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The process used by NASA in the selection of the engine for the Space Exploration Initiative mission is described. The major propulsion requirements of the engine are addressed along with the engine options and key drivers and trades. Special attention is given to the requirements of the propellant feed system and the reaction control system. As a result of the 90-study, four moderate chamber pressure expander-cycle oxygen/hydrogen engines with a thrust level of 20,000 lbf each were selected for the lunar transfer vehicle. The paper also presents results of architecture studies and of advanced engine test bed studies. I.S.

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Engine Selection for the Space Exploration Initiative-A Status Report

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Engine Selection for the Space Exploration Initiative

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Abstract

The paper describes the selection process utilized by NASA during the conduct of the 90-day study of the mission set that has been known as the Lunar/Mars Initiative, the Human Exploration Initiative, and (currently) the Space Exploration Initiative (SEI). It is directed specifically toward the propulsion system selection, with emphasis on the lunar mission, and will focus on the work done to date at NASA's Marshall Space Flight Center and Lewis Research Center to determine the engines to be used for the proposed Lunar Transfer Vehicle and the Lunar Exploration Vehicle. The same engine or derivative could be used also for the Mars Exploration Vehicle. Results of trade studies will be presented which show that selection cannot be readily made on the basis of engine performance alone, because the cost of launching hardware elements of the LTV/LEV and the required propellant are very high. One conclusion reached was that a decision must be made to use either life cycle costs or annual program costs as the economic figure of merit, because they drive the selection in opposite directions. That is to say, using life cycle costs as a figure of merit drives toward the selection of an advanced engine, whereas minimization of annual program costs forces one to consider modifications to existing engines, to avoid the DDT&E costs associated with an advanced engine.

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Introduction

After the President's message on July 20, 1989 in which he directed NASA to study means of returning to the moon and subsequently going to Mars, several teams were formed to carry out an initial assessment of the various ways of accomplishing this goal. The Marshall Space Flight Center (MSFC) was designated as "lead center" for the Transportation Infrastructure for the purposes of this effort, and strong participation from the Lewis Research Center (LeRC) and the Johnson Space Center (JSC) was sought in the area of propulsion system selection and definition. The early activity was conducted principally in an isolated area at MSFC, with teams of NASA engineers at LeRC and JSC, three engine contractors, Aerojet, Pratt & Whitney, and Rocketdyne, and two prime contractors - Boeing and Martin-Marietta, participating there and at their home locations. This paper reflects the process of the 90-day study and the results obtained by these teams, as well as the later, continuing effort. In the companion Exploration Technology Program, LeRC has been designated as lead center for space-based engines, with MSFC as the principal participating center. Figures 1 and 2 depict the lunar mission Transportation Elements.

Approach

From the outset, propulsion was recognized as a key technology by the SEI study team, and special emphasis teams were formed to address the approach to be taken in the selection of the propulsion systems for both the lunar and the Mars missions. Three program development options were formulated for addressing the range of requirements and ways of satisfying those requirements; these are shown in Figure 3. The technology, the timing, and the development approach to vehicle evolution are significantly different for each one. The first, which was used in earlier Orbital Transfer Vehicle (OTV) studies, begins with the simplest and progresses to more complicated vehicles. It starts with low technology for the STV mission, evolves with improved technology to the lunar and eventually to the Mars family of vehicles. The second aproach begins with the objective of designing for the lunar transportation set of requirements and evolves forward and backwards to satisfy the other two sets of mission requirements. Selected high-leverage technologies applicable to later Mars missions are emphasized early; e.g. , propulsion and aerobraking. Initial vehicle concepts could include design "scars" for earlier, expendable Space Transfer Vehicle (STV) missions. This is the approach that was used in a simplified form by the 90-day study, and is now being implemented more rigorously by the Office of Space Flight (OSF)-funded STV studies. The third approach is to start with the Mars mission requirements set as the basis of the transportation systems designs, and accept the resultant design impacts for lunar and STV missions. To do this in all areas of technology requires extensive forecasting of technology maturation and may introduce unnecessary technological obsolescence into the Mars vehicles.

Phase 1: 90-day Study

The objective of the propulsion special emphasis team was to strike an optimum balance between DDT&E cost and schedule, required mass in LEO, and life cycle costs. The trades needed to determine the optimum mix are many and only a few are elaborated on here. These trades have direct impact on the engine as well as significant impact on the vehicle. We have attempted to identify the key drivers for the overall propulsion system, trade these drivers to determine their impact on engine and vehicle, then define the propulsion system we think will best meet the mission objectives. Trades were developed for three main areas; 1) Engine - this includes the gimbal system, health monitoring, and man rating 2) Propellant Management - this includes the tanks, feed system, mass gaging, fill, vent, autogeneous pressurization, purge, and pneumatics systems 3) RCS system - this includes feed system, tanks, thrusters, and health monitoring for the RCS.

Requirements:

The top level requirements for the lunar outpost transportation system were as follows:

- Flight test in 1999; Lunar cargo landing in 2000; First manned landing in 2001
- Cryogenic oxygen/hydrogen engines
- Design for five flights without major maintenance
- LTV/LEV capable of in-space refueling
- LEV sized to provide 27 metric tons to lunar surface from low lunar orbit
- LEV capable of 30 days maximum stay time on lunar surface

These were then reduced to the following major propulsion requirements:

- Reliable, rugged; capable of space-basing; man-rated
- Long life; five flights with no major maintenance
- LEV must be throttleable over an undefined range for lunar landing
- Sufficiently high performance to result in an affordable program
- Capable of in-space propellant resupply
- First flight in 1999; engine new start in 1991
- Common engine for both LTV and LEV
- Minimize fluids required; results in autogenous pressurization capability

At the outset of the 90-day study, a process relating the propulsion system trade studies that would be done to higher level requirements and system-level trades was established, as shown in Figure 4, and the propulsion related trades were categorized into three levels, as shown in Figure 5.

Engine Options:

The engines used for the trades were selected based on varying technology levels. The current off the shelf engine is the RL10A-3-3A soon to be upgraded to the RL10A-4 for the Air Force. The intermediate engine is an RL10 derivative with increased performance. The Advanced Space Engine (ASE) is a completely new engine with high chamber pressure & expansion ratio yielding high performance. The characteristics of each of these engines are shown in Figure 6.

The modified RL10A-4 is shown as the current engine. As available today, it will not meet the mission requirements without modifications for throttling and autogenous pressurization. These modifications will require some DDT&E funding to enhance the existing design. The RL10 derivative will have throttling, autogenous pressurization and somewhat higher Isp but will still have the lower Pc and 20 seconds lower specific impulse (Isp) than the ASE. The ASE offers all of the features mentioned above plus space basing, health monitoring, better operational characteristics and higher performance. The differences are reflected in the DDT&E costs.

The difference in technology levels of the engines is seen most dramatically in the performance differences. The thirty seconds difference in Isp translates into more mass in LEO for a given mission. Assuming a payload of 150K pounds on a Heavy Lift Launch Vehicle (HLLV) and a cost of $300 million per launch the effect of the lower performance is evident in Figure 7, which shows that the RL10 derivative and RL10A-4 will require one more launch per mission. The cost of this extra launch will offset the DDT&E costs of the ASE within a small number of lunar missions, for these cost and launch weight assumptions.

Key Drivers and Trades:

Several drivers that affect the LTV and LEV engine selection are: vehicle thrust to weight, thrust level, number of engines, throttle range, number of perigee burns, man rating, and commonality across multiple program elements. These factors are strongly interdependent, thereby driving one to a complex, iterative evaluation process. An example of how they are interrelated is: Man rating with cryogenic engines requires multiple engines; Symmetry with engine-out capability leads to selection of four engines; Assuming a single perigee burn and a vehicle thrust to weight for the LTV of 0.2 sets the maximum engine thrust; the desire for a common engine and the LEV touchdown "g" limit together set the throttling requirement. Multiple perigee burns will decrease the vehicle T/W needed in LEO which lowers the engine thrust level and in turn decreases the throttle range needed on the LEV. All of these options affect the mass required in LEO, which is used as the scoring factor.

Propellant Feed System:

The current LTV is a 1.5 stage vehicle with two sets of two drop tanks. This configuration is very demanding on the propellant feed system because of the amount of manifolding and number of quick disconnects required. Feed system complexity can result in increased propellant loss due to boiloff. Other areas of concern are propellant acquisition, mass gaging, propellant transfer, reusable quick disconnects, engine NPSP requirements, and the level of sensing/monitoring required on the feed system.

Commonality in the propulsion system is desirable. The requirement to return the propulsion module (engine and feed system) in the Space Shuttle limits the diameter of the module to 15 feet. The module could use two engines in an STV mission, then four engines for the LTV and LEV with possible application to the Mars mission on the lander, second stage TMI, TEI, and midcourse maneuver stage. An example is shown in Figure 8.

Reaction Control System (RCS):

The RCS needs to be considered carefully; it will be used in all flight phases: station keeping, attitude control, settling, pointing, lander maneuvering, and for control during the aerobrake maneuver. The demands range from fine tuned, precise control for the GN&C system to high thrust, quick response during the aeropass. Our trades compared an integrated O/H, a storable bipropellant, and a hydrazine system. The integrated O/H system has the benefit of using existing propellants and lighter weight at the cost of higher risk and more DDT&E. The hydrazine system is more compact, uses flight proven technology, has higher reliability, and less complex operation at the expense of more weight.

90-Day Study Recommendations:

These and other considerations led to the selection of four moderate chamber pressure (1500 psia), expander cycle oxygen/hydrogen engines with a thrust level of 20,000 lbf of thrust each for the LTV. The same engine with a throttle capability of 15:1 is used for the LEV. The engine characteristics are shown in Figure 9. The performance of this engine was used in a series of vehicle trades to drive out the effect of engine selection upon number of HLLV launches. The results of these trades are shown in Figure 10, where it is apparent that use of an RL-10 derivative would require one additional HLLV launch for each lunar mission.

The propellant feed system was manifolded from the drop tanks to the core tanks and then to the engines to provide the lightest and most thermally efficient system. The RCS selected was a combination of O/H for the LTV to save weight and hydrazine for the LEV to avoid increased cryogenic boiloff losses on the lunar surface.

Phase 2: Continued Propulsion Definition Activities

There are two elements of the current SEI propulsion definition activities; the continuing architecture studies being performed by the MSFC and its contractors, Martin and Boeing, under OSF sponsorship, and the Advanced Engine Test Bed being pursued by the LeRC and its contractor, Pratt & Whitney, under OAET sponsorship. In the former, a strong effort is being made to maximize the interaction between engine and vehicle contractors early in the process of architecture development in order to drive out all the requirements and characteristics of the space engine. This is essential to the timely initiation of engine development programs for the SEI. In the latter, an effort has been started to develop an engine test bed in which to pursue component technology for a high performance expander cycle engine, along with other technologies such as advanced integrated health monitoring techniques.

Almost independent of the architecture and the schedule of the SEI, two assumptions can be made. First, chemical propulsion will be required for some phases of the missions. Second, in-space assembly will be required, at least for the Mars missions. The current baseline program assumes chemical propulsion for the lunar stages and assumes initiation of lunar stage design and development in 1995.

Architecture Studies

The Space Transportation and Exploration Office at MSFC has sponsored a series of workshops to examine the engine needs for the Space Transfer Vehicle. Its principal thrusts are to provide information and data that can serve to: focus the engine technology programs, select the STV concept, support contractor and in-house studies, and define the approach to the development of engine design criteria. The first workshop was held in April, 1990, and the next one is planned for mid-July, 1990. The workshops are chaired by MSFC, with participation by LeRC, JSC, JPL, KSC, and SSC from the NASA side, and Martin, Boeing, Aerojet, Pratt & Whitney, and Rocketdyne from the contractor side of the house. The following is a compilation of some of the results of the first workshop.

System Requirements:

System requirements, including those unique to the Lunar Transfer Vehicle (LTV) and Lunar Excursion Vehicle (LEV), also drive the STV engine requirements. These include one flight per year, reusable for five flights; minimum maintenance; in-orbit assembly, mating and checkout; lunar landing; and payload requirement (which dictates thrust level).

STV Engine Requirements

The SEI program and the STV studies provide the opportunity to evaluate the engine requirements for the next generation space engine within the context of a credible but technologically demanding program. Some of these requirements are generic, basically independent of the architecture, and others are mission and configuration dependent.

Generic requirements:

Reliability: High reliability is essential for dependable vehicle operations and safety for all missions, particularly manned missions away from the vicinity of the Earth. Achieving the ultra-reliability demanded may well be the most difficult technical challenge for development of the engine, particularly in a space-based mode of operation.

Space-Basing: Space-basing is necessary for SEI, based on the needs for on-orbit assembly of the large lunar or Mars transportation systems, reusability (to lower the cost of Earth-to-orbit transportation), and the need for routine transportation for permanent human presence beyond Earth's orbit. The need for on-orbit assembly of the vehicle will require the capability to mate, de-mate, inspect, test, refurbish, and maintain the vehicle and its subsystems before, during, and after a mission. In terms of engine requirements, a space-based engine will be designed for minimum maintenance; have a comprehensive health monitoring system utilized for pre-mission checkout, real time safety monitoring and incipient failure mode identification, and post-firing trend monitoring; and will be designed to withstand long exposures to the space environment. As a goal, the engine would have interfaces with the vehicle permitting engine removal and installation by a remote manipulator system (RMS), in order to avoid extra-vehicular activity (EVA) by the astronauts.

Man-Rating: Man-rating is the process of evaluating and assuring that the hardware and software can meet prescribed, safety-oriented design and operational criteria. It is an integral part of the design, development, verification, management, and control process. In terms of engine requirements, man rating is characterized by high reliability, failure tolerance, design and installation for contained damage (no secondary damage to the rest of the vehicle), and design or processing changes in response to failures.

Life and Reusability: As a goal, the engine will be designed for five years, five mission life while exposed to the space environment. The near-Earth environment with its relative abundance of atomic oxygen may well be especially demanding. Possible material degradation must be incorporated into the engine design factors. Material selection and development for space-based engines may emerge as an important technology and design requirement after examination of the available data, particularly that from the Long Duration Exposure Facility (LDEF).

Health Monitoring: A good health monitoring system capable of preflight, flight, and post flight diagnostics, fault isolation, and safety monitoring is essential for a man rated, space-based engine.

Design Margins: Design margins will be driven by the requirement for ultra-reliability. Weight is expected to be a secondary issue. The margin requirement is to be determined by trade studies and other investigations.

<u>Mission and configuration dependent requirements</u> (subject to vehicle trades):

Vehicle/Engine Interfaces: Interfaces must be simple and reliable, preferably having interfaces with the vehicle permitting engine removal and installation by a remote manipulator system, commensurate with the space-basing requirement, but are otherwise subject to vehicle/engine trade studies. Examples of areas to be traded are whether or not purges are required by the engine, autogenous pressurization of propellant tanks vs vehicle-supplied pressurant, vehicle or engine mounting of the engine controller, vehicle command data to the engine, condition monitoring data to the vehicle, hydraulic or pneumatic supply if required, and vehicle or engine mounting of boost pumps if required. Redundancy management and engine system architecture will also affect vehicle/engine interfaces. For example, turbopumps and combustion chambers might be manifolded for redundancy.

Engine throttling: Engine throttling is necessary for accurate and safe landing. Throttling operations will require extensive study. In addition to the throttling range, it is not yet clear how fast the engine must respond to throttling requirements nor whether the engine must operate continuously over the full range or can pass through some ranges in a transient manner.

Performance Specifications: Chief among these are thrust, specific impulse (Isp), and mixture ratio. Size specification, primarily driven by gimbal angle requirements and fixed vehicle diameter, will influence the chamber pressure selection, expansion ratio, and Isp selection. The engine will probably be required to operate over some range of mixture ratios for efficient propellant utilization. A weight specification will probably not constrain the engine design, since reliability and space-basing are paramount design drivers.

Engine System Architecture: The manifolding of combustion chambers and turbopumps for redundancy management and the use of bell nozzles or aeroplug engines are examples of trades that will need to be made with the vehicle.

Operations: Remote installation and automatic checkout are desirable implementations of the space-basing requirement. However, considerations of the cost-benefit ratio for various implementations of remote installation and automatic checkout may require some "hands-on" installation and servicing at transportation system nodes. This may in turn drive the vehicle configuration to permit access in a space environment.

Advanced Engine Test Bed

The propulsion system selection studies identified that a new, high performance engine would result in lower life cycle costs for the SEI transportation infrastructure. Such a system currently being studied by the Lewis Research Center is an oxygen/hydrogen expander cycle engine of 7,500 to 50,000 lb thrust or more; it would achieve high performance through efficient combustion, high combustion pressure, and a high area ratio exhaust nozzle. The engine is likely to require a high degree of versatility in terms of throttleability, operation over a wide range of mixture ratios, autogenous pressurization, inflight engine cooldown and propellant settling. Firm engine requirements include long life, man-rating, reusability, space-basing, and fault tolerant operation.

The Advanced Expander Test Bed (AETB) is a key element in NASA's Chemical Transfer Propulsion Program and is planned to be the focal point for development and demonstration of advanced expander cycle oxygen/hydrogen engine technology and advanced component technology. The AETB will be used to validate the high-pressure expander cycle concept and investigate system interactions, and will also be used to conduct investigations with advanced mission focused components and new health monitoring techniques. It will operate at combustion chamber pressures up to 1200 psia using a split expander cycle at propellant flowrates equivalent to 20,000 lbf vacuum thrust. Its requirements are summarized in Table 1.

Table 1. AETB Requirements

Propellants	Oxygen/Hydrogen
Cycle	Expander
Thrust	> 7500 lb (20,000 lb selected)
Pressure	Nominal 1200 psia
Mixture Ratio	6.0 ± 1.0 (optional operation at 12.0)

Throttling	20% min (5% desirable)
Propellant Inlet Conditions	
Hydrogen	38°R, 70 psia
Oxygen	163°R, 70 psia
Idle Modes	Tankhead (nonrotating pumps)
	Pumped (low-NSPSH pumping)
Life	100 starts
	2 hr (5 hr desirable)

The AETB program spans a 60 month period, including a 9 month preliminary design and 6 month final design phase, followed by fabrication, assembly, and component and engine acceptance testing. The AETB will be acceptance tested at Pratt & Whitney Aircraft, then delivered to LeRC, where the bulk of the testing will be conducted.

Development and verification of advanced design methods is a primary goal of the AETB Program. Steady-state and transient simulation codes will be produced. These two codes and other selected design models will be verified during component and engine acceptance testing.

Summary and Conclusions

The SEI program and the STV studies have helped to clarify the engine requirements for the next generation space transportation propulsion system for manned exploration of the planets. The challenge is to develop a highly reliable, long life, space-based propulsion system that requires minimum maintenance, is reusable and is capable of installation and repair with the use of robotics. The studies have also shown the need to extend the concept of health monitoring to encompass automatic pre-mission checkout. Continued studies are expected to clarify and determine the requirements in the areas of vehicle/engine interfaces, engine system architecture, throttling, and performance.

Whereas much of the technology effort in the past has been focused on performance-related issues, it is clear that much effort will also need to be expended in the future on space-basing, life, vehicle/engine interfaces, and health monitoring if the requirements of the Space Exploration Initiative are to be achieved. Although not normally considered technology, work is also needed to define engine system architecture, margins, DDT&E methodologies, processing, and inspection techniques to achieve the enhanced reliability required of man-rated, space-based engines.

Acknowledgements

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LUNAR TRANSPORTATION SYSTEM
(90 DAY REFERENCE)

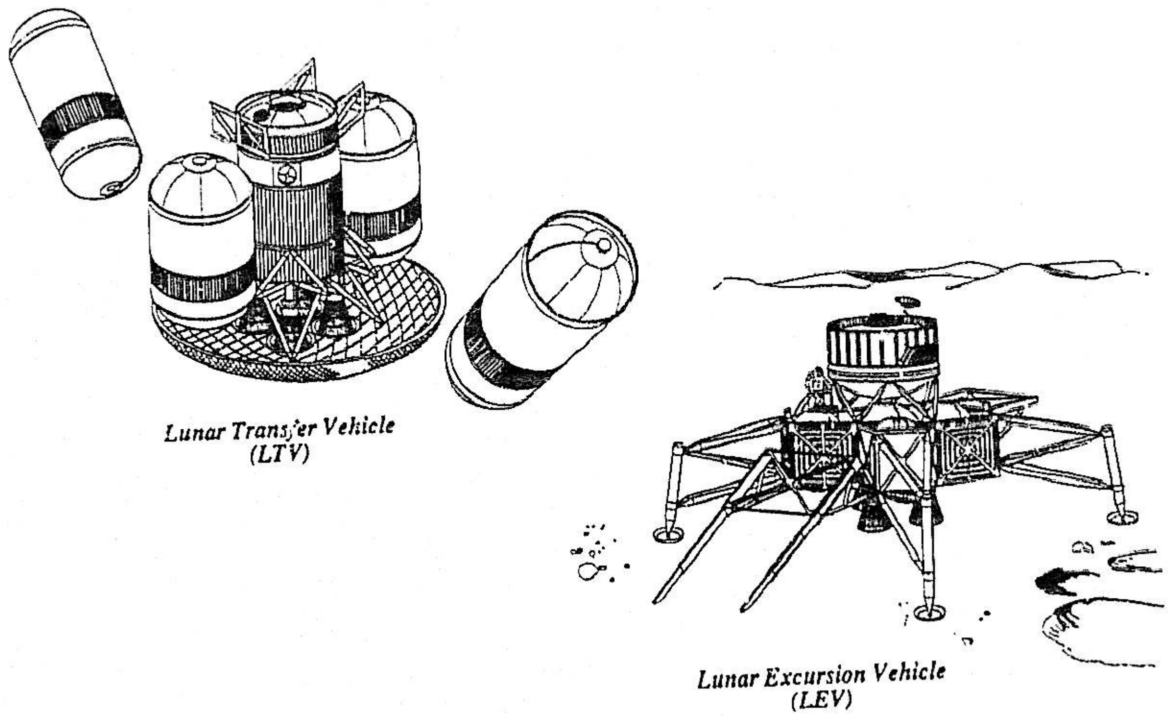


Figure 1

LUNAR TRANSFER OPERATIONS
(90 DAY REFERENCE)

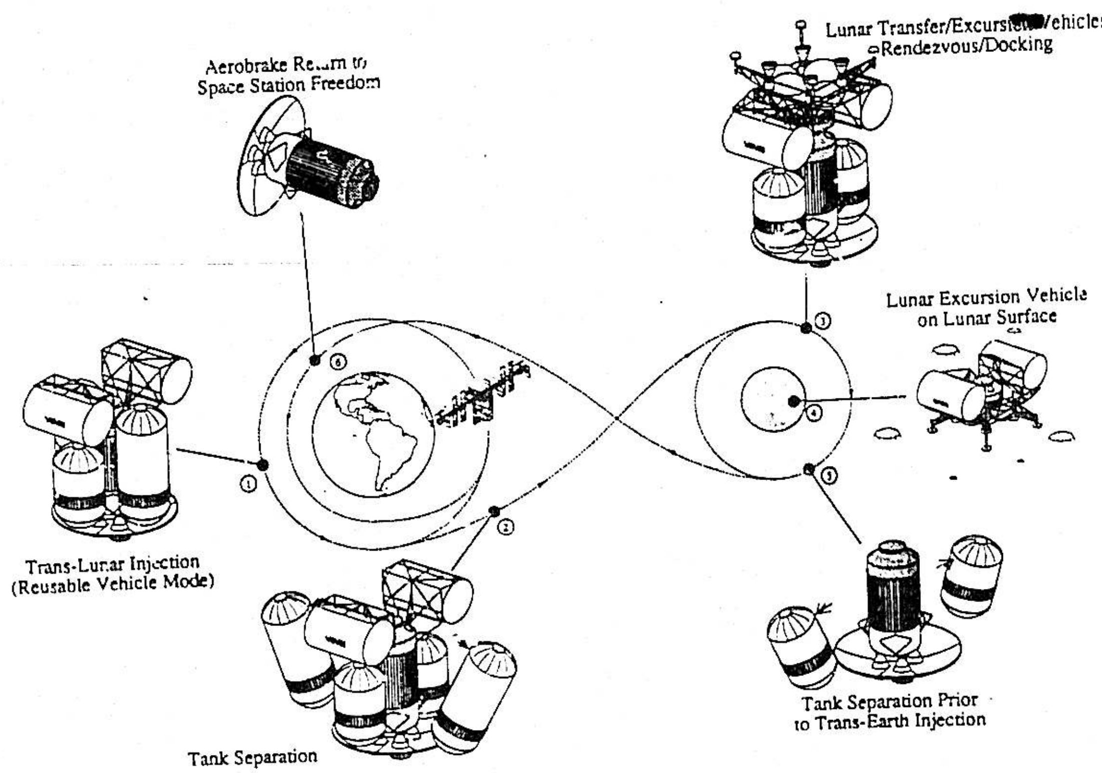


FIGURE 2

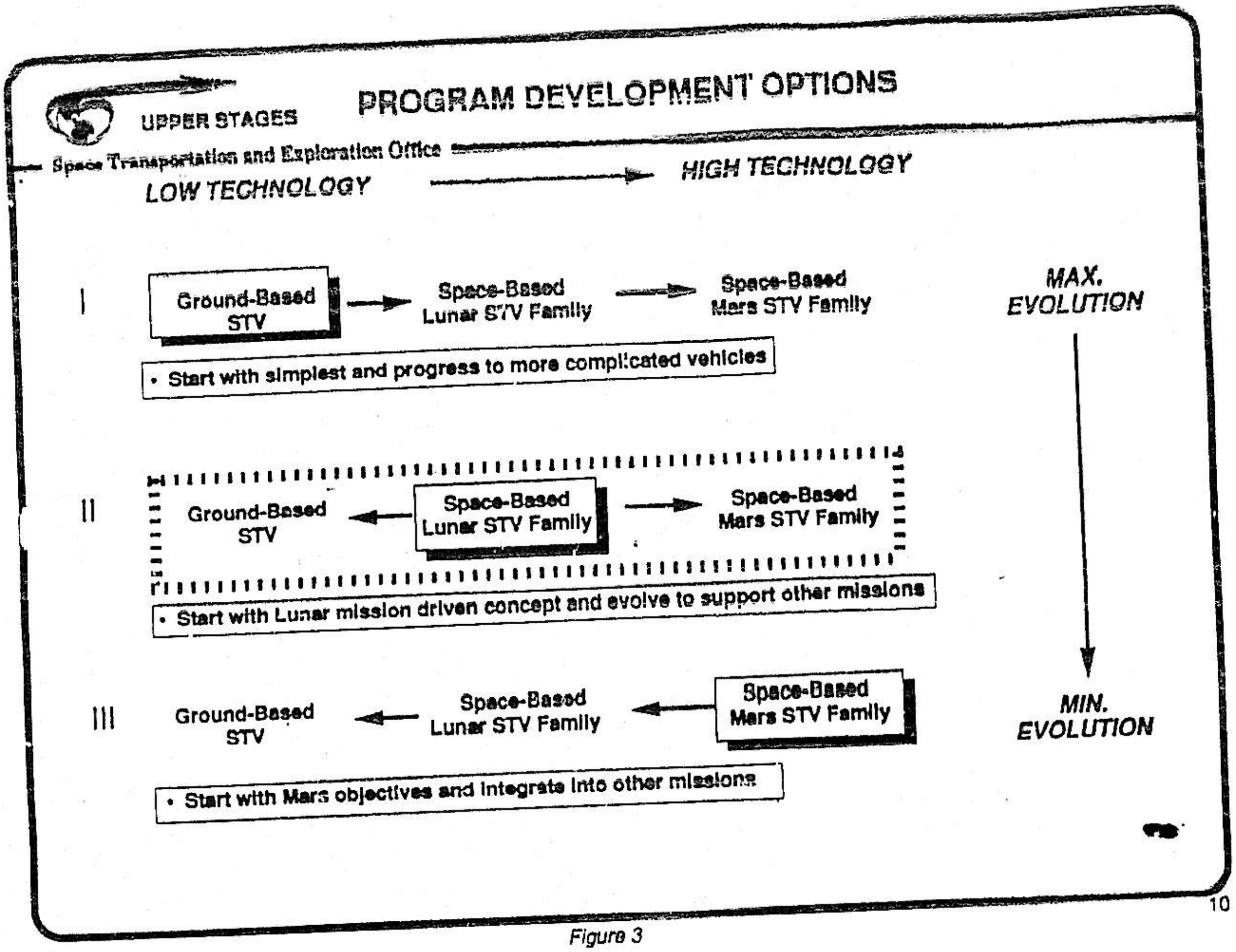


Figure 3

Fig. 4: PROPULSION TRADE PROCESS

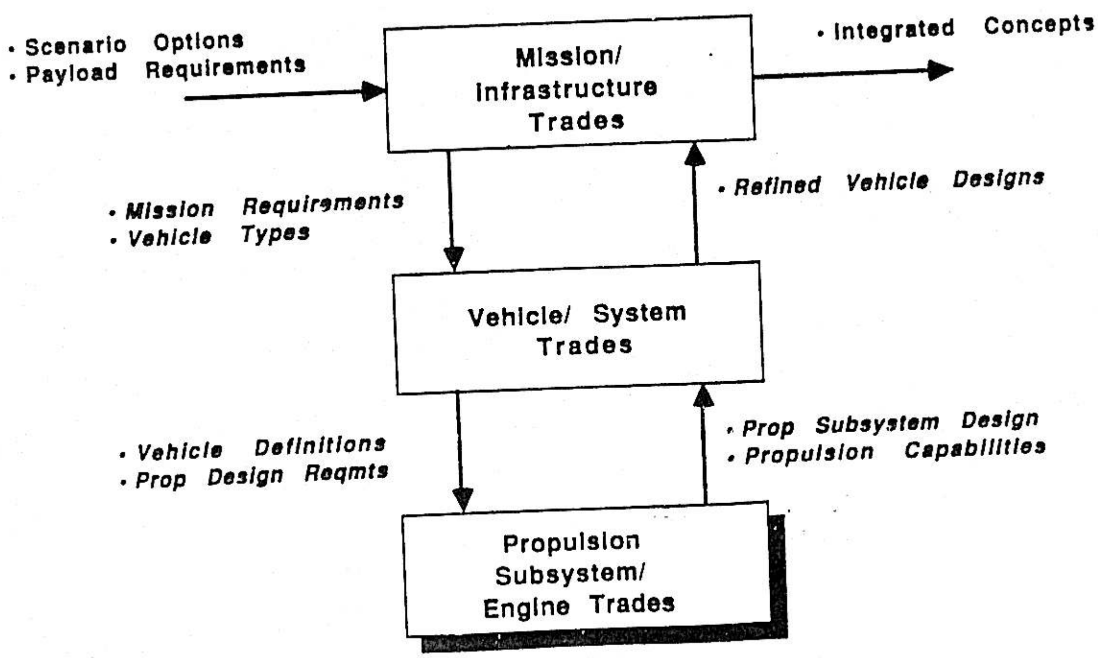


Fig. 5: PROPULSION-RELATED TRADES CATEGORIZED INTO 3 LEVELS

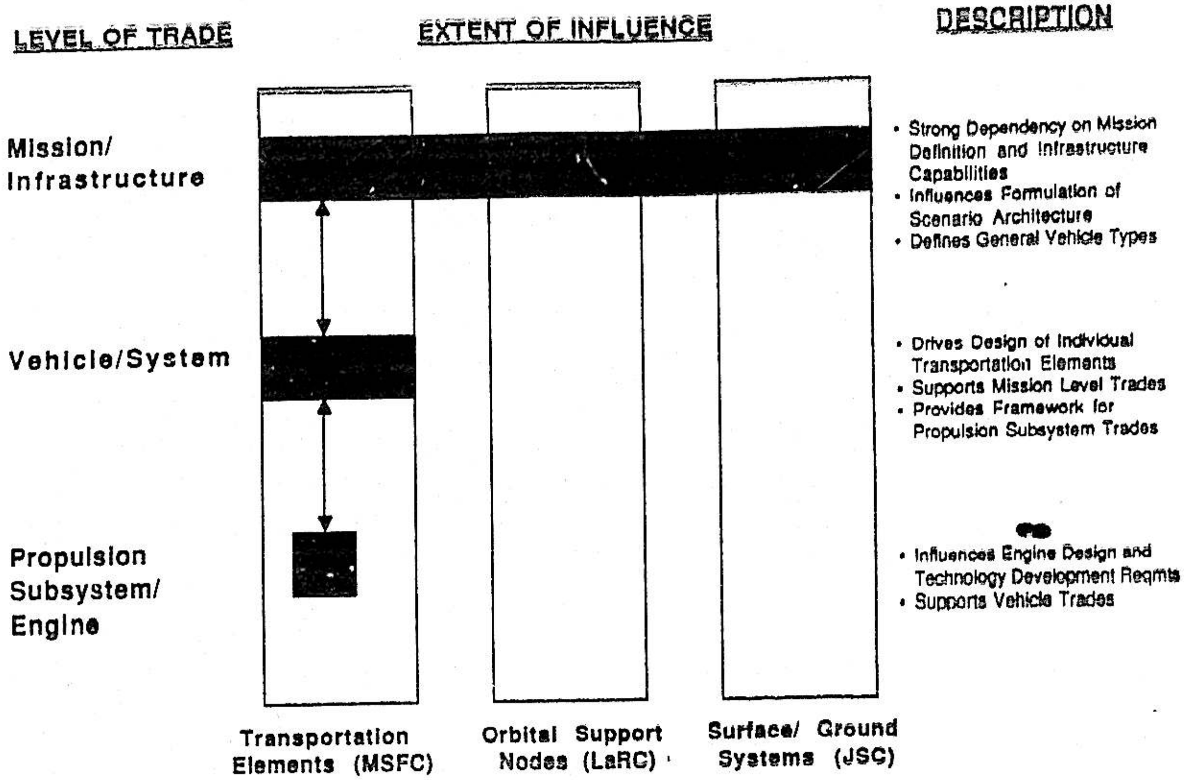
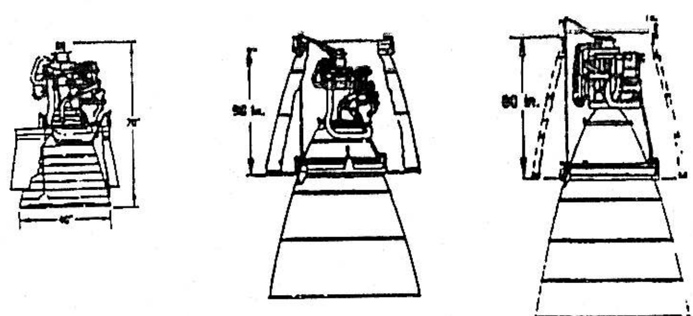


Fig.6: LTV/LEV ENGINE COMPARISON



	CURRENT	ENHANCED	ADVANCED
	MOD RL10 A-4	RL10 IIB	ASE
THRUST vac, lbf	20.5K	15-20K	15-20K
Isp vac, sec	449	460	481
THROTTLING RANGE	10:1	20:1	20:1
MIXTURE RATIO	5	6	6-5
EXP RATIO	83	205	640
PC, psia	565	400	1000-2000
WEIGHT, lb	365	422	460-500
EXIT DIA, in (O.D.)	46	40/70.8	40/64
LENGTH, in	70/90	55/110	60/120
LIFE, firings/hr	20/1.25	190/5	300/10

LAUNCH COST COMPARISON FOR RL10A-4, RL10 IIB, AND ASE ENGINES

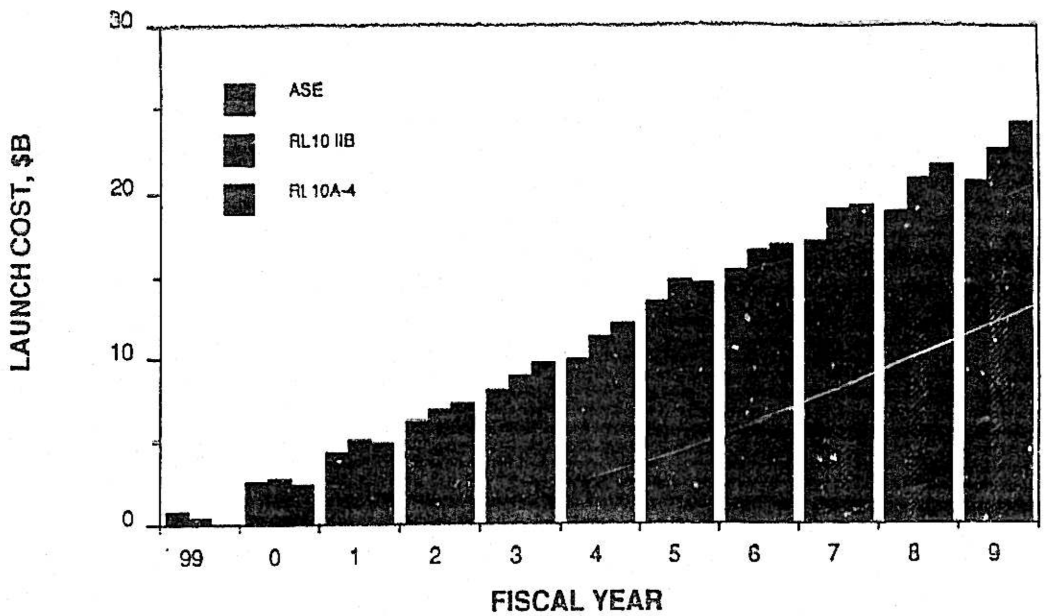


Figure 7

Fig. 8 - LTV AND LEV ENGINE AND FEED SYSTEM COMMONALITY

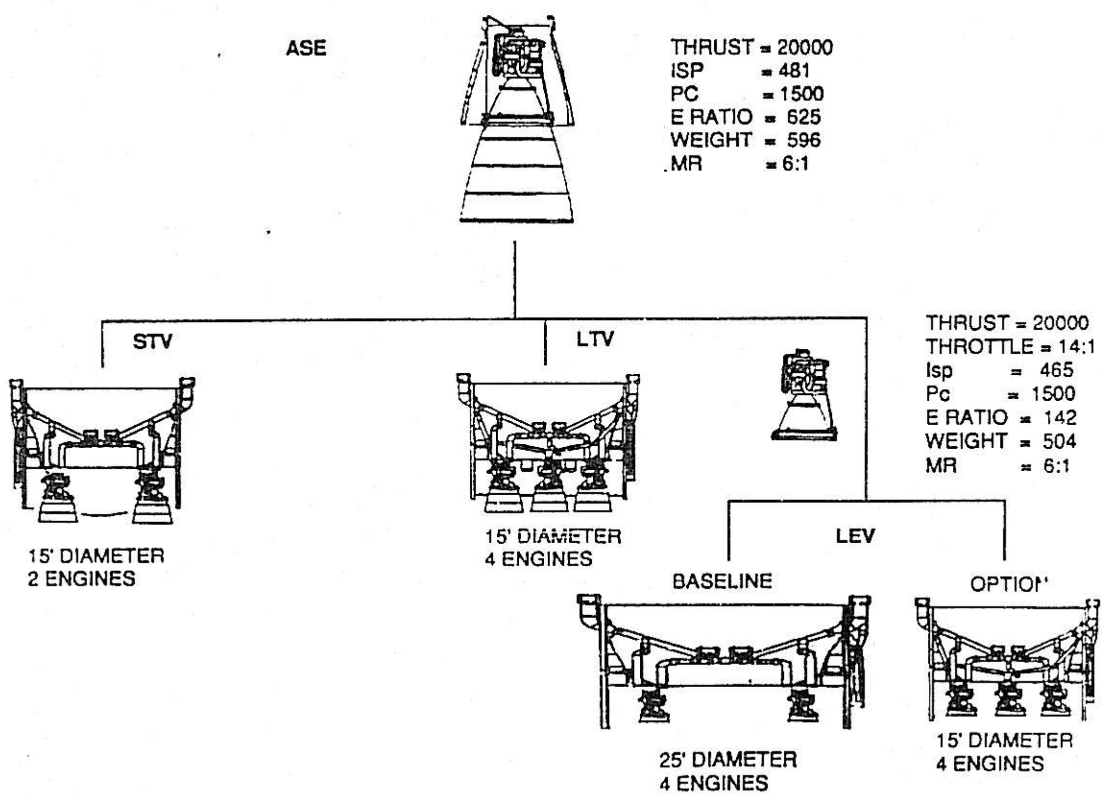
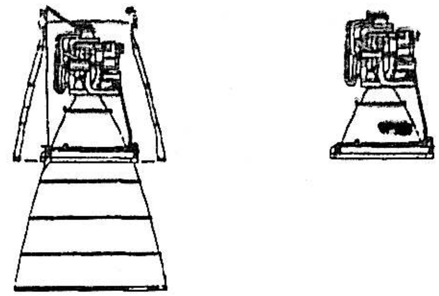


Fig. 9 - LTV/LEV REFERENCE ENGINE



	LTV	LEV
THRUST, Klbf vac	20	20
Isp, sec vac	481	465
CHAMBER PRESSURE, psia	1500	1500
MIXTURE RATIO	6	6
EXPANSION RATIO	625	142
EXIT DIAMETER, in (I.D.)	72	35
ENGINE LENGTH, in	141	85
STOWED LENGTH, in	73	* *
Engine Weight, lbm	596	504
THRUST TO WEIGHT	33.6	39.7
Isp EFF, %	98.1	98.1
THROTTLING RANGE	TANK HEAD IDLE PUMPED IDLE	TANK HEAD IDLE <20:1

Fig. 10 - ENGINE OPTIONS FOR 1.5 STAGE 1ST PILOTED MISSION (27 MT)