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The Pathfinder Chemical Transfer Propulsion Program

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THE PATHFINDER CHEMICAL TRANSFER PROPULSION PROGRAM*

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ABSTRACT

Pathfinder is a research and technology initiative by the National Aeronautics and Space Administration (NASA) intended to strengthen the technology base of the United States civil space program in preparation for future space exploration missions. Pathfinder begins in FY89.

One of the four major thrusts of Pathfinder is Space Transfer technology. A key element of this thrust is the Chemical Transfer Propulsion program which will provide the propulsion technology for high performance, liquid oxygen/liquid hydrogen expander cycle engines which are expected to be operated and maintained in space. These advanced engines will enhance or enable a variety of future space exploration missions.

This paper describes the goals and objectives, management, technical plan, and technology transfer for the Chemical Transfer Propulsion element of Pathfinder.

INTRODUCTION

American leadership on the space frontier requires aggressive technology development. Technological advance will be critical to future space exploration missions.[1] These missions may include an intensive study of the Earth, a return to the Moon, piloted missions to Mars, or the continuing robotic exploration of the Solar System.[2] NASA initiated Project Pathfinder to intensify and broaden the scope of its research and technology program to provide the range of technical options and ensure technological readiness in select areas to enable future space exploration missions.[3]

Pathfinder is organized into four programmatic thrusts: (1) surface exploration, (2) in-space operations, (3) humans-in-space, and (4) space transfer. The space transfer thrust will provide critical technology for transportation to, and return from, the Moon, Mars, and other planets in the Solar System, as well as for reliable and cost-effective Earth-orbit operations.[4] Chemical transfer propulsion is a key element of the space transfer thrust and will provide the technology for high-performance, liquid oxygen/liquid hydrogen expander cycle engines for space-based transfer vehicles, as well as for Lunar and Mars landers.

CHEMICAL TRANSFER PROPULSION PROGRAM OVERVIEW

MISSION STUDIES AND TECHNOLOGY REQUIREMENTS

In its report to NASA in 1987, the Committee on Advanced Space Technology of the National Research Council recommended that advanced propulsion technologies for future space missions be afforded the highest priority of R&D activity within NASA. The committee suggested that NASA pursue a strong program leading to the design and development of reusable cryogenic transfer vehicle engines with features of fault tolerance, high reliability and longevity.[5]

NASA's planning for future exploration the Solar System includes unmanned (precursor) and manned missions to Mars and its moons, as well as a resumption of manned missions to the Moon to establish Lunar observatories. A significant portion of the cost for these missions depends on launch vehicle and on-orbit fuel requirements. One of the keys to reducing cost is to minimize the propellant mass in low-Earth orbit required to achieve a transfer trajectory, to accomplish orbit insertion, to effect a planetary landing, and to return to Earth. Launch of the many millions of pounds required for virtually all future space exploration mission scenarios may be affordable only if advanced propulsion systems can be made available.[5] For example, in the case of a manned Mars mission, an increase of 35 sec in space transfer engine specific impulse saves the cost of at least two Earth-to-orbit vehicle launches.

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Another key to reduced cost is to develop reusable transfer stages that are based in and operated from low-Earth orbit, are operated in LEO to GEO space, and are used in the exploration missions. Technologies that will enable automated in-orbit operation are critical to the successful development and use of space-based vehicle systems. Integrated controls and health monitoring systems will be required for such fault tolerant engines which will be repeatedly operated and maintained in space.

The NASA Office of Exploration (OEXP) is currently studying several mission scenarios to provide recommendations and alternatives for an early 1990's national decision on a focused program for human exploration of the Solar System.[6] A preliminary set of propulsion technology requirements generated by OEXP for these mission scenarios are presented in Table I. These include (1) fault tolerance and high reliability, (2) space basing, long life, and space maintainability, (3) man rating, (4) reusability, restart capability, and checkout before reuse, (5) diagnostic capability (integrated controls and health monitoring), and (6) some level of on-orbit assembly.

TECHNOLOGY ASSESSMENT

The only upper stage liquid oxygen/liquid hydrogen expander cycle engine currently in operation is the RL10 engine which was developed and certified in the late 1950's and early 1960's. Two RL10A-3-3A engines are used on the expendable Atlas Centaur vehicle. The RL10A-3-3A is a regeneratively cooled, turbopump-fed rocket engine that weighs approximately 310 lb and produces a rated vacuum thrust of 16 500 lb.[7] With a chamber pressure of 465 psia, the engine delivers moderate performance (444.4 sec specific impulse at mixture ratio of 5:1 using a 61:1 area ratio nozzle), has limited throttling capability (with significant performance penalties) and no on-board diagnostics. It was designed for and has been used only on expendable vehicles.

In the early 1970's, NASA initiated a technology program directed toward an advanced liquid oxygen/liquid hydrogen upper stage engine, as shown in Fig. 1. The Advanced Space Engine technology program was carried through component verification testing, at which time it was decided that a liquid oxygen/liquid hydrogen expander cycle engine (rather than one utilizing a staged combustion cycle) would better satisfy future mission requirements. The Orbital Transfer Vehicle Rocket Engine technology program, which began in the early 1980's, focused on advanced component technologies for high performance (high pressure), reusable liquid oxygen/liquid hydrogen expander cycle engines which would be space based and man-rated. The basic proof-of-concept of advanced, high-performance liquid oxygen/liquid hydrogen expander cycle components was only partially demonstrated during this program, which has given way to the Chemical Transfer Propulsion Program.

What remains to be accomplished in order to confidently proceed with the development of an advanced high performance liquid oxygen/liquid hydrogen expander cycle engine for future space exploration missions is (1) the validation testing of engine components, (2) testing of components assembled into an engine system (to study component interactions, system transients, system dynamics, and health monitoring/control systems), and (3) the verification of design and analysis methodologies at both the engine component and engine system level. Pathfinder Chemical Transfer Propulsion is a focused program intended to elevate technology readiness (to Level 6 as shown in Table III) by bridging the technology gap between basic research and technology efforts conducted to date (Level 3) and the eventual development of advanced liquid oxygen/liquid hydrogen engines for space transfer vehicles.

CHEMICAL TRANSFER PROPULSION PROGRAM GOALS AND OBJECTIVES

The goal of the Chemical Transfer Propulsion Program is to provide the technology necessary to confidently proceed, in the 1990's, with the development of high-performance, liquid oxygen/liquid hydrogen expander cycle engines for future space exploration missions. Major program objectives are:

(1) Proof-of-concept demonstration of a high performance, liquid oxygen/liquid hydrogen expander cycle 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) The validation of a design and analysis methodologies 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 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) Results of propulsion studies 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

At the present time, future space exploration mission scenarios have not been defined to a point where firm propulsion requirements exist. However, technology goals for an advanced liquid oxygen/liquid hydrogen space engine which support the range of future mission options are presented in Table II. The major technical issues for an advanced liquid oxygen/liquid hydrogen expander cycle engine which will be addressed in the Chemical Transfer Propulsion Program are high performance, deep throttling, reusability, space basing, fault tolerance, and man rating.

The technical approach to be used in the Chemical Transfer Propulsion Program is summarized in Fig. 2. The program consists of propulsion studies, focused advanced component technology efforts, and systems technology activities. Drawing on technology developed in the Orbital Transfer Vehicle Rocket Engine Technology program, advanced liquid oxygen/liquid hydrogen expander cycle engine components will be designed, fabricated and tested in component test stands. The components will then be assembled into a test bed engine for systems testing. 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. The focused advanced engine components emerging from these efforts will be integrated into a focused-technology test bed engine. This engine system will be tested to complete Level 6 of technology readiness.

MANAGEMENT PLAN

WORK BREAKDOWN STRUCTURE

The Chemical Transfer Propulsion Program is divided into three major research areas which allows work to be focused in critical areas and provides a mechanism for raising the technology to higher levels of hardware definition, leading to the eventual testing of an advanced liquid oxygen/liquid hydrogen expander cycle focused-technology test bed engine in the late 1990's. The major work packages are: (1) propulsion studies, (2) mission-focused technologies, and (3) engine systems technologies. Figure 3 illustrates the top-level work breakdown structure elements. The propulsion studies will generate propulsion requirements to guide the selection of mission-focused technologies. Advanced engine subcomponents and components emerging from the mission-focused technology efforts will be tested in an engine system in the focused-technology test bed.

ORGANIZATION AND MANAGEMENT STRUCTURE

Program management responsibilities for the Chemical Transfer Propulsion Program will reside in OAST's Propulsion, Power and Energy Division, Code RP. The NASA Lewis Research Center will be the Lead Center for the Chemical Transfer Propulsion Program. As the lead center, NASA Lewis will assume full responsibility of achieving the goals and objectives of the program, as well as for integrating next-tier assignments in the program both within NASA Lewis and at participating centers.

PROGRAM COORDINATION

The NASA Lewis Project Manager will be kept informed and coordinated with the Office of Exploration (OEXP) and the Office of Space Flight (OSF) to assure that future space vehicle requirements guide propulsion technology efforts within the Chemical Transfer Propulsion Program. OEXP will define scenarios for future, human exploration missions in the Solar System. OSF will establish space vehicle requirements for these future space exploration missions, which will guide the development of propulsion technologies. Mission and vehicle definition will be important in determining propulsion system characteristics.

PROGRAM REVIEWS

Formal reviews of the Chemical Transfer Propulsion Program will be conducted semiannually: midway during, and near the end of, each fiscal year. The focus of the midfiscal year review will be on program content, status and progress versus the Project Plan.

The purpose of the review near the end of the fiscal year will be to evaluate the specific Project Plan against schedule, accomplishments and resources. The Lead Center will be responsible for making an integrated assessment of progress and accomplishments versus the Project Plan. Special, detailed technical reviews will also be conducted as necessary to ensure a planned pace of accomplishment to meet the goals and objectives of the program and to expose any problems or potential malfunctions before committing the program to the next step.

ADVISORY COMMITTEES

The OAST Space Systems Technology Advisory Committee (SSTAC) and the Aerospace Research and Technology Subcommittee (ARTS) will be utilized for the Chemical Transfer Propulsion Program. These advisory groups will provide top-level programmatic and technical guidance to the program. In addition, a Space Propulsion Advisory Committee will provide a more specific advisory function to the Chemical Transfer Propulsion Program. This committee composed of principal managers and technical specialists from NASA, other government agencies, industry and academe and will provide specific programmatic and technical guidance to the program once each year.

TECHNICAL PLAN

TECHNOLOGY READINESS OBJECTIVES

The technology readiness level of the liquid oxygen/liquid hydrogen expander cycle engine, as the Chemical Transfer Propulsion Program is initiated in FY89, can be considered Level 3, as shown in Table III. Key components and related component analytical models for high performance liquid oxygen/liquid hydrogen expander cycle engines, such as pumps, turbines, thrust chambers and health monitoring devices, have been designed, fabricated and tested for proof-of-concept in the Base R&T program over the past several years. With this as a starting point, the Chemical Transfer Propulsion Program will design, fabricate, and test components based on these proof-of-concept designs. These components will be tested in component test stands to determine expected performance and validate analysis and design methodologies.

As the technology readiness will be elevated to Level 4, the components will be integrated into a test bed engine for system characterization testing. Advanced engine components emerging from the mission-focused technology work element will be integrated with the test bed engine to form a focused-technology test bed and elevate technology readiness to Level 5. System validation of hardware and analysis concepts will be conducted in the focused-technology test bed in a simulated space environment to complete Level 6 of technology readiness. At this point in the program, in the late 1990's, the goals and objectives of the Chemical Transfer Propulsion Program will be met. Validated hardware and design methodologies will be available to the development program.

PROPULSION STUDIES

Objectives. Propulsion system studies will be conducted in the Chemical Transfer Propulsion Program to provide engine parametric data to support the mission/vehicle studies being conducted by the OEXP and the OSF. The studies will also identify and assess the technology requirements of candidate propulsion systems resulting from the vehicle studies.

Technical Approach. The initial propulsion system parametric data packages needed for the mission/vehicle studies will be generated as a task under the existing Orbit Transfer Vehicle Rocket Engine Technology contracts with Aerojet TechSystems Company, Pratt & Whitney, and Rocketdyne. These data packages will be provided to the OEXP and OSF contractors. Provisions will be made to enable close coordination between vehicle and engine study contractors such that the impact of vehicle derived requirements on the engine system can be assessed and the results utilized in the vehicle trade studies.

Once propulsion system requirements have been defined, mission-focused propulsion system studies will be conducted to optimize the engine components and/or systems to satisfy the vehicle requirements. These inputs will be used to guide the mission-focused technologies' activities.

Schedule of Milestones and Deliverables. The milestones for this effort are to support the mission/vehicle studies by OEXP and OSF and to implement the results of the mission/vehicle studies into the Chemical Transfer Propulsion Program.

Deliverables are:

(1) Engine parametric data packages	FY89
(2) Special engine parametric data packages	FY90
(3) Mission-focused engine component requirements	FY92
(4) Propulsion trade studies	FY92

MISSION-FOCUSED TECHNOLOGIES

Objective. The objective of mission-focused technologies is to provide mission-specific technology for inclusion into the focused-technology test bed engine that is scheduled for 1994. This technology will complement the results of the earlier engine technology from the Orbit Transfer Vehicle effort. The mission-focused technologies will include those issues that have not yet been defined; but are size, mission, and cycle specific. These issues are not being covered in the early engine technology effort but will be defined as a result of ongoing propulsion studies.

Technical Approach. The Work Breakdown Structure for this Work Package is shown in Fig. 8. The technical approach will be to define those technology issues that are parochial to a space-based, man-rated, reusable, fault-tolerant, liquid oxygen/liquid hydrogen expander-cycle engine that will be used for future space exploration. One aspect of definition will come from the propulsion studies. They will be the thrust level, throttleability range, mixture-ratio range, and size envelope. Where these aspects can not be defined, a broad range of values will be pursued. Up-dating of the configuration and cycle candidates will also be results of the propulsion studies. With this narrowing of configurations, the technology issues parochial to these configurations will be identified.

Once identified, these technology issues will be pursued both as individual components, and as subsystems in a series of proof-of-concept tasks (Level 3). These tasks would lead next to the component validation work at Level 4, and ultimately to the test bed engine demonstration work at Level 5.

Schedule of Milestones and Deliverables. The key milestone for this effort is to provide demonstrated mission-focused components for the build-up of the focused-technology test bed engine in FY94. A supplementary milestone is to have all of the mission-focused components available and characterized by FY97. In order to meet these goals, several intermediate milestones can be listed. One is to have proof-of-concept validated mission-focused components (Level 3) completed in FY92. To accomplish this, work on the mission-focused components must start in FY89.

ENGINE SYSTEMS TECHNOLOGY

Objectives. The objectives of this element are (1) validation of the high pressure, high performance expander cycle concept at the engine system level, (2) verification of the 1989 state-of-the-art methodologies for design and analysis of high pressure, high performance expander cycle components and engine system, (3) investigation of system effects on component design, control functions, and health monitoring techniques, and (4) demonstration of advanced, mission-focused components in a focused-technology test bed engine. The testing of the focused-technology test bed engine in a simulated environment will be the demonstration of the chemical transfer propulsion technology base for future space exploration missions.

Technical Approach. The Engine Systems Technology will consist of a contract effort and an in-house NASA Lewis effort.

Using the technology developed in the R&T Base in the 1980's, a contractor (or contractors) will design, fabricate, acceptance test, and deliver to NASA Lewis an advanced, high pressure, high performance expander cycle test bed engine. The test bed engine design will utilize the state-of-the-art design and analysis methodologies available. These methodologies will be verified during the contractor's testing of engine components and during the NASA Lewis in-house test bed engine test program.

The NASA Lewis in-house effort will be an extensive test program of the test bed engine to:

(1) Validate the high pressure, high performance expander cycle concept at the engine system level.

(2) Investigate engine system interactions, transients, and dynamics and what effect they have on mission-focused component designs.

(3) Investigate engine control functions and health monitoring techniques to help direct the mission-focused technology efforts.

(4) Verify engine system design and analysis methodologies.

As advanced components emerge from the mission-focused technologies efforts, they will be integrated into the test bed engine for system level testing. In this manner, the 1989-technology test bed engine will evolve into a focused-technology test bed engine in the 1994 to 1996 time period.

TECHNOLOGY TRANSFER PLAN

The effective transfer of propulsion technologies from the research center to the development center where the technology will eventually be developed into operational systems for future space transfer missions is recognized as a major goal of the Chemical Transfer Propulsion Program. Planning for the transition of Chemical Transfer Propulsion technology to advanced development in preparation for implementation involves both Headquarters and the field center.

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TABLE I. - CHEMICAL TRANSFER PROPULSION TECHNOLOGY REQUIREMENTS

[Must be compatible with surface heat loads and stay times to reduce propellant losses to mission acceptable levels.]

Mission	Thrust, Klb_f	Fuel	ISP, sec	Burn time, min	Reuse	Throttle-able	Space exposure
Mars transfer (1st and 2nd stage)	75-100	LOX/LH2	>460	<30	Yes (10)	No	Months
Lunar transfer Mars transfer (3rd stage) Mars/Lunar return	20-40	LOX/LH2	>480	45-90	Yes (10)	No	Years
Mars and Moon Descent	20-40	LOX/LH2	>450	10-20	Mars, No Moon, Yes	Yes	Years
Mars and Moon Ascent	20-40	Note 1	Maximum	<20	Mars, No Moon, Yes (10)	No	Years

TABLE II. - TECHNOLOGY GOALS FOR SPACE TRANSFER ENGINE

Parameter	Reference engine system	Space transfer vehicle engine technology goals
Propellants		
Fuel	Hydrogen	Hydrogen
Oxidizer	Oxygen	Oxygen
Power cycle	Expander	Expander
Vacuum thrust	[a]16 500 lbf	[b]5 to 50 Klbf
Vacuum thrust throttling ratio	Not specified	[c]20:1
Vacuum specific impulse	444.4 lbf-sec/lbm	>490 lbf/sec/lbm
Engine mixture ratio,O/F	[a]5.0	[d]6.0
Engine mixture ratio range	4.4 to 5.6	[e]5.0 TBD
Combustion pressure	[a]465 psia	[f]>1500 psia
Nozzle area ratio	61:1	1000:1
Weight	310 lb	[g]TBD
Length	70.1 in.	[g]TBD
Life		
Operational	3 starts, 4,000 sec	>500 starts, 40 hr
Service free	Not specified	>100 starts, 4 hr
Basing	Earth	Space
Human rating	No	Yes
Design criteria		
Operational	Not specified	Fault tolerance
Aerobrake	None	Compatible with aeroassist transfer
Maintenance	Not specified	In-space maintenance
Diagnostic instrumentation	None	Integrated controls and monitoring

[a]Design point.
[b]Thrust goal to be determined. Expected to be in 5,000 to 50 000 lbf thrust range.
[c]Continuous and stable throttling from rated thrust to 5 percent thrust with minimum performance loss.
[d]Mixture ratio goal to be determined. Performance goal specified at a mixture ratio of 6.0.
[e]Engine mixture ratio range to be determined. Broad range desired for compatibility with fault tolerant engine operation and to potentially allow mixture ratio change during mission.
[f]Chamber pressure must be compatible with performance and throttling goals.
[g]To be determined.

TABLE III. - TECHNOLOGY READINESS LEVELS

Basic research	Level 1	Basic principles observed and reported
Feasibility research	Level 2	Technology concept/application formulated
	Level 3	Analytical and experimental critical function and/or characteristic proof-of-concept
Technology development	Level 4	Component and/or breadboard validation in laboratory
	Level 5	Component and/or breadboard demonstration in relevant environment
Technology demonstration	Level 6	System validation model demonstrated in simulated environment
	Level 7	System validation model demonstrated in space

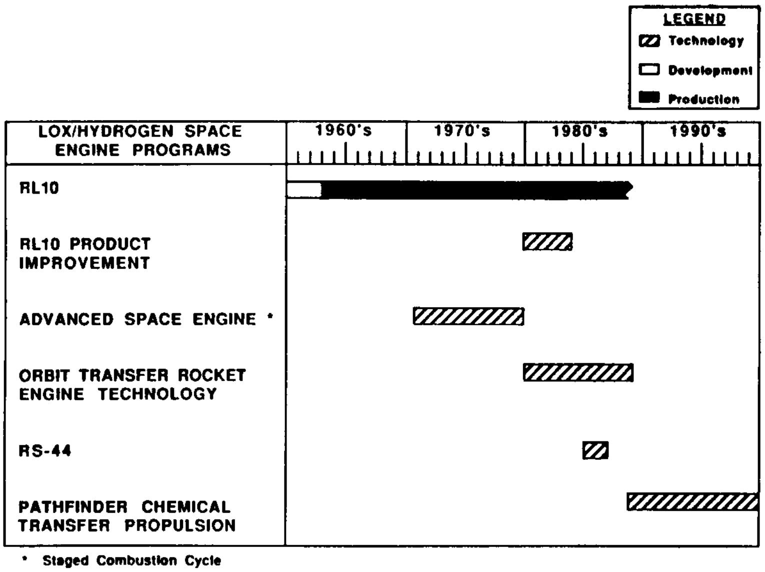

Figure 1: LOX/Hydrogen Upper Stage Engine History

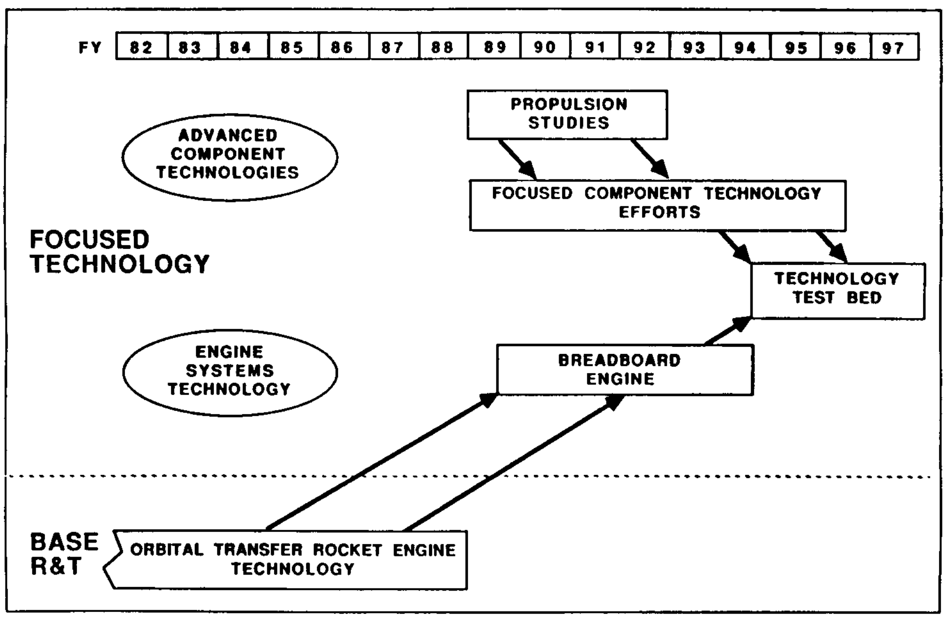

Figure 2: Chemical Transfer Propulsion Technical Approach

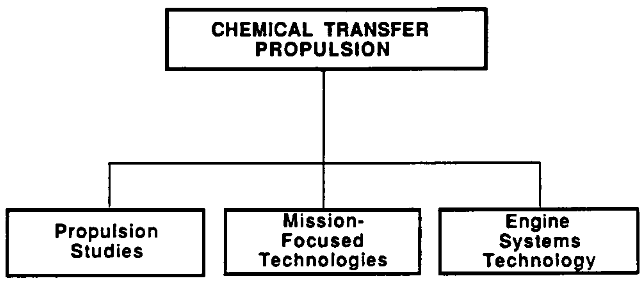

Figure 3: Work Breakdown Structure for Chemical Transfer Propulsion Program

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