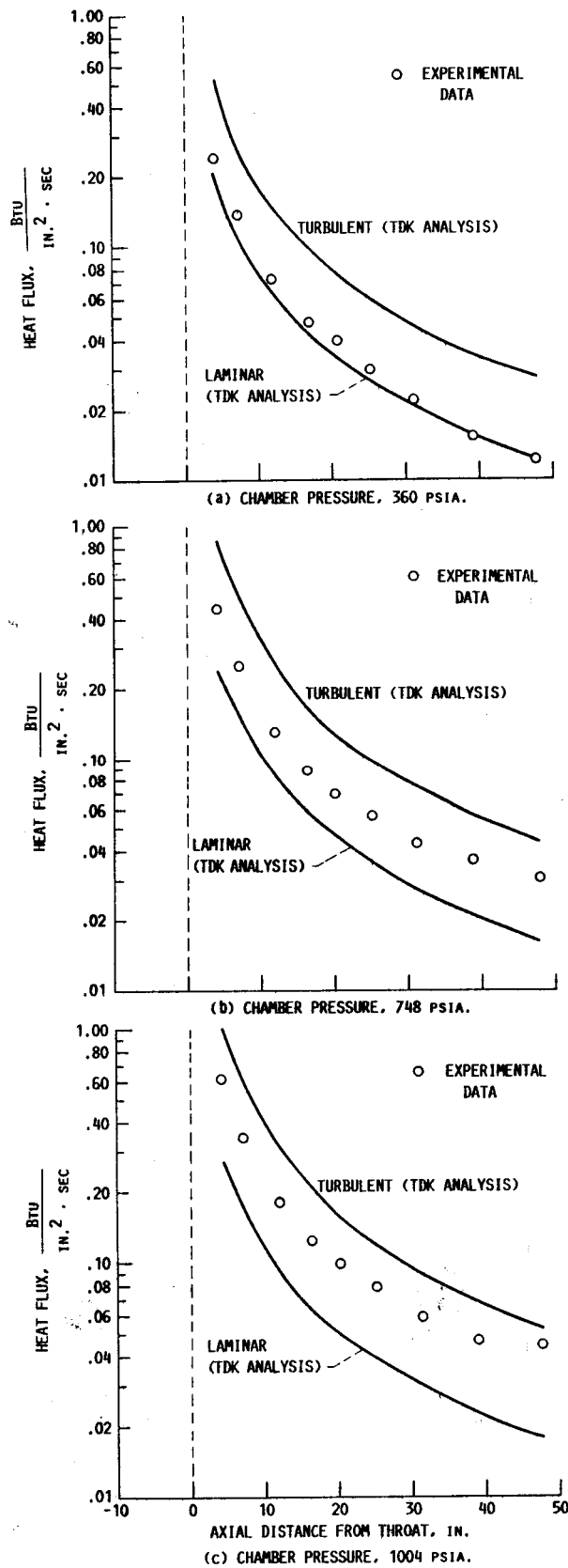WITHOUT SURFACE MODIFICATIONS. OXYGEN PRESSURE, 1000 PSIA.

(a) CHAMBER PRESSURE, 360 PSIA.

(b) CHAMBER PRESSURE, 748 PSIA.

(c) CHAMBER PRESSURE, 1004 PSIA.

FIGURE 12. - EXPERIMENTAL AND PREDICTED WALL HEAT
FLUX AT VARIOUS CHAMBER PRESSURES.

PHASE I

ESTABLISHMENT
OF FEASIBILITY
AND PRACTICALITY

PHASE II

FOCUSED
TECHNOLOGY
PROGRAM

PHASE III

FLIGHT
VALIDATION
PHASE

| | 92 | | 94 | | 96 | | 98 | | 00 | |

FISCAL YEAR
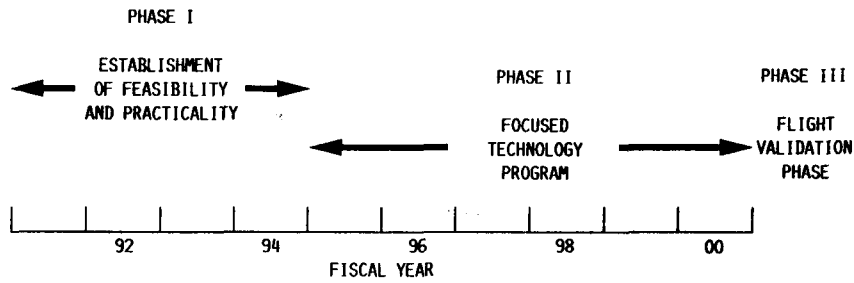
FIGURE 13. - CARGO VEHICLE PROPULSION PROGRAM SCHEDULE.

FISCAL YEAR

90   91   92   93   94   95

SELF FIELD MPD
0.5-2 MW PERF.   1000 HR

APPLIED FIELD MPD
TESLA CLASS NOZZLE   0.5 MW   1000 HR
PERF.

ION THRUSTER
1000 HR AT 50 KW   0.5 MW ION   1000 LIFE   FEAS. ASSESS.
OPTICS   TEST

LAB POWER PROCESSORS
0.5 MW POWER SUPPLY   FLIGHT DESIGN

THERMAL ANALYSES
MW THERMAL
MANAGEMENT

SYSTEM DEFINITION
MW SYSTEM REQUIREMENTS

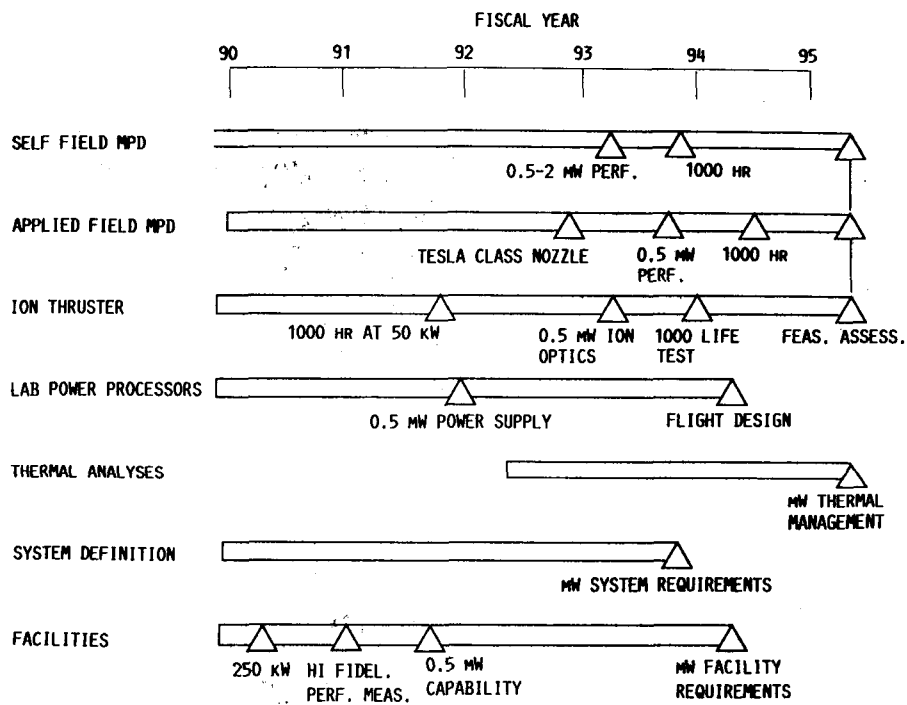FACILITIES
250 KW HI FIDEL. 0.5 MW   MW FACILITY
PERF. MEAS. CAPABILITY   REQUIREMENTS

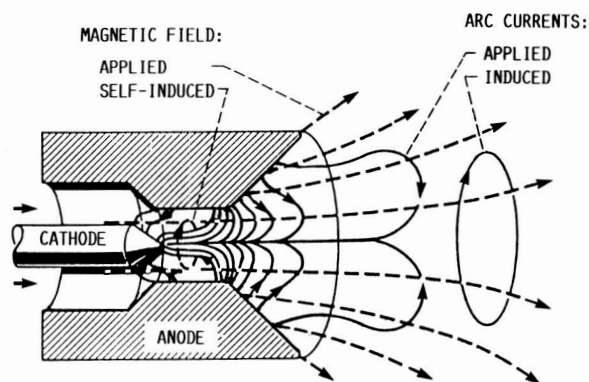FIGURE 14. - PHASE I CARGO VEHICLE PROPULSION PROGRAM SCHEDULE.

FIGURE 15. - MPD ARC THRUSTER CURRENTS AND FIELDS.

C-88-05339

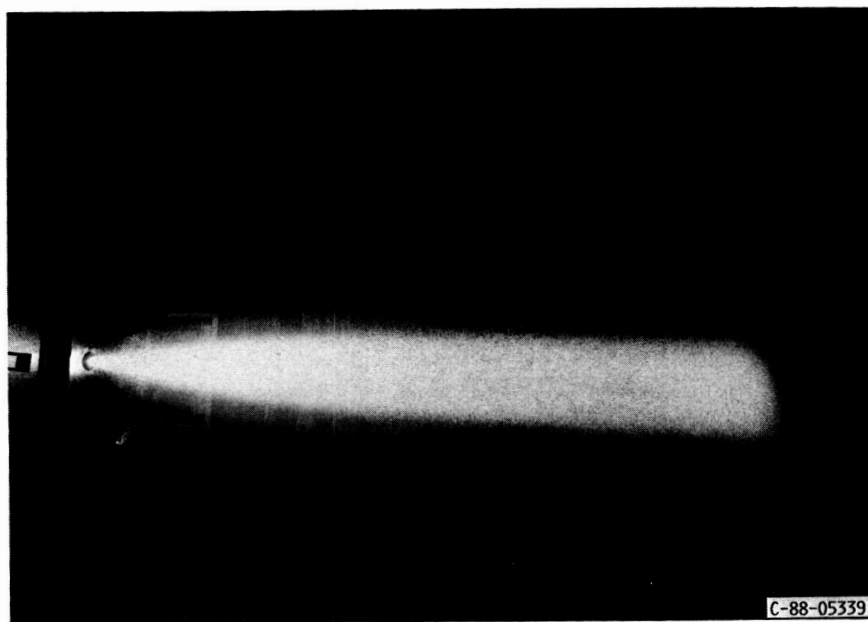FIGURE 16. - MPD ARC THRUSTER OPERATING AT 102 kW INPUT POWER.

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15. Supplementary Notes

16. Abstract

The NASA Project Pathfinder contains programs to provide technologies for future transfer vehicles including those powered by both advanced chemical and electric propulsion rockets. This paper discusses the Chemical Transfer Propulsion and Cargo Vehicle Propulsion elements of Pathfinder. The program requirements and goals for both elements are discussed, and technical activities which are planned or underway are summarized. Recent progress in programs which support or proceed the Pathfinder activities is detailed. In particular, the NASA Program for Advanced Orbital Transfer Vehicle Propulsion, which acted as the precursor for the Chemical Transfer Propulsion element of Pathfinder is summarized.

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