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Lunar Lander and Return Propulsion System Trade Study

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Lunar Lander and Return Propulsion System Trade Study

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National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

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The authors wish to thank the numerous industry and NASA organizations for their indispensable help in the conduct of this trade study. The discussion and information obtained were vital to the completion of this project, even though it is recognized that a consensus on the results was not possible. When the future yields a desire to land on the Moon and return, it is hoped this trade study will be beneficial and that the participants, industry, and NASA will provide the same level of spirited involvement.

ABSTRACT

A trade study was initiated at NASA/Johnson Space Center in May of 1992 to develop and evaluate main propulsion system alternatives to the reference First Lunar Outpost (FLO) lander and return-stage transportation system concept. The reference FLO transportation vehicle, which emphasizes the use of existing technology and hardware, consists of a pump-fed liquid oxygen/liquid hydrogen lander stage driven by four modified Pratt & Whitney RL10A-3-3A engines, and a pressure-fed monomethyl hydrazine/nitrogen tetroxide (MMH/N_2O_4) return stage propelled by three modified Aerojet AJ10-118 engines. Thirteen alternative configurations to this reference design were developed in the trade study to explore the impacts of various combinations of return stage propellants, using either pressure- or pump-fed propulsion systems and various staging options.

Besides two-stage vehicle concepts, the merits of single-stage and stage-and-a-half vehicle configuration staging options were also assessed in combination with high-performance liquid oxygen and liquid hydrogen propellants. Chlorine pentafluoride, a dense, highly reactive oxidizer, was combined with hydrazine in a two-stage configuration to evaluate the performance potential of this pressure-fed Earth-storable propellant. Finally, configurations using an integrated modular cryogenic engine were developed to assess the potential improvements in packaging efficiency, mass performance, and system reliability compared to non-modular cryogenic propulsion system designs.

The selection process chosen to evaluate the effectiveness of the various propulsion system designs is the Analytic Hierarchy Process (AHP). AHP is a structured approach for handling complex problems with interrelated study criteria and subjective priorities.

The trade study showed that a pressure-fed MMH/N_2O_4 return stage and RL10-based lander stage is the best option for a 1999 launch. The return stage should be optimized by using a higher performance single M20/N_2O_4 engine (M20: 80% N_2H_4, 20% MMH) to simplify the baseline system, if 1993 advanced development funds become available. If startup funds for a 1999 launch do not become available soon, the recommendation is to stay with the baseline propulsion system to meet the launch goal. Should the 1999 launch slip to a later date, then advanced engines should be further explored using chlorine pentafluoride or cryogenic integrated modular engines for different mission stages.

Although the results of this trade study are tailored to the FLO requirements, the trade study design data, criteria, and selection methodology are applicable to the design of other crewed lunar landing and return vehicles.

CONTENTS

CONTENTS (Continued)

Section Page

CONTENTS (Continued)

Section Page

TABLES

FIGURES

Figure Page

FIGURES (Continued)

ACRONYMS AND ABBREVIATIONS

AHP	analytic hierarchy process
C/D	development and manufacturing phase
CAD	computer-aided design
cg	center of gravity
CH_4	methane, a fuel
CIS	Commonwealth of Independent States
ClF_5	chlorine pentafluoride, an oxidizer
DDT&E	design, development, test, and evaluation
ΔV	Delta-V, the vehicle velocity change produced from a propulsive maneuver
EMA	electro-mechanical actuator
EP	Propulsion and Power Division
ET	Systems Engineering Division
ExPO	Exploration Program Office
FITH	fire-in-the-hole
FLO	first lunar outpost
FLOX	fluorinated oxygen, an oxidizer
ft	feet
GSE	ground support equipment
HLLV	heavy-lift launch vehicle
HR	hardware readiness
IME	integrated modular engine
Isp	specific impulse
ISRV	in situ resource utilization
JSC	Johnson Space Center
kg	kilogram(s)
KSC	Kennedy Space Center
lbf	pounds force
lbm	pounds mass
LeRC	Lewis Research Center
LH_2	liquid hydrogen, a fuel
LO_2	liquid oxygen, an oxidizer
LOI	lunar orbit insertion
LOI	launch operability index
m	meter(s)
M20	80% N_2H_4/20% MMH
MEOP	maximum expected operating pressure
MLI	multi-layer insulation

MMH	monomethyl hydrazine, a fuel
MS	mission success
mt	metric ton(s)
N_2H_4	hydrazine, a fuel
N_2O_4	nitrogen tetroxide, an oxidizer
NLS	national launch system
OF_2	oxygen difluoride, an oxidizer
psi	pounds per square inch
RCS	reaction control system
SDI	Strategic Defense Initiative
ST	space transportation
ST Seg.	space transportation segment team
TCA	thrust chamber assemblies
TEI	trans-Earth injection
TLI	trans-lunar injection
TRD	technology readiness difficulty
TRL	technology readiness level
VAB	vertical assembly building

SECTION 1.0

INTRODUCTION AND PURPOSE OF TRADE STUDY

The primary purpose of this trade study was to develop and evaluate main propulsion system design alternatives to the first lunar outpost (FLO) lander and return stage reference concepts. The FLO mission scenario is shown conceptually in figure 1-1. The basic mission is to send a crew to the Moon to explore and to perform lunar experiments that will pave the way for permanent habitation of the Moon. The mission begins with the landing of a habitat module on the Moon and is followed by the landing of crew.

This trade study fits in with other trade studies that examined (1) alternate mission modes, such as lunar orbit rendezvous and direct, (2) alternate methods of habitat placement on the lunar surface, and (3) heavy-lift launch vehicle size.

The reference FLO vehicle, which emphasizes the use of existing technology and hardware, consists of a cryogenic, pump-fed lander stage driven by four modified Pratt & Whitney RL10 engines and a hypergolic, pressure-fed return stage propelled by three modified AJ10-118 engines. The 13 alternative vehicle configurations were developed to explore the impacts of various combinations of return-stage propellants, feed systems, staging options, and advanced engines on the cost, schedule, performance, and risk associated with the FLO transportation system.

The propulsion system schematics and design data from this study are also applicable to a wide range of other aerospace vehicle design projects. The analytical methods and information presented in the study provide the means to assess the relative merits of other propellant combinations and feed systems. Cost, schedule, and risk are evaluated by using criteria such as system supportability, operability, complexity, reliability, and hardware readiness level.

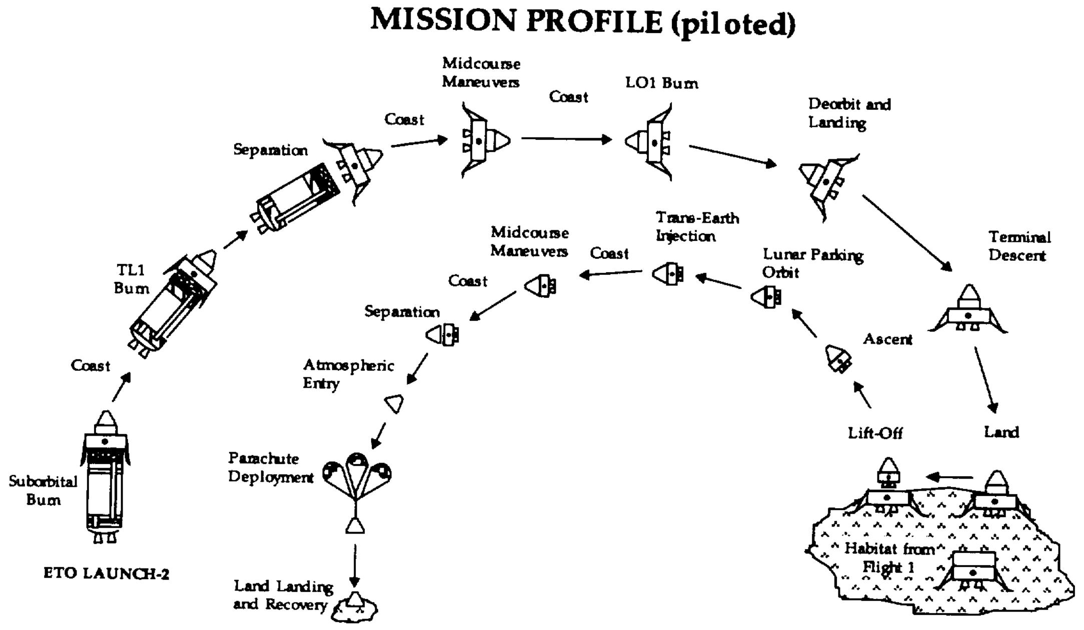

Figure 1-1. FLO mission profile.

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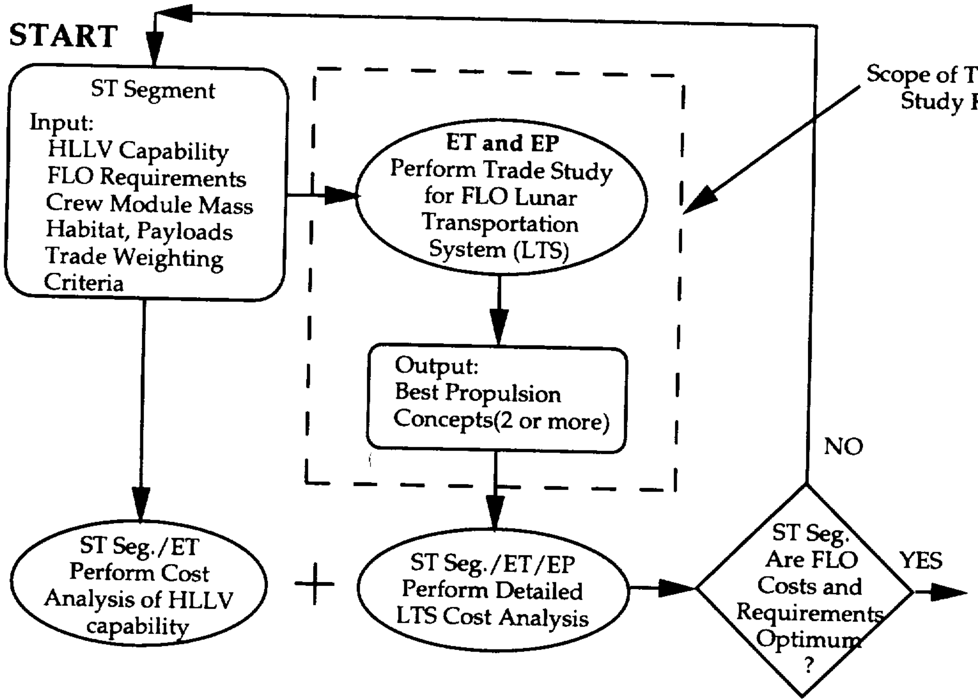
SECTION 2.0

OVERVIEW OF PROPULSION SYSTEM TRADE STUDY

This trade study was initiated at NASA/Johnson Space Center (JSC) in May of 1992 to develop and evaluate main propulsion system alternatives to the reference, two-stage First Lunar Outpost transportation system concept. The FLO Propulsion System Trade Study team was chartered to perform the following tasks:

- Examine the reference FLO two-stage propulsion system in more detail.
- Examine broad propulsion system staging and propellant options for FLO to determine the most promising propulsion system concepts.
- Perform vehicle propulsion system level trades on FLO reference design and promising alternative propulsion system concepts, including their effect on heavy-lift launch vehicle (HLLV) costs (fig. 2-1).
- Recommend limited number of propulsion system concepts for future in-depth analysis.
- Recommend areas of interest requiring future technology development.



ST Seg. = Space Transportation Segment team ET = Systems Engineering EP = Propulsion and Power

Figure 2-1. Iterative FLO trade process to include HLLV costs.

During the trade study effort, two workshops were held with industry and other NASA organizations and centers. The workshops were used to facilitate the flow of information and design concepts between study team members and all interested parties. Results from these workshops, which influenced trade study efforts and results, are documented throughout this report.

2.1 Heavy-lift Launch Vehicle Cost Impact

The cost of the heavy-lift launch vehicle (HLLV) can be the major cost driver in human lunar and planetary missions. For the FLO mission, as currently defined, the HLLV costs were not significantly affected by lunar vehicle mass over the range of propulsion systems studied. A large HLLV capability was also viewed as necessary for future Mars missions. Following is an explanation of the level at which HLLV costs were considered.

An overall mission and launch vehicle trade was not within the scope of this trade study, as shown in figure 2-1. At the space transportation (ST) segment level, figure 2-1 shows how the launch vehicle costs could be iterated to achieve the optimum mission. The ST segment defines the FLO requirements and some target HLLV capability. The ST segment also defines the relative importance of cost, schedule, and risks. Iterations that involve changes to launch vehicle performance/capability, mission requirements, or trade study weighting criteria should be made at this point to achieve the optimum program.

At the lower level, the Systems Engineering Division (ET) and the Propulsion and Power Division (EP) performed trade studies based on ST segment input. At the second workshop with industry, the Exploration Program Office (ExPO) at JSC presented design, development, test, and evaluation (DDT & E) cost and total vehicle launch cost sensitivity calculations as a function of post trans-lunar injection (TLI) mass for both a National launch system (NLS)-derived HLLV and a Saturn V-derived HLLV. Graphs showing the relative DDT & E cost sensitivity to post TLI mass for both HLLV concepts are shown in figures 2-2 and 2-3. These figures show that the HLLV costs varies from 2 to 3% over the range 76 to 96 metric ton (mt) of payload mass, which is in the noise level.

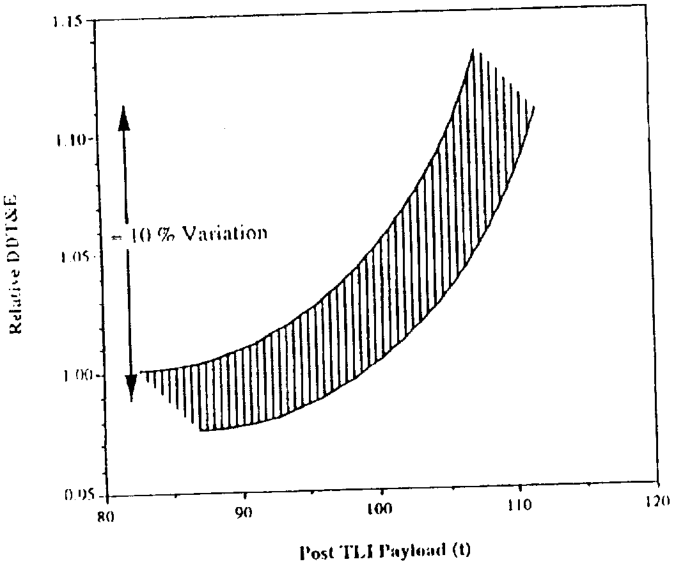


Figure 2-2. NLS derived HLLV cost versus TLI mass.

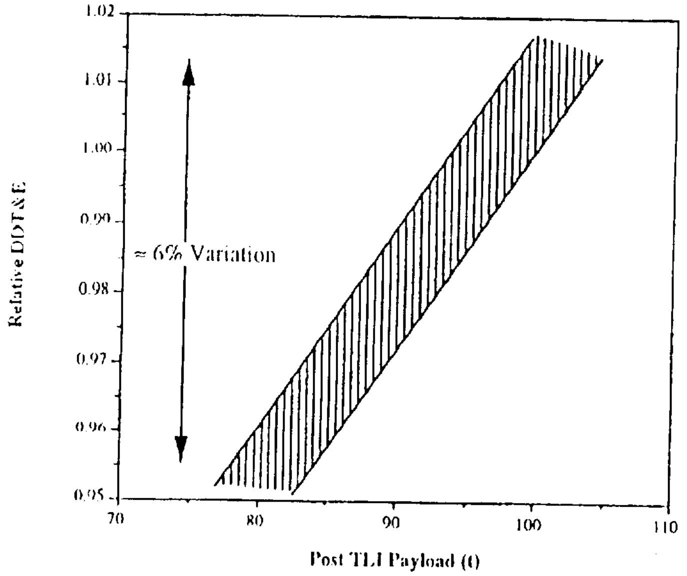


Figure 2-3. Saturn V derived HLLV cost versus TLI mass.

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SECTION 3.0
FLO DESIGN REQUIREMENTS

The goal of the FLO mission, as currently proposed, is to develop a space transportation system capable of delivering a habitat and a crew of four astronauts to the lunar surface for a 45-day mission (including 3 days contingency). The habitat and crew would be launched on two separate vehicles. Each vehicle would use as much common hardware as possible.

Following are the requirements, goals, and constraints, which were utilized in the trade study:

- Direct vehicle landing from lunar orbit with no lunar orbit rendezvous for crew return options.
- Mission abort capability to lunar orbit or Earth orbit at all times.
- As a minimum, zero fault tolerant lander propulsion, single fault tolerant return propulsion.
- Maximum hardware and design commonality between crew and cargo vehicles.
- Lunar surface crew duration of 45 days (3 days included for contingency)
- Crew vehicle design to include Apollo-type crew module with reaction control system (RCS) (7426 kg) with 5000 kg of cargo payload to lunar surface and 200 kg cargo payload returned from lunar surface to the Earth.
- Cargo vehicle design to include 32 mt payload (including habitat) to lunar surface.
- Post-trans-lunar injection (TLI) vehicle mass not to exceed 96 mt (TLI-stage adapter not included).
- Both crew and cargo vehicle designs must fit within launch vehicle shroud dimensions of approximately 10 m diameter and within vertical assembly building (VAB) height limitations of HLLV
- All hardware must meet development and manufacturing phase (C/D) start in 1995/96 timeframe and must support launch by end of 1999.
- Vehicle designs must meet FLO Delta-V requirements outlined in table 3-I.

Table 3-I. FLO Delta-V Requirements

LANDER VEHICLE		ASCENT VEHICLE	
Propulsive Maneuver	Delta-V Req't (m/s)	Propulsive Maneuver	Delta-V Req't (m/s)
Midcourse Correction	30	Lunar Ascent	1826
Lunar Orbit Insertion (LOI)	852	Trans Earth Injection (TEI)	945
Deorbit, Descent, and Site Redesignation	1898	Midcourse Correction	30
Total	2780		2801

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SECTION 4.0
DOWNSELECTION OF TRADE OPTIONS

One of the tasks chartered to the FLO Propulsion System Trade Study was to examine broad propulsion system staging and propellant options for FLO to determine the most promising propulsion system concepts for further analysis. The range of propulsion system trade options considered in the trade study are shown in table 4.1. These options were required to have past test or development experience and greater performance than N_2O_4 and MMH.

Table 4-I. Propulsion System Trade Options

Stage Configuration	Propellant Feed	Oxidizer	Fuel	General Systems
Single Stage	Pressure Fed	Liquid Oxygen (LO_2)	Liquid Hydrogen (LH_2)	Metallized/Gel
Stage & 1/2	Pump Fed	Nitrogen Tetroxide (N_2O_4)	Monomethyl Hydrazine (MMH)	Solid
Two Stage	• Expander	Fluorinated Oxygen (FLOX)	Methane (CH_4)	Hybrid
	• Gas Generator	Oxygen Difluoride (OF_2)	Hydrazine (N_2H_4)	Nuclear
	• Staged Concepts	Chlorine Pentafluoride (ClF_5)	M20 (80% N_2H_4/ 20% MMH)	• Electric
			RP1	• Thermal

4.1 Elimination of Metallized Propellants

In addition to normal liquid Earth-storable and cryogenic propellants, the study also considered metallized/gelled propellants. Even though studies have been performed on metallizing cryogenic propellants, only metallized gelled Earth-storable propellants were considered, because the density and Isp increases for metallizing hydrogen were not significant enough to overcome the anticipated development and design complexities. MMH and N_2O_4 were used as the representative metallized/gelled propellant combination. It was originally believed that the increase in specific density of the metallized/gelled MMH/N_2O_4 would decrease the propellant volume and structural mass compared to the baseline liquid MMH/N_2O_4 ascent vehicle. The propellant volume and mass, however, actually increases for the metallized/gelled Earth-storable option. Although the metallized fuel density is higher, the shift in mixture ratio decreases the oxidizer requirements, the density of which is greater than both the liquid and gelled fuel, causing the overall increase in volume and mass. This factor, combined with the low technology readiness level, led to the elimination of this propellant option from the trade study.

4.2 Elimination of Fluorinated Oxygen and Oxygen Difluoride Oxidizers

Fluorinated propellants, such as fluorinated oxygen (FLOX) and oxygen difluoride (OF_2) received attention in the 60s and 70s because of the high performance potential of these oxidizers with a wide variety of fuels. During this time, Pratt & Whitney performed tests on a version of the RL10 engine using FLOX and methane propellants. A consensus was reached at the first workshop meeting with industry that these oxidizers should not be pursued. The consensus was based on material compatibility safety concerns with these oxidizers and on the technology readiness of these oxidizers, which would not easily support the FLO transportation system development schedule.

Like FLOX and OF_2, chlorine pentafluoride (ClF_5) first received attention in the 60s and 70s. Some may argue that this oxidizer should also be eliminated from the trade study due to the same consensus reached for FLOX and OF_2. However, after discussions with industry and government personnel who have used ClF_5 in propulsion system tests, the material compatibility, safety, and technology readiness of ClF_5 can be more easily addressed. The U.S. Defense Department has successfully tested ClF_5 for more than 20 years, including recent development tests for an antiballistic missile defense interceptor using ClF_5 and hydrazine (N_2H_4) propellants. The Commonwealth of Independent States (CIS), formerly the Soviet Union, is believed to have produced large quantities of this oxidizer and to have a test facility compatible with ClF_5 propulsion systems.

4.3 Elimination of All but LO_2/LH_2 and ClF_5/N_2H_4 From the Lander Stage Main Propulsion System

In addition to the reference FLO pump-fed liquid oxygen $(LO)_2$/liquid hydrogen$(LH)_2$ lander main propulsion system, the trade study initially considered a wide variety of other propellant and feed system options. Performance models using the propellant combinations of LO_2/methane (CH_4), LO_2/N_2H_4, and MMH/N_2O_4, for the lander stage main propulsion system, resulted in vehicle TLI masses at or above the 96 mt vehicle mass limit for both pressure- and pump-fed propulsion system designs. These propellant combinations were thought to have some advantages over the reference FLO lander stage main propulsion system. The propellant combination of MMH/N_2O_4 was flown successfully on all the Apollo missions. Also, the problems of cryogenic storage for CH_4 and LO_2 are fewer than those associated with LH_2. Because of their performance limitations, however, these lander stage propellant combinations were eliminated from the trade study. It should be noted that if the FLO vehicle payload requirements are reduced or changed significantly, these propellant options should be reinvestigated. As was shown in the Apollo program, a pressure-fed storable propulsion system can be a viable lander propulsion system candidate.

A pressure-fed LO_2/LH_2 propulsion system was also considered. It was thought that pressure feeding these propellants would reduce complexity of the propulsion system and increase its reliability while maintaining the high-performance characteristics of an LO_2/LH_2 system, however the pressure-fed LO_2/LH_2 lander propulsion system option was eliminated for being too massive. The option was later added, however, as an alternative ascent propulsion system option to allow technology improvements and alternative pressurization systems to be addressed.

The only non-LO_2/LH_2 lander propulsion system option that was found to meet the FLO TLI vehicle mass requirements was the propellant combination of ClF_5/N_2H_4. Since the ClF_5/N_2H_4 pressure-fed propulsion system option was found to be more than satisfactory, a pump-fed option was not considered. It was believed that the increase in propulsion system complexity and decrease in reliability, compared to a pressure-fed system, would outweigh the performance gains achieved from a pump-fed system. Also, even though a stage-and-a-half design is feasible with ClF_5/N_2H_4, the high density/small volume of the propellants does not allow for any mass savings compared to a two-stage design.

4.4 Elimination of Solid and Hybrid Propulsion Systems

Even though solid propellants can provide good density impulse (density* specific impulse (Isp)), solid propellants were eliminated in the FLO propulsion system trade study. Numerous reasons were cited for its elimination, such as inadequate performance and lack of engine restart capability.

Hybrid propulsion systems that use solid fuels and liquid oxidizers overcome the lack of engine restart capability of solid motors while at the same time providing greater performance. However, preliminary analysis of a LO2/Polybutadiene (HTPB) hybrid propulsion system on the FLO crewed return vehicle indicated that it would exceed the post-TLI mass limit of 96.5 mt, as well as take up much more volume than the baseline FLO return vehicle. Since the overall performance of the hybrid design did not exceed that of the baseline FLO return vehicle design, it was eliminated from the trade study. Because hybrid propulsion systems can be extremely simple and safe, they should be reconsidered in future trade studies as the hardware readiness level of this propulsion system concept matures.

4.5 Elimination of Nuclear Propulsion Systems

Currently, two main classes of nuclear propulsion systems are receiving close attention: solid core nuclear thermal propulsion systems and nuclear electric propulsion systems. The first, solid core nuclear thermal propulsion systems, produce high performance (800 to 1000 sec of Isp) and thrust by heating hydrogen in a solid fueled reactor and expelling it through a nozzle. This type of system was tested extensively in the 60s and 70s in the U.S. Rover/Nuclear Engine for Rocket Vehicle Applications programs. Even though this kind of propulsion system can provide excellent performance, it was eliminated from the trade study since the radiation shielding requirements for the crew and the engine thrust-to-weight ratio would be prohibitive for a crew lander of this size class. The second class of systems, nuclear electric propulsion systems, can provide extremely high performance (1000s of sec of Isp) at relatively low thrust. The system works by powering small electro/magnetic thrusters with a small closed-loop nuclear power reactor. Even if a power source besides a nuclear reactor were used to support the electric thrusters in a propulsion system, the low thrust would require long transit and engine burn times. For this reason, and the low technology readiness of electric thrusters, nuclear electric propulsion was also eliminated from the trade study space.

4.6 Inclusion of Advanced Engines

All of the trade alternatives are selected to meet the key design criteria described in section 3.0, and none survived the downselection that did not meet the minimum requirements. Three of the thirteen trade alternatives to the baseline, however, pose considerable risk of not being able to meet the 1999 launch goal without an "Apollo type," well-funded development program. These three trades were added as a result of suggestions during the first and second FLO workshops with industry and the desire to identify the effects that advanced propulsion systems would have on the FLO propulsion system selections. The three alternative trades added to the study were (1) a two-stage cryogenic vehicle with integrated modular engines (IME), (2) a stage-and-a-half cryogenic vehicle with IME and (3) a two-stage vehicle with pressure-fed ClF_5/N_2H_4 on both stages. These three are included in the trade study with considerable risk because funding is not expected to achieve the levels required to meet a 1999 launch.

The IME design philosophy uses redundant pumps, pressurizing multiple chambers with a high-pressure manifold. The design philosophy increases performance, reduces complexity, and takes advantage of state-of-the-art manufacturing techniques. The IME design, however, is currently a paper engine with only limited breadboard testing experience, and concerns exist that could preclude its use. These concerns include startup transients, instability harmonics, redundant pump operations, low head pressure liquid pump development, and balanced high-pressure manifolds.

The ClF_5/N_2H_4 propellant combination for FLO is believed to be more predictable than the IME design. It requires scaling from the current 1000 pounds force (lbf) thrust class to a 30,000 lbf thrust class. Development concerns primarily include scaling the engine to the higher thrust class, increasing the operating life of current designs from 10s to 100s of sec, providing a 5:1 throttling capability for the lander engines, and understanding Environmental Protection Agency (EPA) requirements for high thrust/long burn test facilities.

For alternative vehicle trade concepts incorporating advanced nonthrottling engines using ClF_5/N_2H_4, $LO2/N_2H_4$ or LO_2/CH_4 propellants on the return stage only, the development risk is more acceptable than the three vehicle trade concepts described above. The acceptable risk attributed to these concepts is contingent upon a dedicated early development program and is minimized by requiring only the development of a non-throttling return-stage engine. These alternative concepts are less expensive than trying to develop two advanced engine stages where the lander stage requires throttling. Additionally, it is possible that if any design or funding difficulties are encountered during the advanced development phase, the baseline return stage possibly could be substituted with acceptable hardware impact and, perhaps, tolerable mission impact. In contrast, if early advanced development for the two-stage ClF_5/N_2H_4 vehicle concept is not successful, replacing the propellant combination on both the lander and return stages would require significant hardware and mission design changes to meet a 1999 launch.

4.7 Downselection Results

At the conclusion of the downselection process, 13 promising alternative propulsion systems were identified for further analysis. The 13 alternative propulsion systems identified and the reference FLO concept are the nonshaded options shown in table 4-II. The Post TLI mass and technology numbers displayed in table 4-II were initial estimates for these trade options and may not conform with the data summary numbers shown in table 7-I of section 7. Even though the numbers changed during the trade study, the post-TLI mass numbers generally increased as the trade progressed and the analysis became more detailed. Therefore, trade options eliminated at the conclusion of the downselection process due to exceeding the post-TLI mass limit were not reevaluated.

Table 4-II. FLO Propulsion System Trade Space

Prop Feed System	SINGLE LO_2/LH_2 PUMP	SINGLE LO_2/CH_4 PUMP	SINGLE LO_2/N_2H_4 *	SINGLE LO_2/RP1 *	SINGLE FLOX/* *	SINGLE OF_2/* *
POST TLI MASS	90	103	104	105		
TECHNOLOGY						
ENG	7	5	5	5	3	3
FEED	6	5	5	5	3	3
TANK	5	5	5	5	3	3

Stage Confide. Prop Feed System	Stage 1/2 LO_2/LH_2 Pump	Stage 1/2 LO_2/CH_4 *	Stage 1/2 LO_2/N_2H_4 *	Stage 1/2 LO_2/RP1 *	Stage 1/2 FLOX/* *	Stage 1/2 OF_2/* *
POST TLI MASS	78	96	97	98		
TECHNOLOGY						
ASCENT FEED	6	5	5	5	3	3
ASCENT TANK	5	5	5	5	3	3
LANDER ENG	7	6	5	5	3	3
LANDER FEED	5	5	5	5	3	3
LANDER TANK	5	5	5	5	3	3

Stage Confide. Ascent Prop Ascent Feed Lander Prop Lander Feed	TWO LO_2/LH_2 Pump LO_2/LH_2 Pump	TWO LO_2/CH_4 Pump LO_2/LH_2 Pump	TWO LO_2/CH_4 Pressure LO_2/LH_2 Pump	TWO LO_2/N_2H_4 Pressure LO_2/LH_2 Pump	TWO LO_2/RP1 Pressure LO_2/LH_2 Pump	TWO NTO/MMH Pressure LO_2/LH_2 Pump
POST TLI MASS	78	87	90	90	90	93
TECHNOLOGY						
ASCENT ENG	7	5	5	5	5	9
ASCENT FEED	6	5	5	5	5	7
ASCENT TANK	5	5	5	5	5	7
LANDER ENG	7	7	7	7	7	7
LANDER FEED	7	7	7	7	7	7
LANDER TANK	7	7	7	7	7	7

Stage Confide. Ascent Prop Ascent Feed Lander Prop Lander Feed	TWO NTO/MMH Pump LO_2/LH_2 Pump	TWO $ClF_5/N2H4$ Pressure LO_2/LH_2 Pump	TWO LO_2/LH_2 Pressure LO_2/LH_2 PUMP	TWO ClF_5/N_2H_4 Pressure ClF_5/N_2H_4 Pressure	TWO * * * Pressure	TWO OF_2/* * OF_2 *	TWO FLOX/* * FLOX *
POST TLI MASS	89	87	98	93	>96		
TECHNOLOGY							
ASCENT ENG	5	5		5	5	3	3
ASCENT FEED	7	5		5	5	3	3
ASCENT TANK	7	5		5	5	3	3
LANDER ENG	7	7	5	5	5	3	3
LANDER FEED	7	7	5	5	5	3	3
LANDER TANK	7	7	5	5	5	3	3

*Indicates all options considered.

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SECTION 5.0

PROPULSION SYSTEM DESIGN

The third task chartered to the FLO Propulsion System Trade Study team was to perform vehicle propulsion system level trades on the FLO reference design and on all promising propulsion system concepts. Results from the propulsion system downselection process described in section 4 and information exchanged at the two workshops led to the identification of 13 promising alternative propulsion system concepts to the FLO reference design. Following are the 14 propulsion system options studied.

1. Baseline: Pressure-Fed NTO/MMH Return, Cryo Lander
2. Pressure-Fed LO_2/N_2H_4 Return, Cryo Lander
3. Pressure-Fed ClF_5/N_2H_4 Return, Cryo Lander
4. Pressure-Fed Optimized NTO/M20 Return, Cryo Lander
5. Pressure-Fed LO_2/CH_4 Return, Cryo Lander
6. Pump-Fed NTO/MMH Return, Cryo Lander
7. Pump-Fed LO_2/CH_4 Return, Cryo Lander
8. Pump-Fed LO_2/LH_2 Return, Cryo Lander
9. Single-Stage LO_2/LH_2
10. Stage-1/2 LO_2/LH_2
11. ClF_5/N_2H_4 in Both Stages
12. Two-Stage, Optimized IME LO_2/LH_2 for Both Stages
13. Pressure-Fed LO_2/LH_2 Return Stage, Baseline Lander Stage
14. Optimized IME Stage-1/2

The design methodology consisted of (1) creating schematics, (2) creating performance models, (3) determining the operational and parts complexity counts, and (4) assessing hardware readiness. Much of the information came from industry or other NASA centers. A summary of the design parameters is shown in table 5-1

A complete schematic, which meets fault-tolerance requirements, is the key to conducting a realistic trade study. Each schematic shows all components, from check valves to regulators to engine components, using the key shown in figure 5-1.

Engines are not treated as single components but, rather, as an assembly of components. For example, IMEs used this to advantage by integrating the engine components and feed system to reduce overall system complexity. Primary structure, tanks, and engine chambers were exempted from application of redundancy requirements, since structural failure is a low probability. The IME and single-engine-chamber designs take advantage of this requirement by treating the engine chamber as a pressure vessel or structure.

Table 5-1. A summary of design parameters

	TR-1	TR-2	TR-3	TR-4	TR-5	TR-6	TR-7	TR-8	TR-9	TR-10	TR-11	TR-12	TR-13	TR-14
RETURN STAGE														
ISP (lb-sec)	320	348	353	331	350	344	358	440	440	440	353	480	440	480
MIXTURE RATIO	1.9:1	0.77:1	2.5:1	1.33:1	2.77:1	2.02:1	3.5:1	6.0:1	6.0:1	6.0:1	2.5:1	6.0:1	6.0:1	6.0:1
ENG. THRUST (lbf)	9750	30000	30000	30000	30000	15000	18900	15000	20800	16500	30000	10000	30000	15000
NO. ENGINES	3	1	1	1	1	4	4	4	4	4	1	3	1	4
NUM. OX TANKS	2	2	2	2	2	2	2	1	1	1	2	2	3	1
NUM. FU TANKS	2	2	2	2	2	2	2	4	1	1	2	2	3	1
VEH. MASS (mt)	96.5	94.3	87.2	94.2	100.9	92.6	92.4	93.5	101.4	87.4	91.2	70.9	95.3	67.9
RET. PROP. VOL. (m^3)	16	16	10	15	24	14	20	45	68	43	10	35	44	32
TOT. PROP. VOL. (m^3)	155	151	135	150	168	147	152	179	218	169	45	128	180	121
LANDER STAGE														
ISP (lb-sec)	440	440	440	440	440	440	440	440	440	440	353	480	440	480
MIXTURE RATIO	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	6.0:1	2.5:1	6.0:1	6.0:1	6.0:1
ENG. THRUST (lbf)	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500	20800	16500	30000	15000	16500	15000
NO. ENGINES	4	4	4	4	4	4	4	4	4	4	2	4	4	4
THROTTLE RANGE	5.0:1	5.0:1	5.0:1	5.0:1	5.0:1	5.0:1	5.0:1	5.0:1	6.0:1	5.0:1	5.0:1	5.0:1	5.0:1	5.0:1
NUM. OX TANKS	2	1	1	1	1	2	2	2	2	2	3	2	1	2
NUM. FU. TANKS	6	4	4	4	4	4	4	4	6	6	3	4	4	6

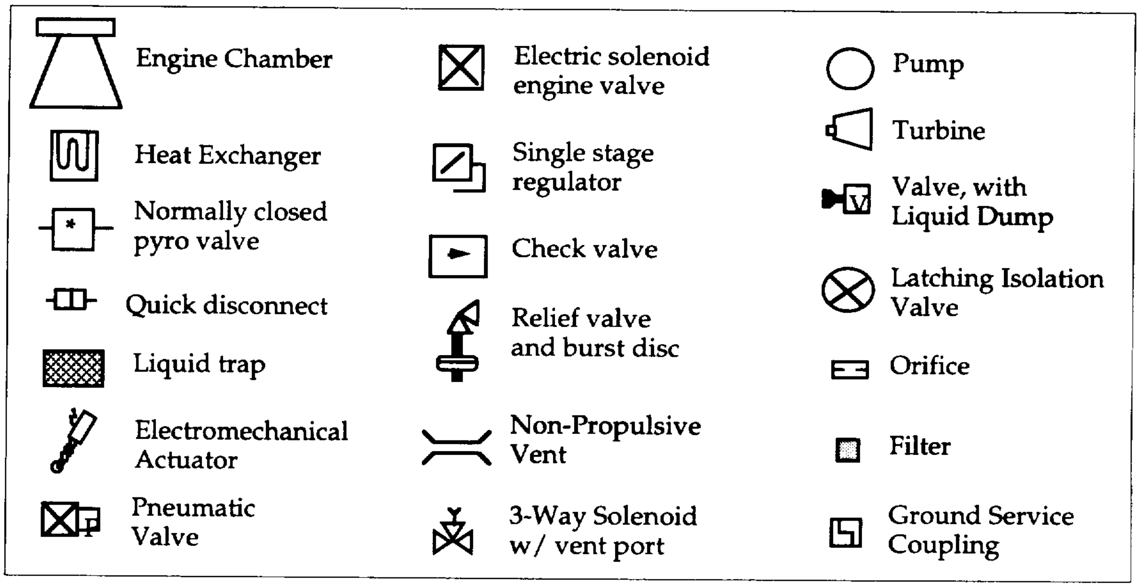

Figure 5-1. Component key.

A 4-engine configuration was selected for pump-fed engines on the return stage to meet redundancy requirements. If one engine were to show indications of impeding failure, the opposing engine would be shut down in parallel. This option was chosen over gimbaling the remaining engines should an engine fail. Preliminary analysis using the LO_2/CH_4 pump-fed ascent vehicle from Trade #7 showed that gimbaling the remaining three engines though the vehicle's center of gravity was not possible during all return flight phases if the engines conform to the baseline FLO ±8 gimbal angle limit. Lacking gimbal authority for all mission phases could have a significant impact on the vehicle's ACS size and requirements. Also, for pump-fed engines with no throttling capability, the roll angle induced by the failed engine could be excessive before gimbaling the remaining engines can compensate for the thrust imbalance. A 2-engine LO_2/CH_4 pump-fed ascent vehicle was also analyzed to determine the impact of a single engine failure. For this case, gimbaling through the vehicle's center of gravity was physically impossible with the remaining engine. Since the 4-engine confirmation was not sufficient to cover an engine-out failure during all flight phases, a 3-engine configuration as not analyzed. Should a pump-fed ascent stage option be chosen fro future FLO vehicle consideration. a more detailed investigation should b e performed to determine the optimum number of main engine, ACS size, and the desired engine failure recovery method.

A description of the performance models used in the FLO vehicle trade study is presented in section 5.1, and the code for these models can be found in appendix B. A brief description of the FLO reference design and the 13 alternative concepts are presented in section 5.2; a complete, detailed description of each propulsion system examined can be found in appendix A. Configuration layouts for the FLO reference design and the 13 alternative concepts are presented in section 5.3.

5.1 Performance Models

A number of computer models were created during the FLO Propulsion System Trade Study to help establish FLO vehicle performance, mass, and size characteristics for each trade option considered. Models created for the trade study were the *crew* FLO Lander/Return Vehicle Sizing Model, the FLO

Habitat/Cargo Vehicle Sizing Model, and the Cryogenic Propellant Vent Timeline and Duration Models. Variations of the *crew* FLO Lander/Return Vehicle Sizing Model were generated for the single stage, stage-and-a-half, and two-stage vehicle options. Computer codes for the models can be found in appendix B.

The *crew* FLO Lander/Return Vehicle Sizing Model calculated the propellant and vehicle masses and volumes required for both the lander and return portions of the FLO mission. *All of the variations of the model generated during the trade study utilized the same universal inputs and modeling assumptions except for engine mass when not applicable.* Universal inputs are shown in table 5-IV.

Modeling assumptions used in the crew FLO Lander/Return Vehicle Sizing Model program are as follows:

1. Pressurization systems available in the model include helium systems with and without heat exchangers, autogenous hydrogen and oxygen pressurization, and cryogenically stored helium. Pressurant system mass is based on pressurant tank mass and total helium mass required. Autogenous pressurization system masses are included in overall propellant tank and mass calculations. Helium mass calculations are based on propellant volume, pressure, and temperature, as well as helium storage tank pressure and assuming isentropic expulsion. Since the time between stage propulsive maneuvers would allow for ullage/propellant temperature equalization, the ullage temperature assumed in the pressurant calculations is conservatively set at either the normal boiling temperature of the propellant at 15 pounds per square inch (psi) or 300°R, whichever is lowest. This also accommodates the desire to start the engines with subcooled propellant.

2. Using the rocket equation, propellant consumed during propulsive maneuvers is calculated

$$e^{\left(\frac{\Delta V}{Isp*g}\right)} = \frac{mass_{initial}}{mass_{final}}$$

3. Propellant boiloff calculations utilize information on heat rates and MLI configurations provided by the NASA Lewis Research Center. Boiloff is calculated based on a 4-day trajectory, table 5-II, and a 45-day lunar stay, table 5-III. Boiloff calculations are based on the following:

Table 5-II. 4-Day Outbound Trip

Propellant	Heat Flux Rate (Btu/hr*ft^2)	MLI		Foam lbm/ft^2
		No. Layers	lbm/ft^2	
LO2	0.2	20	0.493	0.273
LH2	0.2	20	0.493	0.0

Table 5-III. 45-Day Lunar Stay

Propellant	Heat Flux Rate (Btu/hr*ft^2)			MLI	
	Lunar Day	Lunar Night	Ave.	No. Layers	lbm/ft^2
LO2	0.076	0.0042	0.0521	113	0.54
LH2	0.11	0.013	0.0777	88	0.48
LCH4	0.11	0.0	0.073	76	0.36

4. The total propellant residual and reserve mass is 3% of the propellant required to meet the vehicle Delta V specifications. The residual mass is 1%, and the reserve mass is 2%.

5. No cryogenic propellant dumping for pre-abort engine conditioning is assumed in propellant requirement calculations.

6. Stage structure requirement is based on a historical curve fit provided by JSC/ET, which calculates structural mass as a function of cylindrical surface area based on stage volume. The historical data includes hypergolic landers and cryogenic propellant launch vehicle stages. The equation used is

$$\text{Mass}_{\text{structure}} = 8.89*\left(\text{Area}_{\text{surface}}\right)^{1.1506}$$

Note: mass is in kilograms (kg) and area is in m^2.

7. The landing gear mass is 3% of the total landed mass.

8. All propellant tanks use a safety factor of 1.5 from the designed maximum expected operating pressure (MEOP) to burst. The material of each tank is selected on a case-by-case basis and is based on propellant compatibility and lowest mass where compatibility provides a choice. Minimum gage thickness is used unless the tank is an overwrap tank where less than minimum thickness is available. For overwrap tanks, liners and wrap mass are calculated separately. Mass for tank mounts and bosses is assumed to be 20% of the tank shell mass. A 5% total volume for ullage is assumed in all propellant tank volume calculations.

9. Tank secondary structure and support mass is assumed to be 30% of the total tank mass with multi-layer insulation (MLI) (if required).

10. Growth factor for the vehicle dry mass is 20%.

11. Propulsive velocity (ΔV) required for propulsive maneuvers is constant for all trades. Even though true ΔV is a function of the vehicle thrust-to-weight ratio, there is a region where ΔV varies only slightly with respect to vehicle thrust-to-weight. All trades were required to be within this region. Delta Vs used are shown in table 3.I, FLO Delta V Requirements.

12. The required engine throttling ratio is calculated by dividing the descent stage total thrust by 80% of the vehicle landed mass times lunar gravity.

13. No degradation in Isp due to engine throttling is assumed. Propellant requirements are based on a constant Isp throughout the mission.

Table 5-IV. Universal Trade Inputs For Sizing Model

Descent Propulsion System	Mass (kg)	Ascent Propulsion System	Mass (kg)
Prop. Feed System	294	Prop. Feed System	153
RCS	270	RCS	0
Protection	425	Protection	169
Power	154	Power	1,278
Non-Prop Fluids	1,050	Non-Prop Fluids	202
Avionics	105	Avionics	131
Environmental	0	Environmental	238
Engines (4 RL10)	873	Return Cargo	200
		Deliverable Cargo	5,000
For cargo Mission:		Crew Module	7,426
Habitat and Payload	32,000		

The FLO Habitat/Cargo Vehicle Sizing Model was created to determine which of the FLO vehicles, the crew vehicle or the cargo/habitat vehicle, had the greatest TLI mass. Also, the model calculated the TLI mass difference for the two vehicles. The FLO Habitat/Cargo Vehicle Sizing Model assumes that the descent stage for the Habitat/Cargo vehicle is the same as that calculated for the crew descent vehicle. The model is very simple and uses masses calculated in the crew FLO Descent/Return Vehicle Sizing Model. Masses used in the model that were calculated in the crew FLO vehicle sizing model are primary structural mass, landing gear mass, total propellant tank mass (including MLI and secondary structure), and pressurant system mass (including helium mass). The model also uses the descent propulsion system universal inputs shown in table 5-IV.

The FLO Habitat/Cargo Vehicle Sizing Model uses the rocket equation, with the inputs described above, to calculate the propellant required to deliver a 32-mt payload to the lunar surface, as well as the vehicle TLI mass. A propellant mass less than that specified for the crew vehicle suggests the stage propellant tanks are only partially filled. A propellant mass greater than that specified for the crew vehicle suggests that the habitat/cargo vehicle is the propellant mass driver of the two vehicles, and that the propellant tankage/vehicle structure needs to be resized to meet the propellant requirement of the cargo vehicle.

Two FORTRAN models were created during the trade study to help determine the number and duration of cryogenic tank venting operations required for the outbound trip and on the lunar surface. The first model, Cryogenic Propellant Vent Timeline, calculated the time between venting operations and the volume of ullage vented based on the heat leak into the tank. Since venting operations assumed venting from 50 psi down to 15 psi, an ullage mass difference could be calculated. Using the heat leak rate, the time required to vaporize a volume of liquid to produce the calculated mass difference can be determined. By tracking the ullage volume after each venting operation, the total number of vehicle venting operations can be discerned. The number of venting operations required for each trade option are included in the detailed vehicle descriptions in appendix A.

The second FORTRAN model, Cryogenic Propellant Vent Duration, was created to help determine the duration of each venting operation as a function of the venting system piping configuration. The amount of time each venting operation would require was of interest since the current FLO descent stage does not use a zero-g vent system. Therefore, a propulsive maneuver is required first to settle the liquid propellant and then to allow the gaseous ullage to vent. The duration of each venting operation will, therefore affect the total RCS propellant mass required to perform all the venting operations during the coasts between the Earth and the Moon. The output of this model is currently not affecting the RCS propellant mass required but will be considered in more refined trade option definitions. The model output is being used to help determine whether a zero-g vent system should be baselined for all FLO cryogenic propulsion system options. Vent durations of between 4 and 8 sec are required for a 3 in. diameter, 2 ft-long vent pipe system.

5.2 Design Descriptions

5.2.1 Trade 1 System Description - N_2O_4/MMH Pressure-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

This is the baseline propulsion system first conceptualized in the spring 1992 FLO study. The propulsion system was designed to utilize as much off-the-shelf hardware and as many flight-experienced systems as possible.

The return stage (fig. 5-2), employs three pressure-fed MMH/N_2O_4 Aerojet AJ10-118 engines. The feed system incorporates parallel redundant flow paths. There are no single-point mechanical failures in the propulsion system. Since the AJ10-118 engine is an ablative engine, no fuel purge system is required after engine shutdown.

There are two fuel and two oxidizer titanium tanks in the return-stage propulsion system design. The stage propellants are both Earth-storable, so no active venting is required during flight operations and lunar stay. Since three engines are used in the return-stage propulsion, the current vehicle configuration requires that part of the return engine nozzles protrude into the descent-stage structure. Concern for the possible negative effects from "fire in the hole" (FITH) has been identified as requiring future analysis and testing.

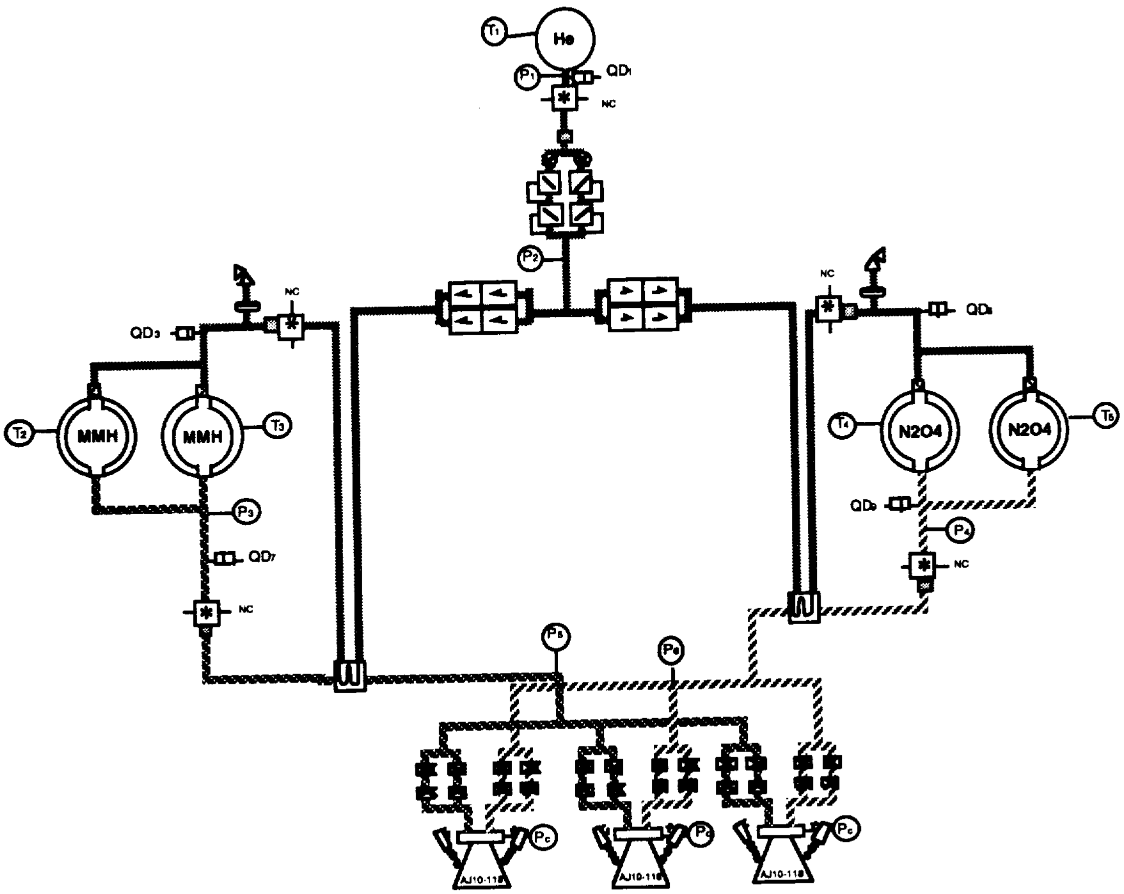

Figure 5-2. MMH/N_2O_4 return stage.

The descent stage (fig. 5-3) is a LH_2/LO_2 pump-fed system using RL10A-3-3A engines modified for 5:1 throttling. The throttling range of 5:1 was identified as a limit at which modifications to the engines were not as significant as those for throttling ranges greater than 5:1. Also, the 5:1 throttling range is adequate for the descent-stage hover requirements.

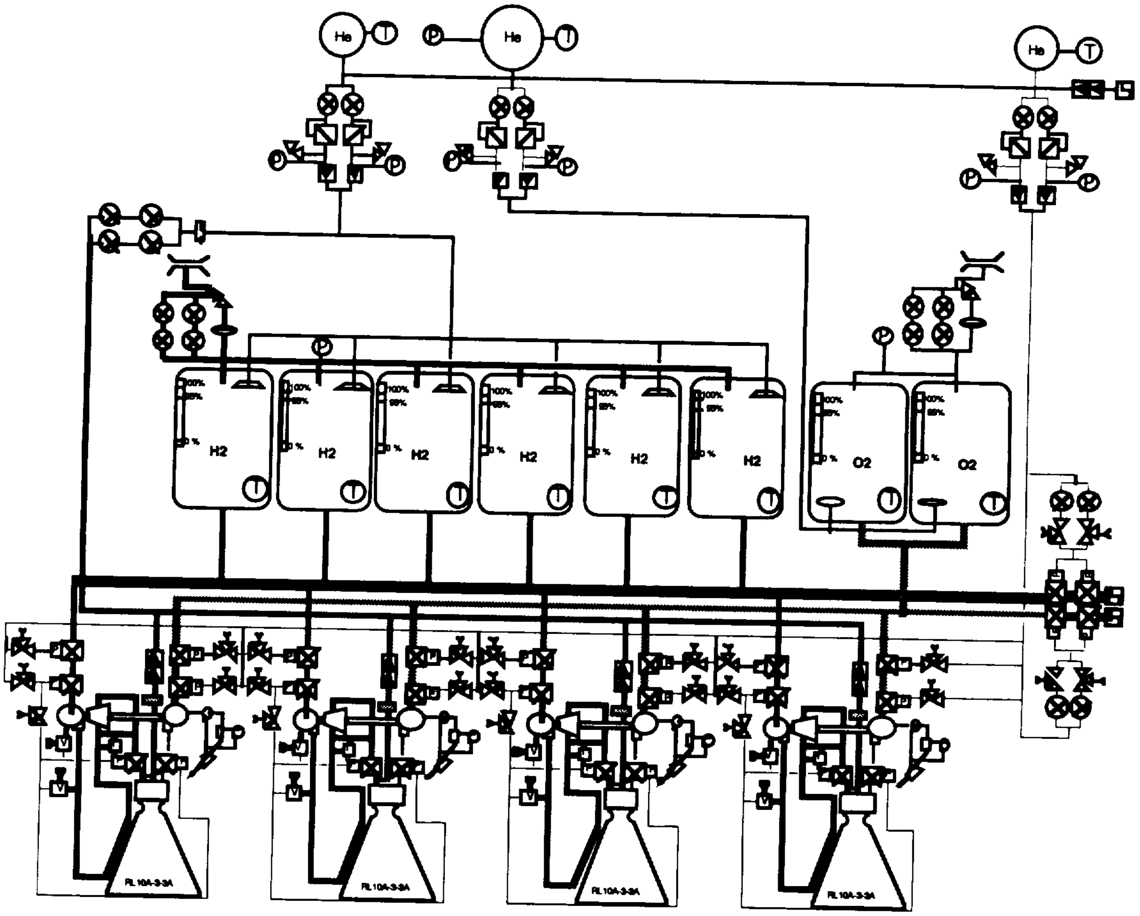

Figure 5-3. Lander stage, LH_2/LO_2 propulsion system.

5.2.2 Trade 2 System Description - LO_2/N_2H_4 Pressure-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

The propulsion system in the return stage of this concept (fig. 5-4) uses a single pressure-fed engine combusting LO_2/N_2H_4 propellants. This propellant combination has several beneficial characteristics: (1) LO_2 and N_2H_4 are relatively easy to store on the lunar surface, (2) engine performance is higher than many other storable propellant combinations, (3) propellant density is relatively high, and (4) propellant experience is relatively high for each of the propellants.

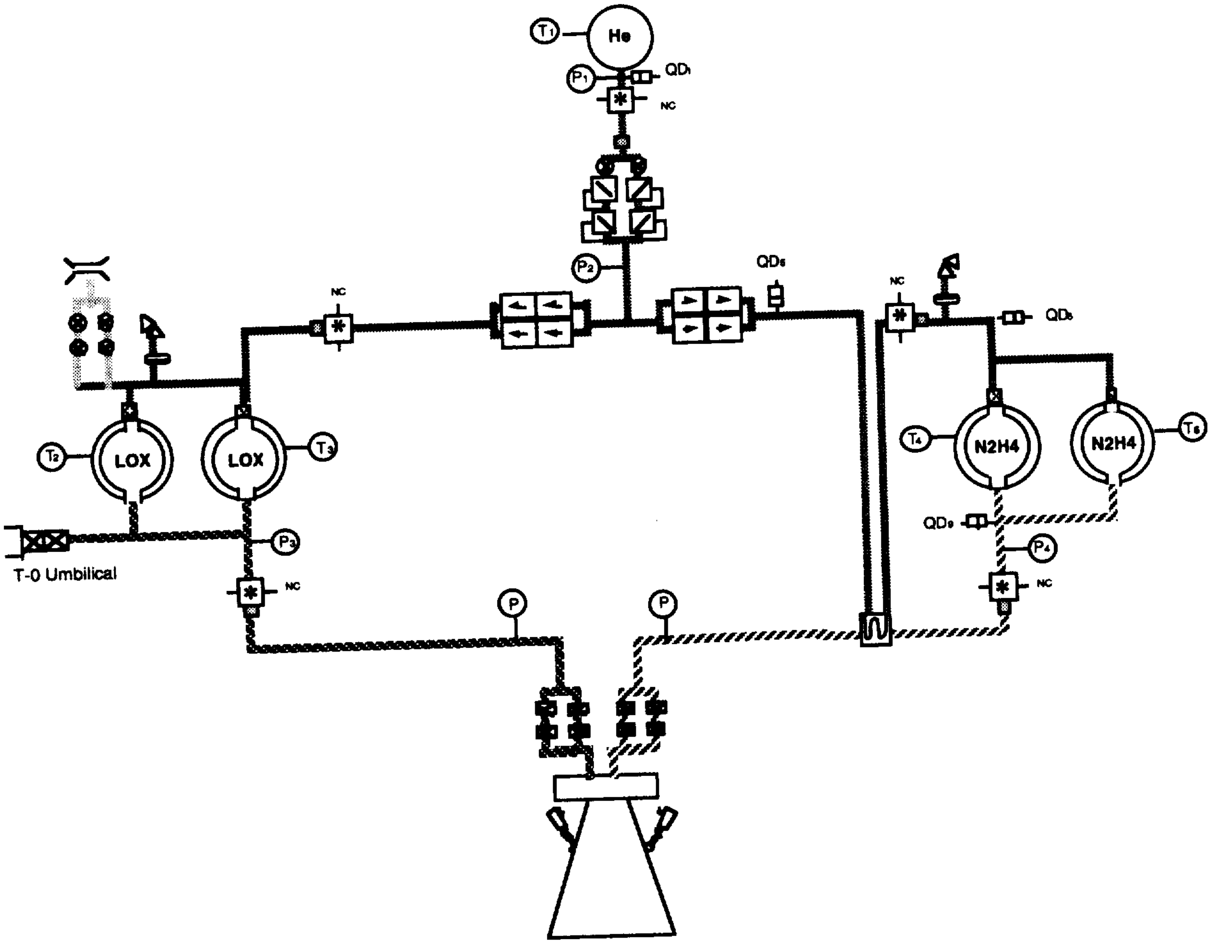

Figure 5-4. LO_2/N_2H_4 pressure-fed return stage.

The engine is sized from data provided by TRW for a LO_2/N_2H_4 engine. The engine chamber pressure is 125 psi, since quick-look trades indicate that higher chamber pressures would increase total stage weight due to the tank weight increase. The engine length is approximately 120 in., and the Isp is 348 sec. A return engine development program is required. It was believed that using a single return engine would provide an advantage over multiple engine configurations by allowing the engine to be recessed farther within the stage, thereby eliminating FITH concerns and reducing the component count of the propulsion system.

An active vent system is used in the return propulsion system design to maintain LO_2 tank pressures during transit and on the lunar surface. The LO_2 and the hydrazine tank are both graphite epoxy overwrapped aluminum-lined tanks. The nominal tank operating pressure for both propellants is 250 psi. The current return stage configuration uses two LO_2 tanks and two N_2H_4 tanks.

The lander stage (fig. 5-5) uses the same basic propulsion system as the baseline vehicle design, including engines and components. The exception is the lander-stage tanking configuration, which has been reconfigured to remove the hole in the middle, since the single return engine does not protrude significantly. Instead of the six LH_2 and two LO_2 tanks used in the baseline lander stage, this lander-stage option uses one large LO_2 tank surrounded by four LH_2 tanks.

This descent stage configuration of tanks has a significant advantage in that it allows cargo to be stored on the sides of the lander in areas where tanks do not occupy space, unlike the baseline design. This puts the cargo closer to the lunar surface for easier unloading.

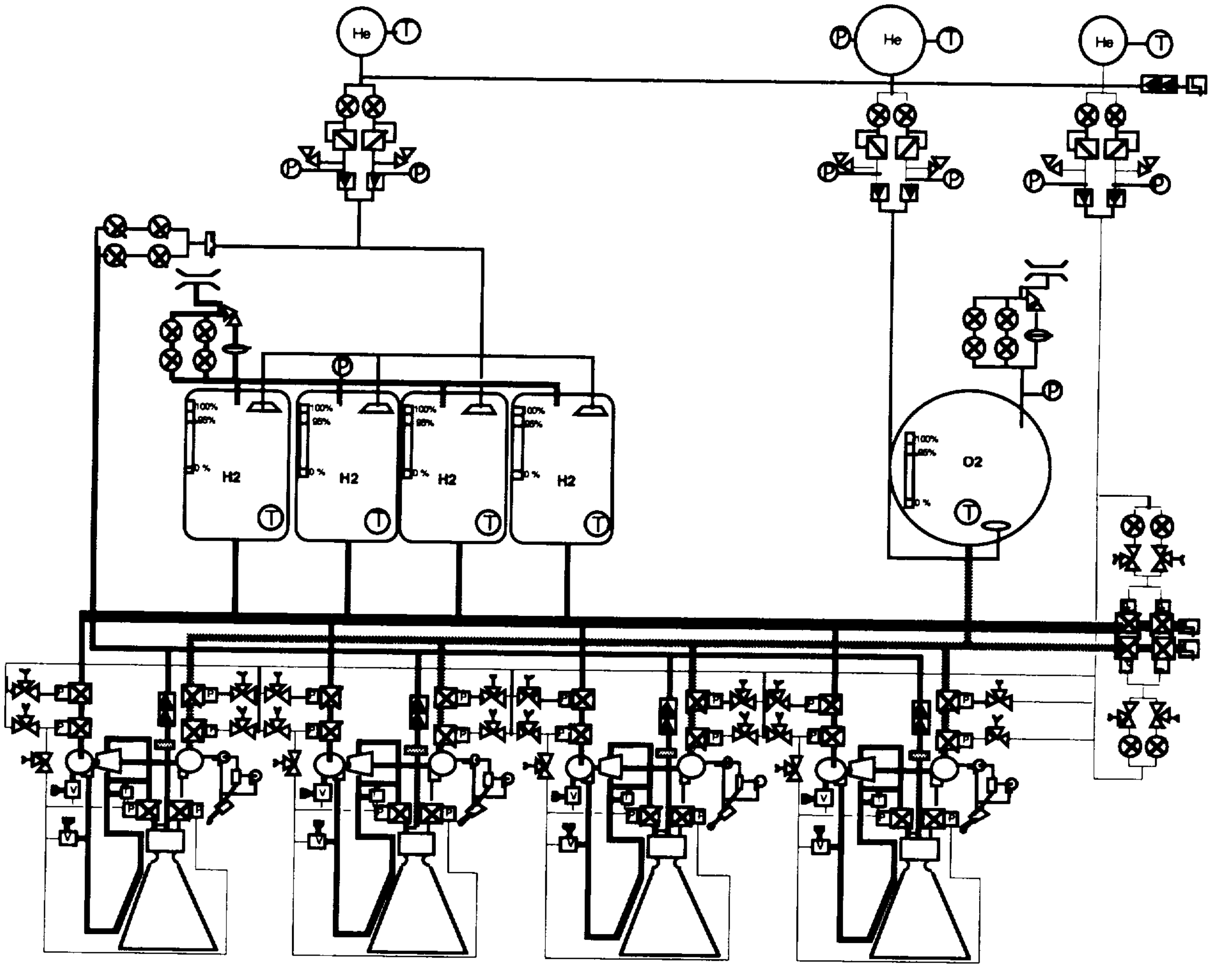

Figure 5-5. LO_2/LH_2 lander stage for single-engine return stage.

5.2.3 Trade 3 System Description - ClF_5/N_2H_4 Pressure-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage.

The propulsion system for the return stage of this option (fig. 5-6) uses the hypergolic propellant combination of ClF_5 and N_2H_4 in a single pressure-fed engine configuration. A single-engine concept was chosen for the same reasons outlined for the return stage in trade 2, section 5.2.2. This propellant combination was chosen because of its high packing efficiency and performance, combined with the hardware development base initiated through the U.S. Strategic Defense Initiative (SDI).

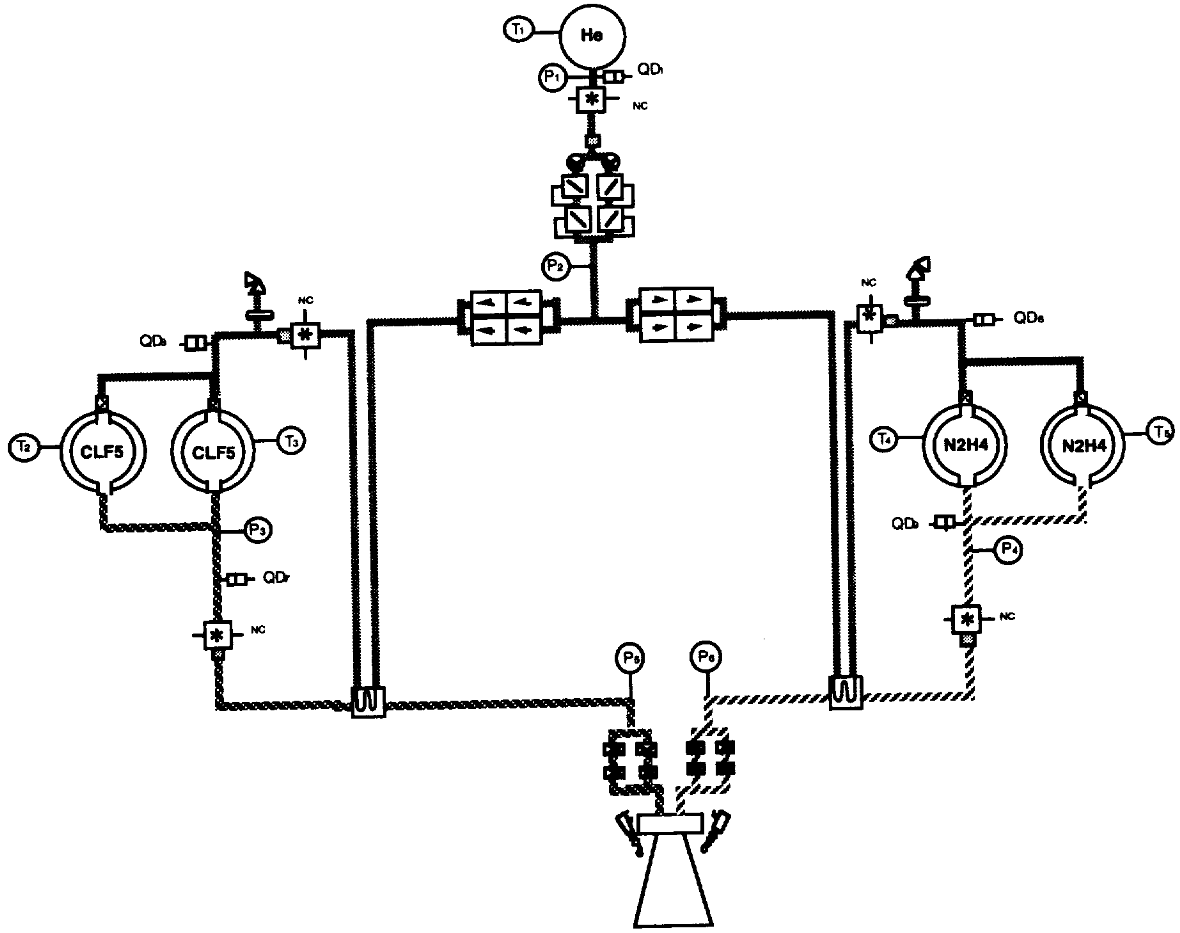

Figure 5-6. ClF_5/N_2H_4 pressure-fed return stage.

The Isp of 353 sec is perhaps conservative, since the theoretical Isp is nearly 20 sec higher, but previous engines have been estimated in this performance range. The mixture ratio of 2.5 contributes to the high packing efficiency of this propellant combination, since ClF_5 is extremely dense at 1793 kg/m^3. The engine concept does not require a purge between burns, since the volume of the propellants is small between the engine valves and the vacuum of space, and sufficient time will elapse between firings to evacuate propellant residuals naturally. A return engine development program would be required to support this stage concept.

The redundant feed system incorporates conventional hardware on the N_2H_4 side, but there are no soft seals on the ClF_5 side. Previous SDI experience has proved this to be an insignificant issue. SDI experience, however, has been limited to short life/low thrust propulsion system designs, and the inability to design with soft seals increases the difficulty associated with the ClF_5 hardware readiness (HR) level. The CIS produces ClF_5 in quantities that could support this program, and U.S. chemical companies have stated they will produce ClF_5 only if the quantity per year justifies the production effort.

The return-stage propulsion system design has two fuel and two oxidizer tanks, both of which are constructed of graphite epoxy overwrapped aluminum. Aluminum is required, since titanium is not compatible with ClF_5. The stage propellants are both Earth-storable, so no active venting is required during flight operations and lunar stay.

The lander stage is similar to the lander stage described in section 5.2.2, trade 2 and is shown in figure 5-5.

5.2.4 Trade 4 System Description - N_2O_4/M20 Pressure-Fed High Efficiency Single Engine Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

A single new optimized N_2O_4/M20 pressure-fed engine is used in this return propulsion system, in comparison to the reference FLO return stage concept, which uses three existing engines. A single-engine configuration, shown in figure 5-7, was chosen for the same reasons outlined in the previous single-engine return configuration options.

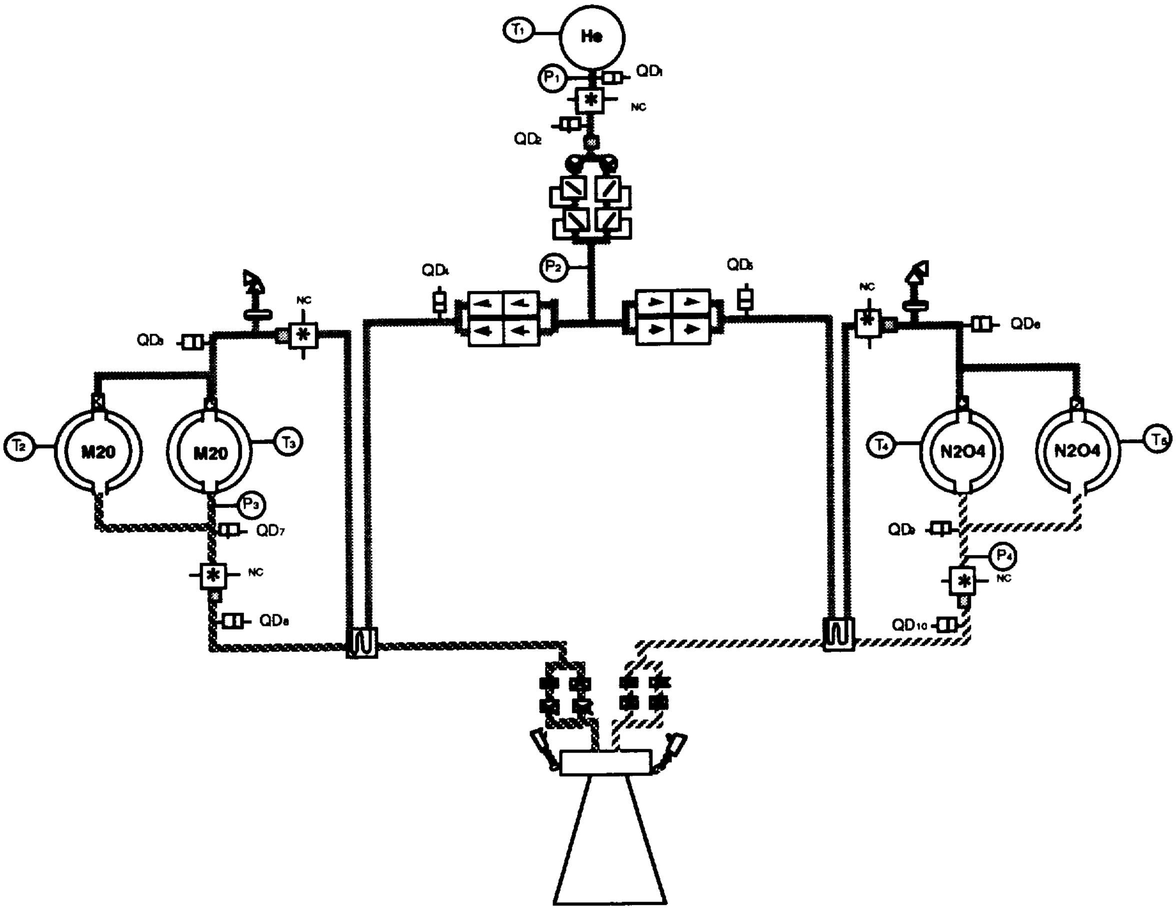

Figure 5-7. N_2O_4/M20 pressure-fed high-efficiency single-engine return stage.

Estimates show that a single N_2O_4/MMH engine operating at a chamber pressure of 200 psi with an area ratio of 250 would provide 330 sec of Isp. Unfortunately, this area ratio, at the 30,000 lbf thrust required for the stage, would require an unwieldy nozzle of more than 200 in. length and 140 in. diameter. To reduce the nozzle dimensions and maintain performance, the propellant combination was changed to N_2O_4/M20 (80% N_2H_4 mixed with 20% MMH), which provided 5 more sec of Isp to trade with the optimal area ratio in the design. The higher performance allows a reduction in the nozzle length to 160 in. with an exit diameter of 115 in., while providing an engine Isp of 331 sec. Overall, this provides a reasonable 2.5-3.0 mt post-TLI mass savings over the baseline FLO configuration. A return-engine development program would be required to support this stage concept.

Although tailoring engine performance characteristics to an optimal vehicle design provides much more design flexibility than specifying existing hardware, the main benefit of this trade option over the reference FLO vehicle is the simplification obtained from building a propulsion system around one engine as opposed to three. In comparison to the reference FLO return stage, this configuration reduces the number of components in the propulsion system and allows the engine to be recessed farther into the return stage so that it does not protrude into the lander stage, thereby reducing any FITH concerns.

The lander stage is similar to the lander stage described in section 5.2.2, trade 2.

5.2.5 Trade 5 System Description - LO_2/CH_4 Pressure-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

The return stage propulsion (fig. 5-8) uses a single pressure-fed engine combusting LO_2/CH_4 propellants. Like LO_2/N_2H_4, this propellant combination has several beneficial characteristics: (1) LO_2 and CH_4 are relatively easy to store on the lunar surface, (2) performance is higher than most storable, (3) CH_4 is inexpensive and relatively non-toxic, and (4) propellant experience is high for both propellants, however the density of CH_4 is relatively low.

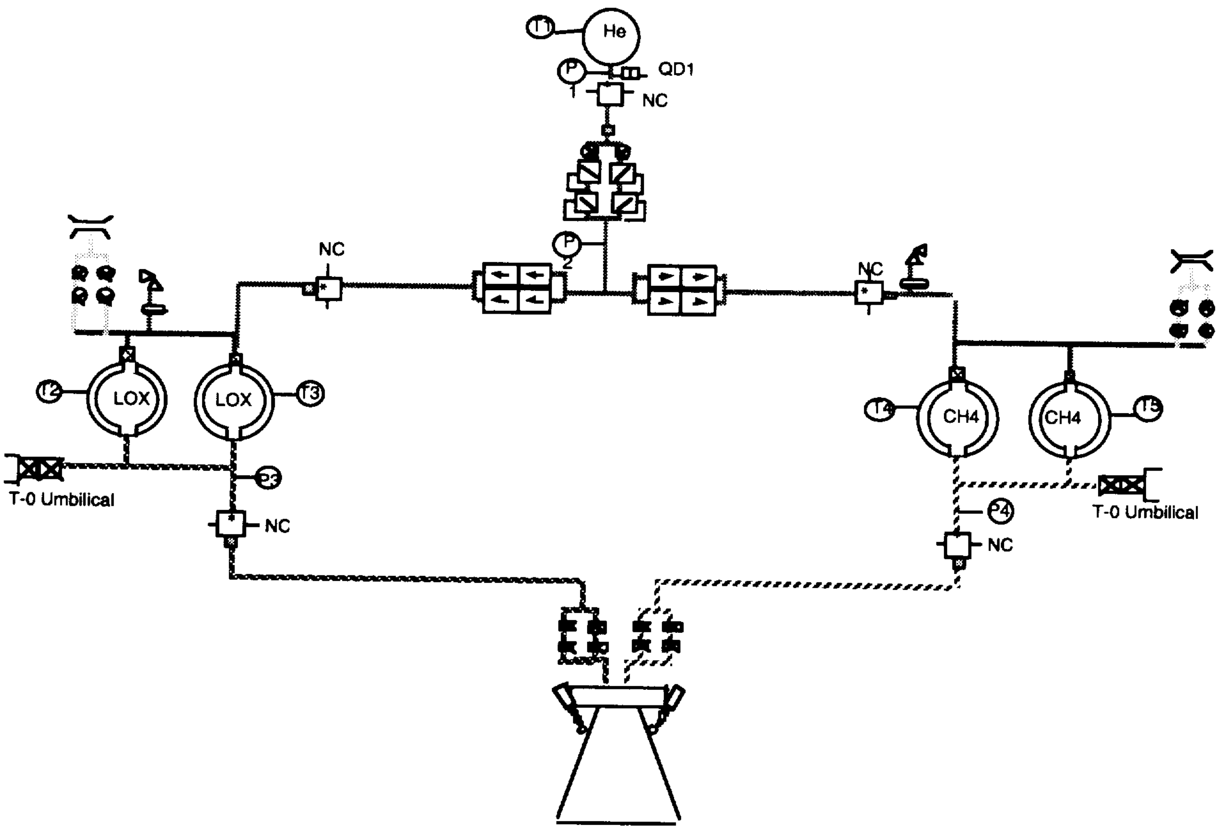

Figure 5-8. LO_2/CH_4 pressure-fed return stage.

The return engine was sized by using similarity to the LO_2/N_2H_4 30,000 lbf thrust ablative engine in Trade 2. The chamber pressure chosen is 125 psi. The engine length is approximately 120 in., and the Isp is 350 sec. A single-engine configuration was chosen for the same reasons outlined in previous single-engine return trade study options. An engine development program would be required.

An active vent system is utilized in this return propulsion system design to maintain LO_2 and CH_4 tank pressures during transit and on the lunar surface. Both the LO_2 and the CH_4 tanks are graphite epoxy overwrapped aluminum-lined tanks with a nominal operating pressure of 250 psi.

The lander stage is similar to the lander stage described in section 5.2.2, Trade 2.

5.2.6 Trade 6 System Description - N_2O_4/MMH Pump-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

The two-stage, pump-fed, Earth-storable return stage vehicle concept (fig. 5-9) incorporates two MMH and two N_2O_4 tanks for return propellant storage and uses four advanced XLR-132 pump-fed engines. Each engine will have a regenerative oxidizer-cooled chamber and a fuel-rich gas generator to produce 15,000 lbf of thrust at 1500 psi chamber pressure. The engine is estimated to produce an Isp of approximately 344 sec. Currently, both Aerojet and Rocketdyne are testing XLR-132 flight-weight prototype engines at 1500 psi chamber pressure and 3750 lbf thrust. A return-engine development program, based on existing XLR-132 work, would be required to support this stage concept.

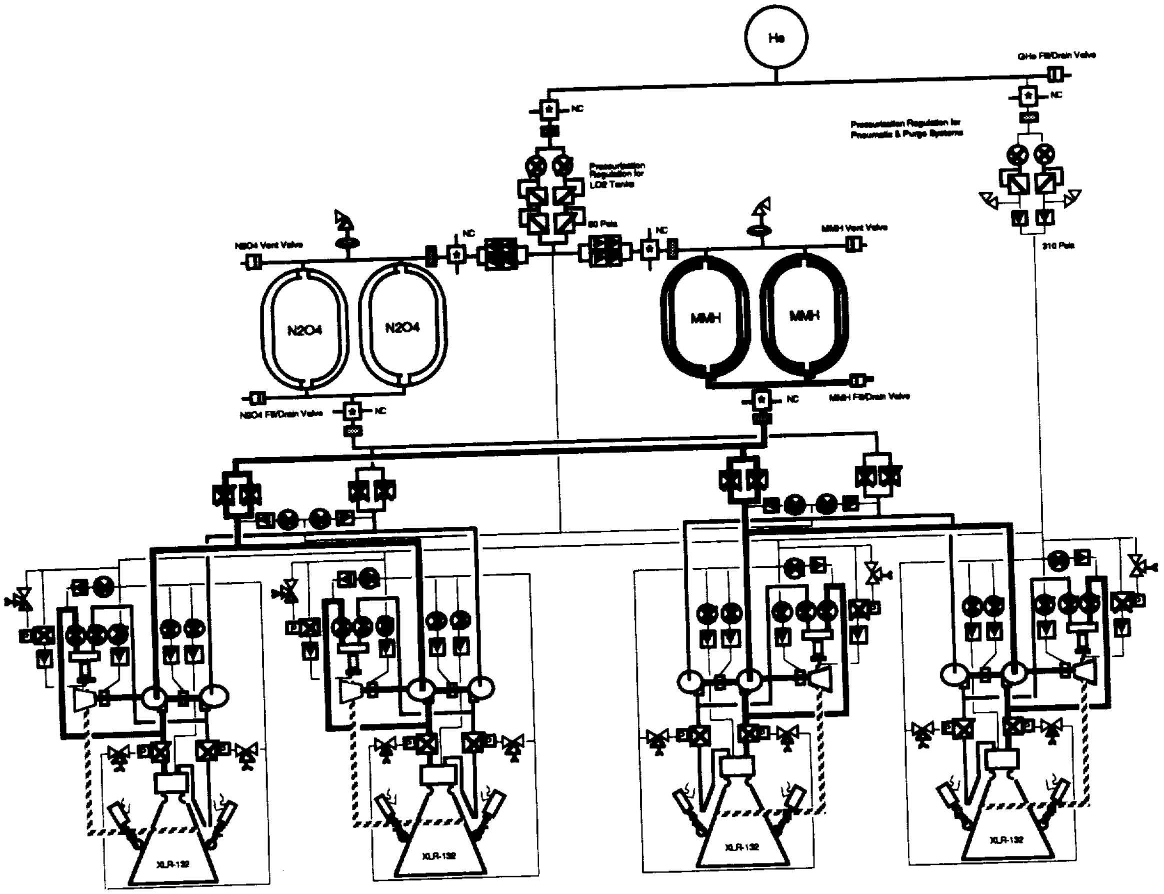

Figure 5-9. N_2O_4/MMH pump-fed return stage.

Since the current design for the XLR-132 contains nonredundant turbo machinery, four engines are used to meet the single fault-tolerant stage requirement. In the case of engine failure during return, the opposing engine is shut down. This failure-abort mode was chosen over gimbaling the remaining engines, since it is believed that gimbaling through the return stage cg would require rapid actuator responses and large gimbal angles. For this reason, the propellant feed system of the return stage is designed to isolate engine pairs. Since the engines are nonthrottling, twice the stage thrust is required should an engine failure occur using this failure abort-mode approach. Additional discussion on main engine redundancy is provided in section 5.0.

The return propulsion system requires purge, pressurization, and pneumatic subsystems. Because of this and the fact that pump-fed engines are used, this return-stage concept has greater than average complexity and mission operation counts. The pump-fed engine abort reaction time is greater than typical pressure-fed systems. Should the lander stage fail and return-stage separation is required, the abort reaction time would be no more than 2 sec maximum. Since the stage propellants are Earth-storable, no active venting is required during flight operations and lunar stay.

The lander stage utilizes the same basic propulsion system as the baseline vehicle design, including engines and components. The exception is the lander stage tanking configuration, which uses larger diameter tanks to reduce the number of LH_2 tanks required. Instead of the six LH_2 and the two LO_2 tanks used in the baseline lander stage, this lander stage option uses two LO_2 tanks and four LH_2 tanks with larger diameters. The single LO_2 tank configuration is not used since the multiple engines may protrude significantly into the lander stage.

5.2.7 Trade 7 System Description - LO_2/CH_4 Pump-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

The two-stage, pump-fed, LO_2/CH_4 return stage vehicle option (fig. 5-10) incorporates two oxygen and two methane tanks for return propellant storage and uses four concept RL10M-1 pump-fed LO_2/CH_4 engines. Each engine produces 18,900 lbf of thrust and has a 2:1-step throttling capability. The RL10 derivative engine is estimated to produce an Isp of approximately 358 sec. Pratt & Whitney has run RL10 engines with LO_2/CH_4 propellants in the past; however, a new engine development program would be required to support this stage concept.

Since the current RL10 design contains nonredundant turbo machinery, four engines are required to meet the single fault-tolerant stage requirement. In the case of engine failure during return, the opposing engine is shut down. Since the engines are throttleable, each engine will nominally operate at 50% thrust, so in case of engine failure, the opposing engine is shut down, and the remaining two engines are throttled up to 100% thrust. Additional discussion on main engine redundancy is provided in section 5.0.

The return propulsion system requires both pressurization and pneumatic system regulation and management subsystems. Since the stage propellants are cryogenic, an active venting subsystem is required during flight operations and the lunar stay. Because of these subsystems, and the fact that pump-fed engines are used, this return-stage concept has greater than average complexity and mission operation counts. Since pump-fed engines are used, the abort reaction time, should the lander stage fail and return-stage separation is required, is greater than typical pressure-fed systems and is approximately 2 sec maximum. Pre-abort chilldown of the engines may not be required to meet the abort reaction time listed.

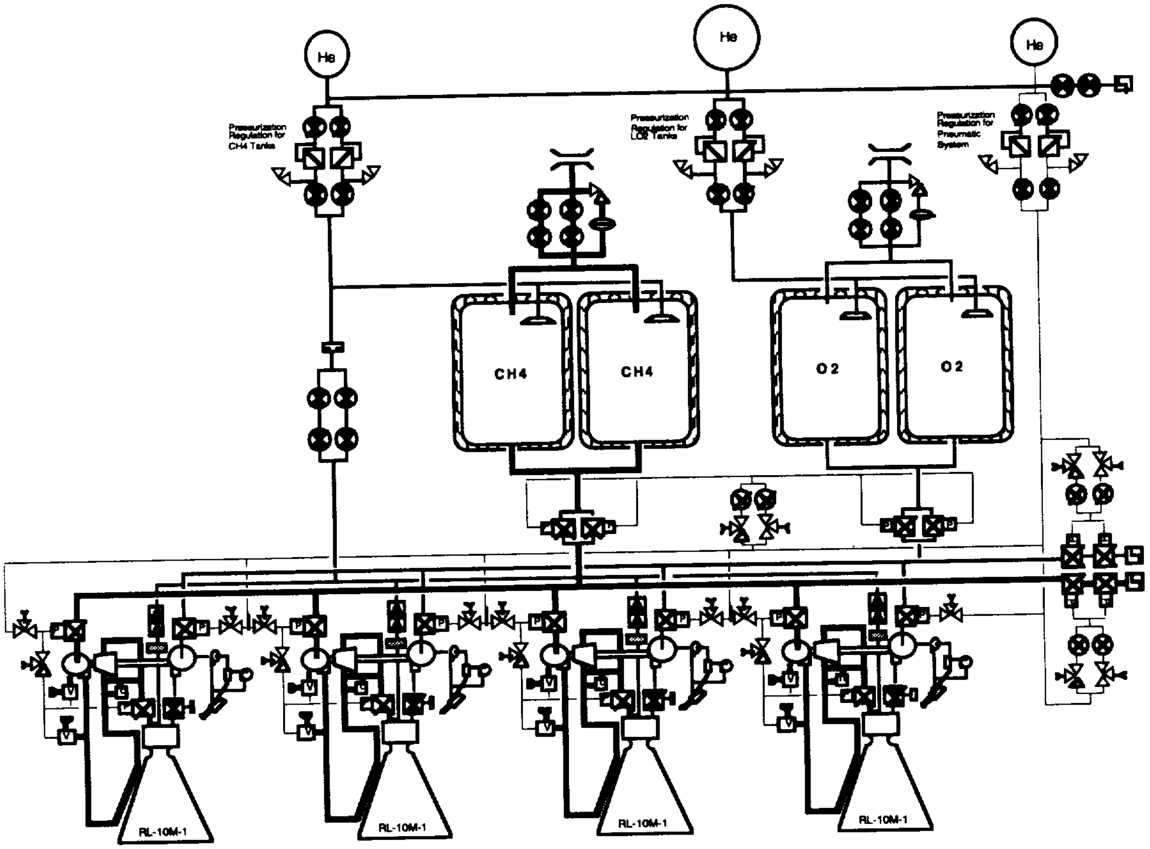

Figure 5-10. LO_2/CH_4 pump-fed return stage.

The lander stage is similar to the lander stage described in section 5.2.6, Trade #6.

5.2.8 Trade 8 System Description - LO_2/LH_2 Pump-Fed Return Stage and LO_2/LH_2 Pump-Fed Lander Stage

The two-stage, pump-fed, LO_2/LH_2 return-stage vehicle concept (fig. 5-11) incorporates one oxygen tank surrounded by four hydrogen tanks for return propellant storage and uses four modified RL10A-3-3A pump-fed engines. The return-stage engine is the same engine used on the lander stage except for slight modifications to the chilldown vent valves. Instead of allowing the liquid hydrogen to vent out to space, the normal procedure for RL10 chilldown, the vent exit is tied back into the propellant feed and pressurization system. Pumps have been added to the propulsion system to recirculate hydrogen through the engine during chilldown. The recirculation pumps maintain a high-quality fluid in the propellant feed system for a rapid abort capability. Poor quality liquid in the propellant feed system could cause up to an additional 1-sec delay for full 90% thrust startup.

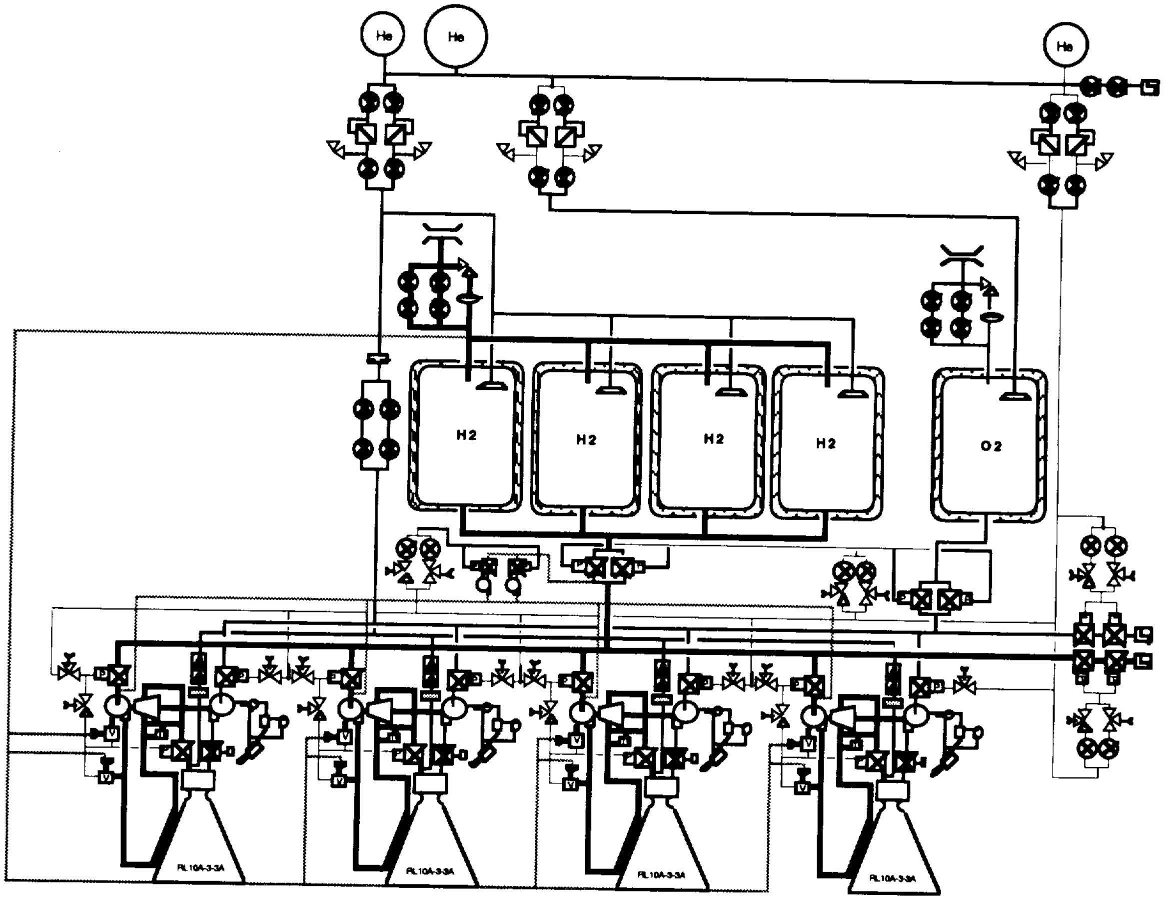

Figure 5-11. LO_2/LH_2 pump-fed return stage.

Since the current RL10 design contains nonredundant turbo machinery, four engines are required on the return stage to meet the single fault-tolerant return requirement. In the case of engine failure during return, the opposing engine is shut down. Since the engines are throttleable, each engine will nominally operate at 50% thrust, so in case of engine failure, opposing engines are shut down, and the remaining two engines are throttled up to 100% thrust. Additional discussion on main engine redundancy is provided in section 5.0.

The return propulsion system requires both pressurization and pneumatic system regulation and management subsystems. Since the stage propellants are cryogenic, an active venting subsystem is required during flight operations and lunar stay. Because of these subsystems, and the fact that pump-fed engines are used, this return-stage concept has greater than trade average complexity and mission operation counts. Since pump-fed engines are used, the abort reaction time, should the lander stage fail and return stage separation is required, is greater than typical pressure-fed systems and is no more than 2 sec maximum. Pre-abort chilldown of the engines is required to meet the abort reaction time listed.

The lander stage is similar to the lander stage described in section 5.2.6, Trade 6.

5.2.9 Trade 9 System Description - LO_2/LH_2 Pump-Fed Single-Stage Vehicle

The single stage LO_2/LH_2 pump-fed vehicle concept (fig. 5-12) incorporates six hydrogen and two oxygen tanks for lander propellant storage and incorporates one hydrogen and one oxygen tank for return propellant storage. The single-stage vehicle concept incorporates four modified Pratt & Whitney RL10A-4 engines, to be used for both return and lander propulsion. Each engine produces 20,800 lbf of thrust and provides a 6:1 throttling capability. The engines are estimated to produce an Isp of approximately 449 sec. Currently, non-throttling RL10A-4 engines are in production; however, an engine modification program would be required to support this stage concept.

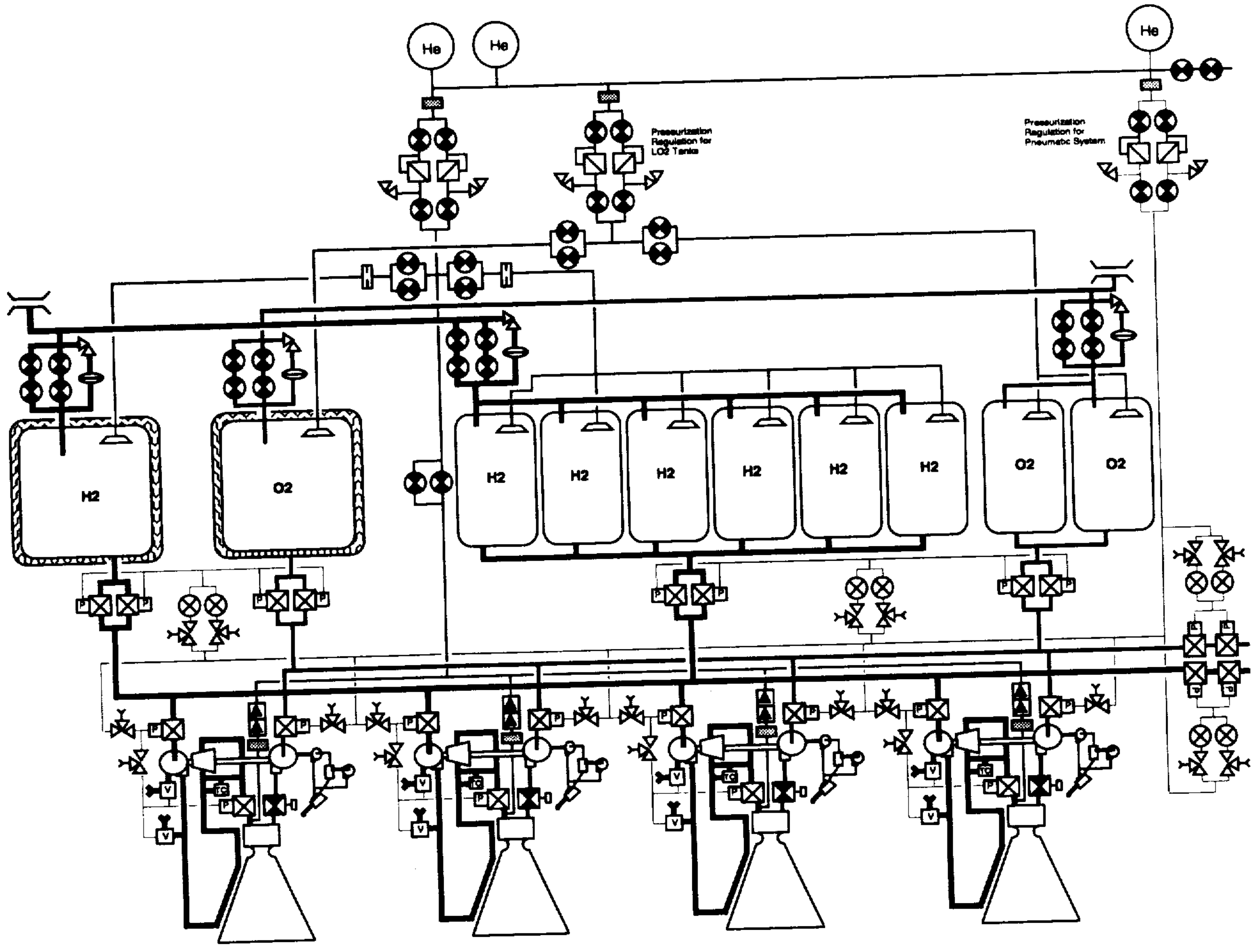

Figure 5-12. LO_2/LH_2 pump-fed single-stage vehicle.

Six hydrogen and two oxygen tanks for lander propellant storage, and one hydrogen and one oxygen tank for return propellant storage were chosen because of the structural mass equation used in the stage-sizing program. Other tank configurations were considered, including common propellant tanks for return and lander propellants; however, the packaging configuration chosen produced the lowest total vehicle mass. Since the structure mass equation is based on the surface area of the cylinder into which the stage design can fit, the 8-tank configuration produced a lower calculated structural mass than taller, less numerous tank configurations. The structural mass penalty for taller, less numerous tanks was greater than the boiloff and tank mass penalty for smaller, more numerous tanks since the main propellant volume is subjected to only 4 days of boiloff conditions. Use of itemized structural mass calculations are required before a truly optimized tank configuration can be calculated for the single-stage vehicle concept.

The single-stage propulsion system requires both pressurization and pneumatic regulation and management subsystems. The return and lander propellants in the current tank configuration are isolated from each other with pneumatic valves. Since cryogenic propellants are used, an active vent subsystem is required for flight operations and lunar stay. Since a single propulsion system is used for both return and lander staging and the engines are throttleable, opposing engines are shut down and the remaining two engines are throttled up in the event of an engine failure.

Even though the single-stage vehicle design can provide lower overall system complexity and greater vehicle reusability compared to all other options, current technology does not allow for a vehicle design that meets the FLO 96 mt vehicle TLI mass limit. If the technology for a cryogenic integrated modular engine is developed, however, the single-stage vehicle design will again become a viable FLO candidate, as well as possibly providing a reusable system for long-term evolution capability.

5.2.10 Trade 10 System Description - LO_2/LH_2 Pump-Fed Stage-and-a-Half Vehicle

The stage-and-a-half design (fig. 5-13) is very similar to the single-stage vehicle concept described in section 5.2.9 except for the fact that the lander tanks and structure for the stage-and-a-half design are left behind on the lunar surface. The single-return LO_2 and LH_2 tanks and the four RL10 engines are incorporated into a common structure that separates from the lander tanks structure. Separation is accomplished with cryogenic and gas disconnects between the dropped lander tanks and the return propellant feed system. Engine throttling of 7:1 is required to meet the hover requirement for the stage-and-a-half vehicle.

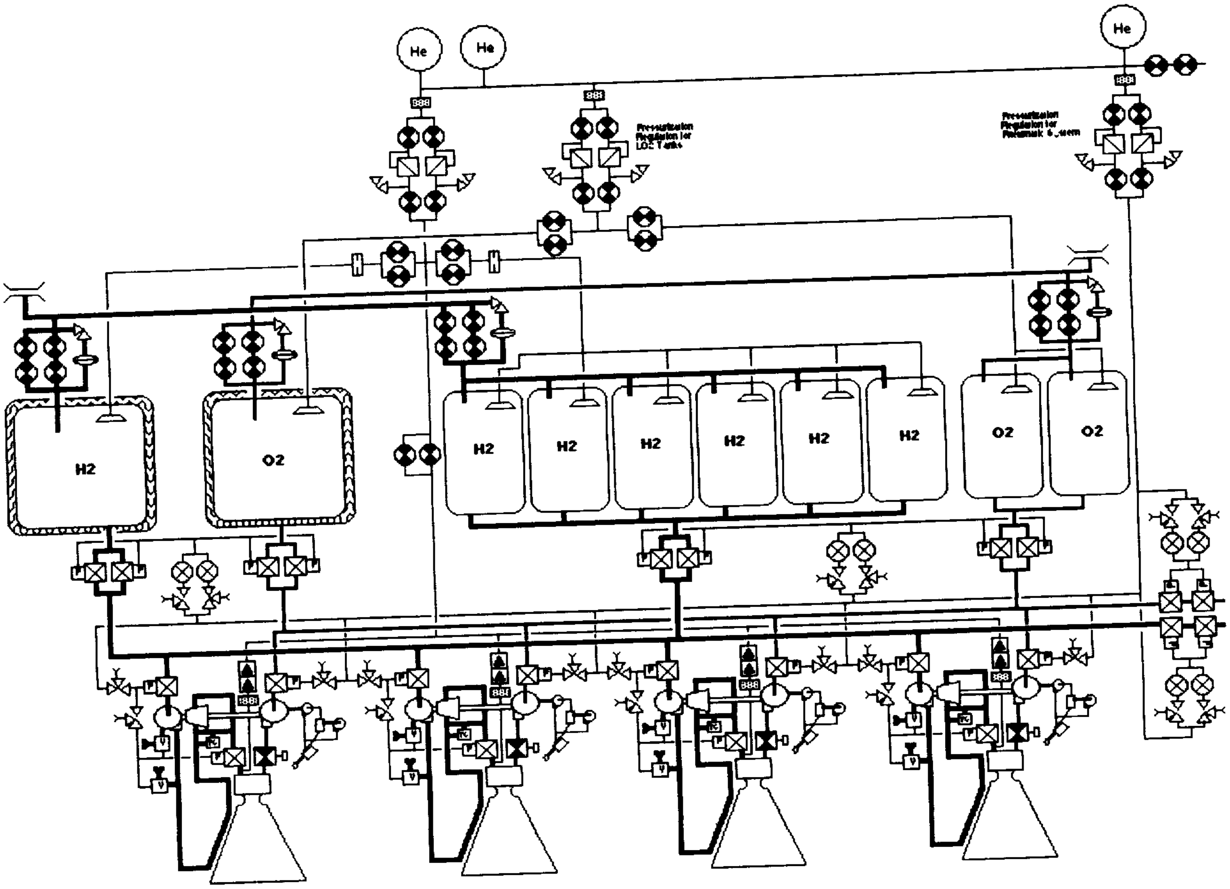

Figure 5-13. LO_2/LH_2 pump-fed stage-and-a-half vehicle.

5.2.11 Trade 11 System Description - ClF_5/N_2H_4 Pressure-Fed Return and Lander Stages

The propulsion system in this return stage uses the same single 30,000 lbf pressure-fed engine described in section 5.2.3, Trade 3. As in Trade 3, the engine has an estimated Isp of 353 sec and runs at a propellant mixture ratio of 2.5. The return propulsion system consists of two ClF_5 and two N_2H_4 propellant tanks constructed of graphite epoxy over wrapped aluminum.

The lander stage propulsion system (fig. 5-14) is very similar to the return stage propulsion system. Instead of a single engine, the lander stage uses two 30,000 lbf throttling ClF_5/N_2H_4 engines to meet the lander thrust requirement. Propellant for the two engines in this stage are fed from three ClF_5 and three N_2H_4 graphite epoxy overwrapped aluminum tanks. Features may need to be incorporated to allow the propellant tank pressurant to be vented in order to safe the propulsion system and prevent propellant leakage on the lunar surface after landing.

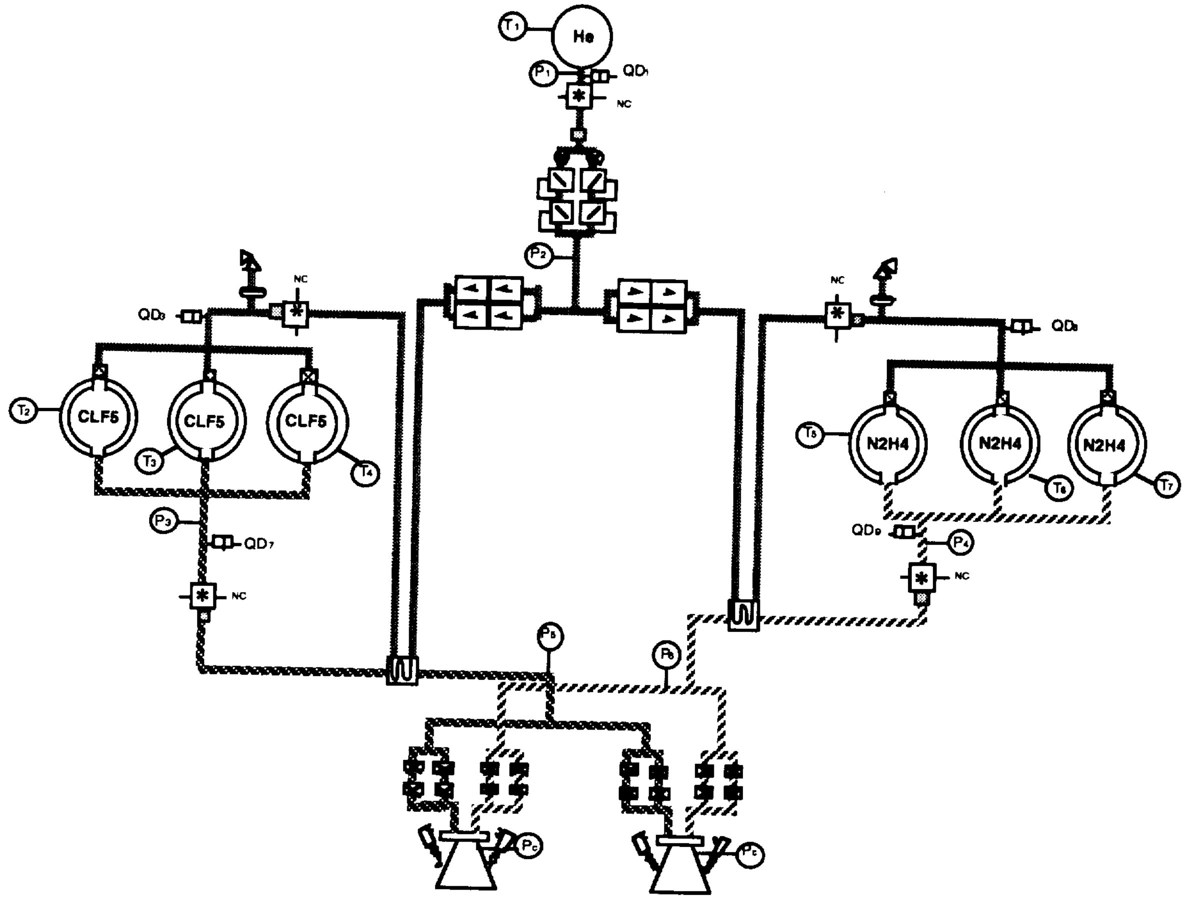

Figure 5-14. ClF_5/N_2H_4 pressure-fed lander stage.

The ClF_5/N_2H_4 lander and return-stage configuration would provide an approximate post-TLI mass savings of 5 mt over the reference FLO vehicle configuration, while providing a much simpler (and, therefore, more reliable) vehicle, since no cryogenic propellants or pump-fed engines are used in the system. Also, because of the high density of the propellants compared to LO_2/LH_2, the lander-stage diameter needs only to be approximately 6 m in diameter instead of the 9.4 m diameter used by all other trade options in this study.

5.2.12 Trade 12 System Description - Optimized IME LO_2/LH_2 Return and Lander Stages

This stage propulsion system concept incorporates an IME cryogenic propellant design. A number of IME designs have been suggested, using various engine configurations and pump-fed engine operating cycles. For simplicity, only one design was used to examine the possible merits of an IME-propelled stage design, and the one chosen was based on data obtained from Rocketdyne. The return IME propulsion system design (fig. 5-15) incorporates redundant propellant pumps feeding a high-pressure manifold that connects three separate 10,000 lbf thrust engines' chambers. The LH_2 turbopump is run by an expander cycle, and the LO_2 turbopump is run by an oxygen preburner. Each engine incorporates redundant throttling valves to fulfill overall stage thrust throttling and engine gimbaling requirements and eliminates the need for LO_2/LH_2 hydraulic or electro-mechanical actuator (EMA) gimbaling. Since the only moving parts on each engine are the throttling valves, and they are redundant, there is no engine-out failure mode requirement to meet the baseline single fault-tolerant return criteria.

The IME LO_2/LH_2 return stage propulsion system concept incorporates two oxygen and two hydrogen tanks for return propellant storage. Both the oxygen and hydrogen tanks are autogenously pressurized. This fact, combined with the use of low head pressure liquid pumps, eliminates the need for a helium pressurization system. Also, the IME design incorporates only EMA valves, eliminating the need for a hydraulic or pneumatic system. Like all other cryogenically propelled stages, an active vent subsystem is required during transit and on the lunar surface. Since the feed system and the engines are closely interrelated, a large-scale propulsion system (not only engine) development program would be required to support this stage concept.

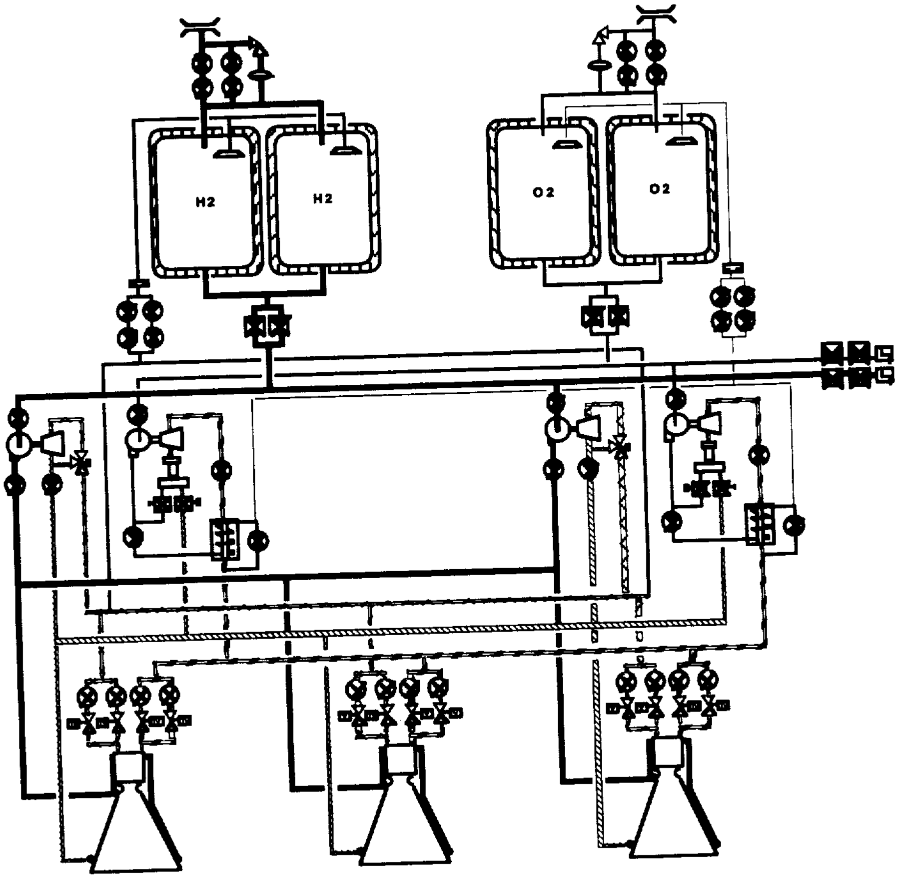

Figure 5-15. Optimized IME LO_2/LH_2 return stage.

The IME design, as specified, provides many advantages over conventional pump-fed cryogenic propulsion system designs. The IME design eliminates the need for helium pressurization, engine actuation, and pneumatic subsystems, thereby reducing complexity and increasing overall system reliability. However, since the state-of-the-art needs to be pushed for this design to be realistic, it most likely will not be ready for the 1999 FLO launch date.

The lander stage propulsion system (fig. 5-16) uses the same IME design propulsion system as that in the return stage, with only a few modifications. The lander stage requires four 15,000 lbf thrust engines chambers instead of the three 10,000 lbf thrust engine chambers used on the return stage. Also, four hydrogen and two oxygen propellant tanks are used to feed the uprated IME design.

Further analysis is required to determine IME chilldown requirements as well as abort reaction time capabilities.

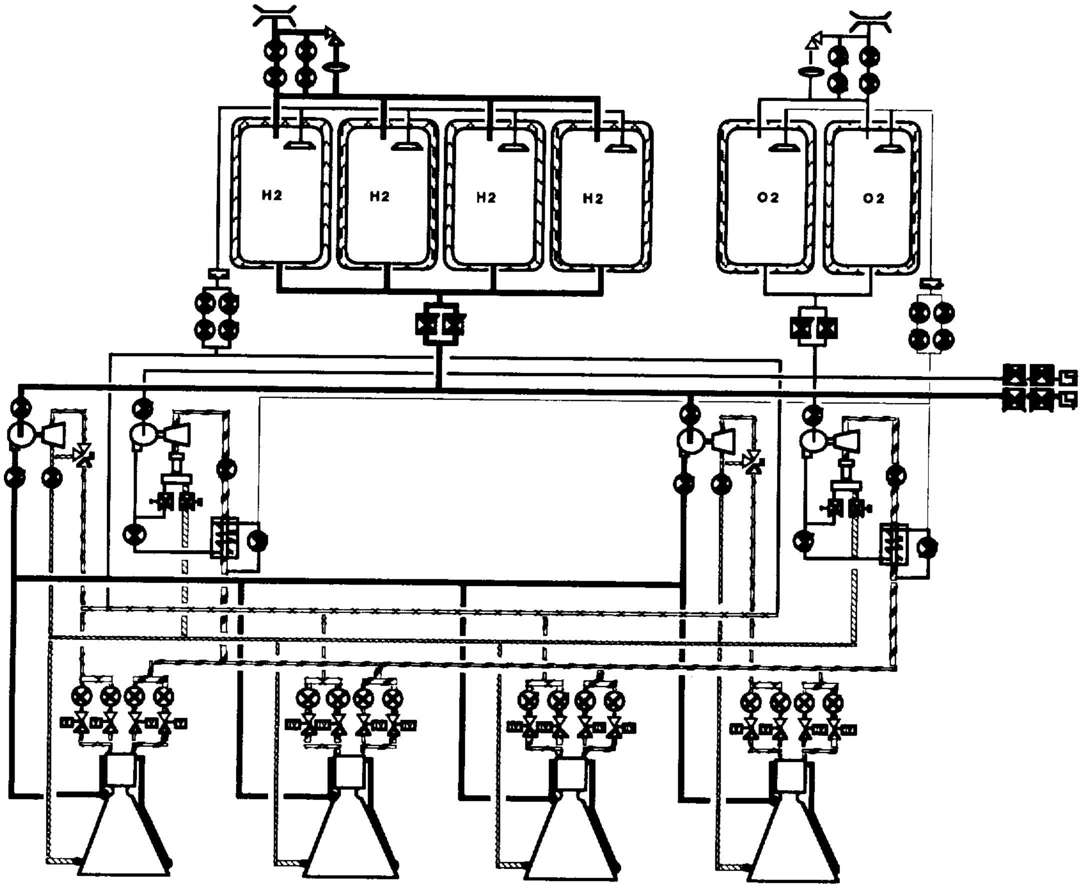

Figure 5-16. Optimized IME LO_2/LH_2 lander stages.

5.2.13 Trade 13 System Description - LO_2/LH_2 Pressure-Fed Return and Pump-Fed Lander Stages

The propulsion system for this return stage (fig. 5-17) uses a single 30,000 lbf pressure-fed LO_2/LH_2 engine developed specifically for this stage concept. The ablative engine concept is estimated to have an Isp of 440 sec at a chamber pressure of 125 psi. The return-stage propellant feed system incorporates three LH_2 tanks and three LO_2 tanks, with the helium pressurant cryogenically stored in tanks located within the LH_2 tanks. To pressurize the propellant tanks, the cold helium pressurant is released from the high pressure, cryogenically stored tank and is regulated to a lower pressure before running through a thrust chamber heat exchanger.. The warmed helium is then allowed to pressurize the propellant tanks.

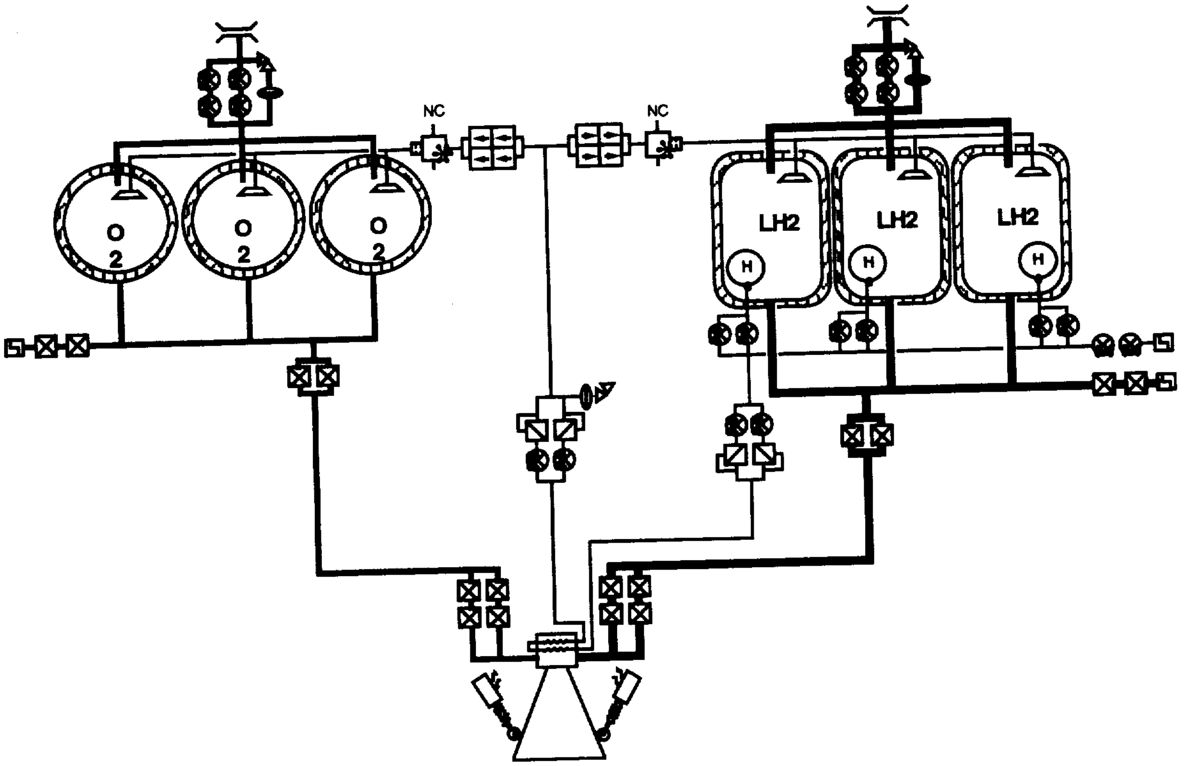

Figure 5-17. LO_2/LH_2 pressure-fed return.

Since the return stage propellants are cryogenic, an active venting subsystem is required during flight operations and lunar stay. Pre-abort chilldown of the engines may be required to meet the lunar lander abort requirements.

The lander stage is similar to the lander stage described in section 5.2.6, Trade 6.

5.2.14 Trade 14 System Description - IME LO_2/LH_2 Pump-Fed Stage-and-a-Half Vehicle

The IME stage-and-a-half design (fig. 5-18) is very similar to both the baseline stage-and-a-half design outlined in section 5.2.10, Trade 10 and the all-IME vehicle design outlined in section 5.2.12, Trade 12. Like Trade 12, the IME stage-and-a-half design utilizes the lander stage IME propulsion system design to meet its thrust requirements. Like Trade 10, this option also leaves the lander propellant tanks and structure behind on returning to Earth, as well as using the same propellant tank stage configuration. Separation of the stages is accomplished with cryogenic and gas disconnects between the dropped lander tanks and the return propellant feed system. The IME propulsion system design allows the already high performance stage-and-a-half concept proposed in Trade 10 to be even lighter and less complex.

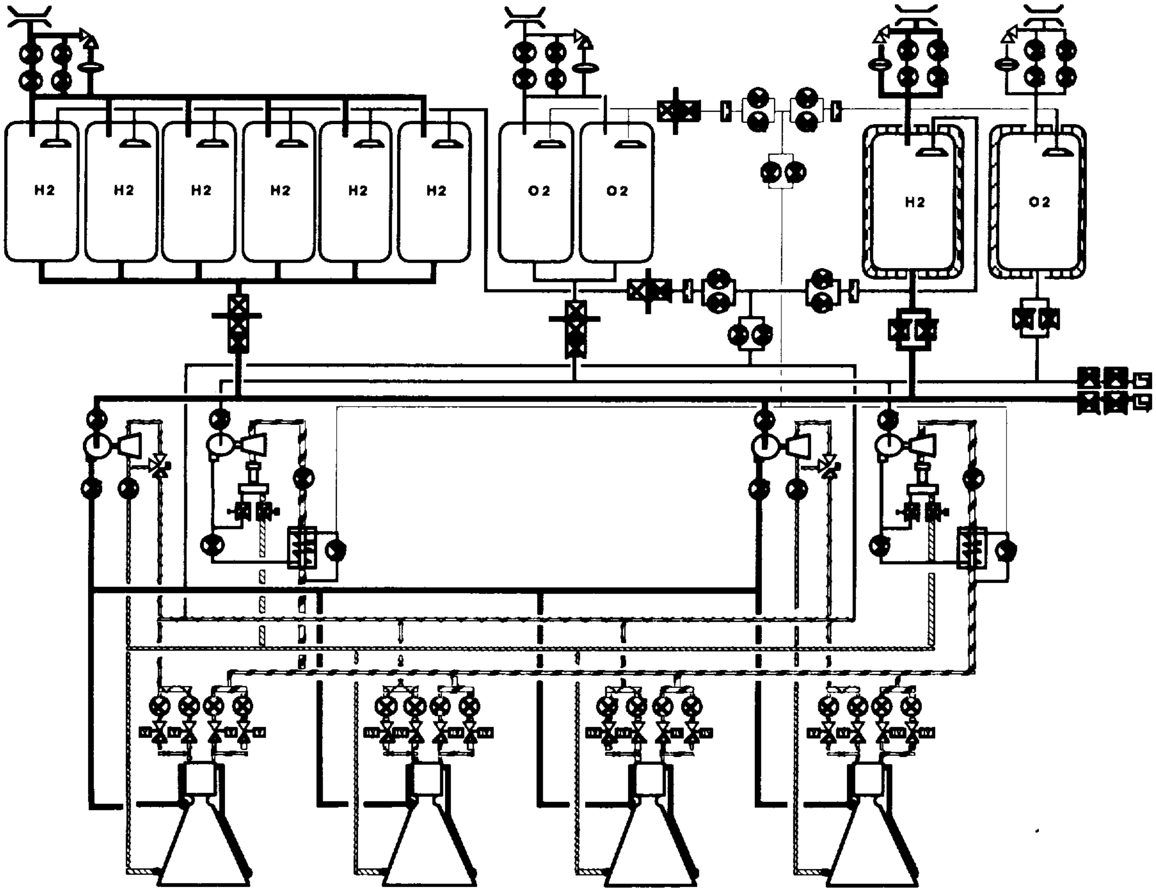

Figure 5-18. IME LO_2/LH_2 pump-fed stage-and-a-half vehicle.

5.3 Vehicle Configuration Layouts

5.3.1 Crew Vehicle Configurations

Simple computer aided design (CAD) models were developed for evaluating the relative merits of each crew vehicle configuration in terms of vehicle propulsion system packaging, touchdown cg, and cargo packaging. A scale drawing of the crew vehicle configurations is provided in figure 5-19. The configurations were built to the following set of design guidelines:

- 10 m maximum usable diameter for the HLLV payload fairing (project requirement)
- 1 m clearance between the crew module and the return-stage tanks to provide volume for crew module support equipment (e.g. fuel cells/reactant tanks)
- 0.5 m clearance (minimum) between the return-stage engine nozzle(s) and any significant engine blockage (e.g. lander-stage tanks)
- 0.3 m clearance (minimum) between the engine power head and the tanks to provide space for propellant lines and manifolds

For simplicity, the landing gear is not shown in figure 5-19. For any of the configurations, the initial vertical clearance between the footpads and the bottom of the lander stage is expected to be in the range of 1.5 to 2.0 m to provide a minimum ground clearance of about 1.0 m after the impact attenuation stroke. The length of the landing gear for a given configuration, therefore, is a function of the landing gear tread radius required to provide a specified stability rating, based upon the touchdown cg height of the vehicle. Note that the cg heights listed for the crew vehicle configurations are referenced to the bottom of the lander-stage engines (fig. 5-19) and not to the lunar surface itself.

The 14 vehicle configurations can be loosely grouped into 3 main categories based on the staging options:

- single stage (Trade 9)
- 1-1/2 stage (Trades 10 and 14)
- two stage (Trades 1 to 8 and 11 to 13)

The single-stage and stage-and-a-half vehicle configuration have characteristics different from the two stage vehicles. Trades 9, 10, and 14 were all configured with the lander and return propellant divided into separate sets of tanks. The lander propellant is contained in a ring of eight tanks (two LO_2 and six LH_2), and the return propellant is contained in a pair of tanks stacked in the central hole of the tank ring. The engines are centered below the return oxidizer tank. In the 1-1/2-stage configuration, the core tanks and the engines must disconnect and slide out from the center of the lander tank ring. Trades 9, 10, and 14 demonstrated superior touchdown cg's because of the favorable location of the return oxidizer. The cargo for Trades 9, 10, and 14, however, must be packaged around the return LH_2 tanks, limiting the cargo volume to less than 20 m^3. The height of the cargo platform is approximately 7 m for any of the three options.

The majority of the two-stage options (Trades 1 to 5) consisted of a pressure-fed storable return stage (space- and/or Earth-storable propellants) mounted on a cryogenic LO_2/LH_2 lander stage. Trade 1, the FLO reference configuration, used three existing AJ10-118 engines for the pressure-fed return stage. The three AJ10-118 engines were inset into the central hole of the descent tank ring to reduce the overall height of the vehicle. Like the single-stage and 1-1/2-stage configurations, the cargo for Trade 1 must be packaged on a high platform around the return-stage tanks, limiting the available cargo volume to less than 20 m^3. Trades 2 to 5 represent variations on the return-stage propellants and the overall tank packaging philosophy relative to the reference configuration. Because Trades 2 to 5 involve the development of a new pressure-fed engine, the central hole in the lander stage was eliminated to provide a flat interstage interface. The cryogenic lander propellant was packaged in five tanks rather than eight with four hydrogen tanks positioned around a central oxygen tank. The large spaces between the hydrogen tanks are available for lunar cargo, providing a minimum usable cargo volume of 20 to 35 m^3 located in close proximity to the lunar surface. The tank configurations for Trades 2 to 5 have two drawbacks, however. First, the 10 m diameter limitation (in combination with only four LH_2 tanks) tends to increase the height of the lander stage relative to the Trade 1 configuration. Second, the use of a flat interstage interface forces the addition of a 0.5 m gap between the lander and return stages to reduce the back pressure on the single return-stage engine at ignition.

Trades 6 and 7 look quite similar to Trade 1. The primary differences from the reference configuration are the use of pump-fed rather than pressure-fed return-stage engines and the use of six lander-stage tanks rather than eight. The lander stages for Trades 6 and 7 consist of two LO_2 and four LH_2 tanks arranged in a ring around a central hole. As in Trade 1, the return-stage engines are inset into the central hole to reduce the overall height of the vehicle. From a configuration standpoint, there appears to be little benefit from the use of a pump-fed rather than a pressure-fed storable return stage. The cg and cargo packaging characteristics for Trades 6 and 7 are very similar to those of Trade 1.

Examples of two-stage cryogenic configurations are provided in Trades 8, 12, and 13. Trade 8 uses RL10 pump-fed engines on both the lander and return stages, while Trade 13 uses an RL10 pump-fed lander stage and a pressure-fed return stage. Both of the configurations are considered to be inferior to the other options in term of touchdown cg height and cargo volume. In addition, the large volumes of the Trade 8 and Trade 13 return stages tend to drive the nose of the HLLV payload fairing toward a very blunt profile, leading to larger aerodynamic losses and higher peak aerodynamic loading during ascent. Trade 12 uses high performance IMEs for the lander and return stages, which considerably reduces the total cryogenic propellant load relative to Trades 8 and 13. The net effect of the IMEs and the low-bulk density cryogenic propellants is a vehicle with a moderate cg height at touchdown and moderate cargo volume, similar in external appearance to the configurations for Trades 6 and 7.

Trade 11, a two-stage ClF_5/N_2H_4 pressure-fed vehicle, is the unique configuration of the trade study group. The high Isp and high-bulk density of this propellant combination resulted in an extremely compact vehicle. The height of the vehicle is essentially driven by the stacked length of the lander and return-stage pressure-fed engines, with the nose of the crew module just topping 10 m. The estimated touchdown cg height is approximately 5 m. The Trade 11 vehicle is also the only configuration that did not use the full 10 m diameter of the payload fairing. It should, therefore, be possible to match the cargo volume of any of the other 13 configurations by taking advantage of the full payload fairing diameter.

5.3.2 Cargo Vehicle Configurations

Although the majority of the work focused on the crew vehicle configurations, several cargo mission configurations were also considered. figure 5-20 shows a lunar habitat packaged on a cryogenic lander stage. The central hole of the lander stage is filled with the fuel cell reactant tanks and other habitat subsystems. If a common lander stage is used for both the crew and cargo missions, the cargo configuration provided in figure 5-20 is representative of the cargo lander geometry for all of the configuration options except for Trade 11. The geometry variations between the various options will be minimal, with the lander-stage platform height varying from approximately 5 to 6 m relative to the bottom of the lander engine nozzles. In contrast, the lander stage for Trade 11 provides a platform height of less than 3 m.

A second option is to reconfigure the propellant tanks specifically for the cargo mission. A partial representation of a ClF_5/N_2H_4 cargo propulsion system is provided in figure 5-21. The propellant is divided into two pairs of tanks that are mounted on each side of the habitat along with a 30 klbf pressure-fed engine. Note that the fuel cell reactant tanks for the habitat (not shown in fig. 5-21) would also have to be integrated into this cargo stage. In contrast, the most viable option for a cryogenic cargo lander is to move the tank set above the lunar habitat with a new feed system to deliver propellant to the bottom-mounted engines.

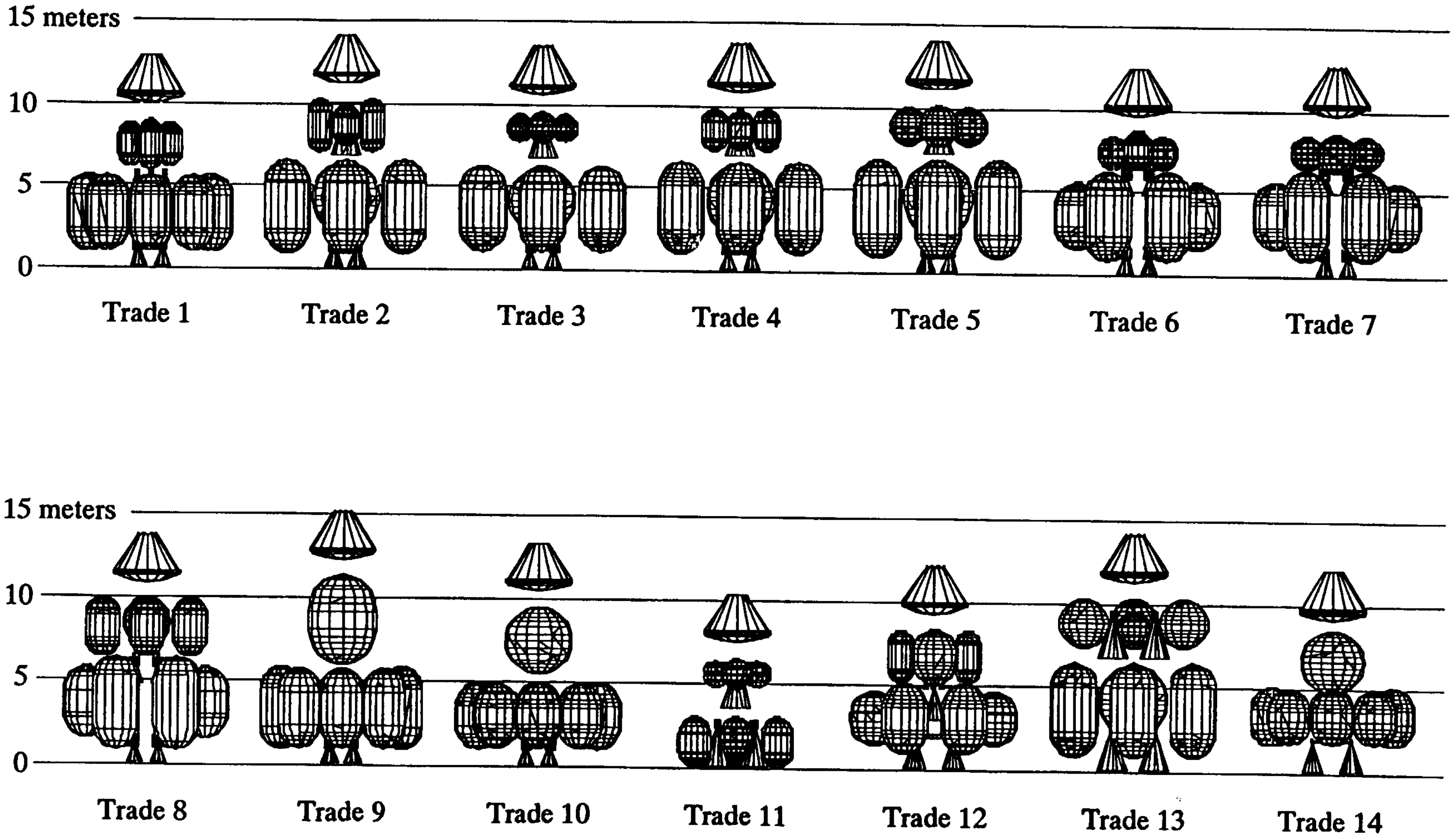

Figure 5-19. Scale drawing of vehicles.

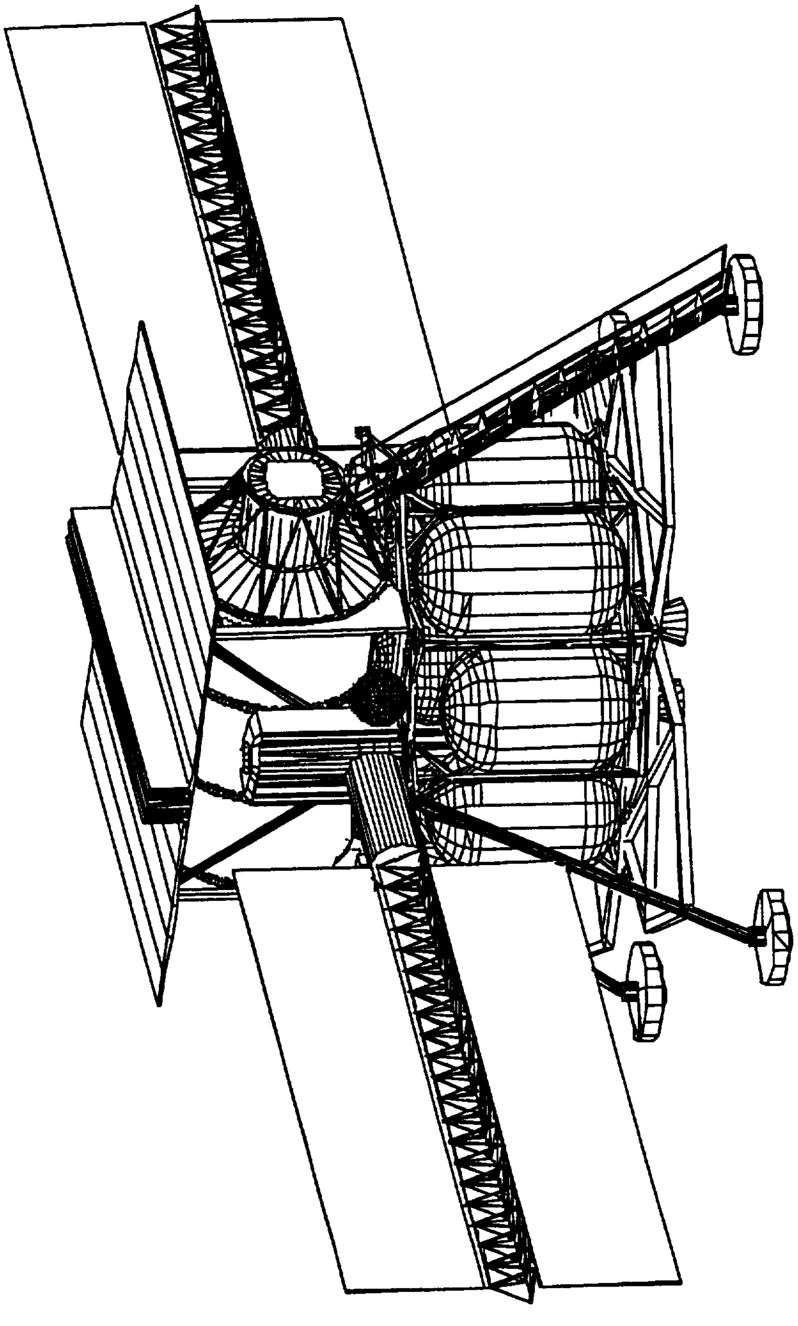

Figure 5-20. Habitat lander for LO_2/LH_2 vehicles.

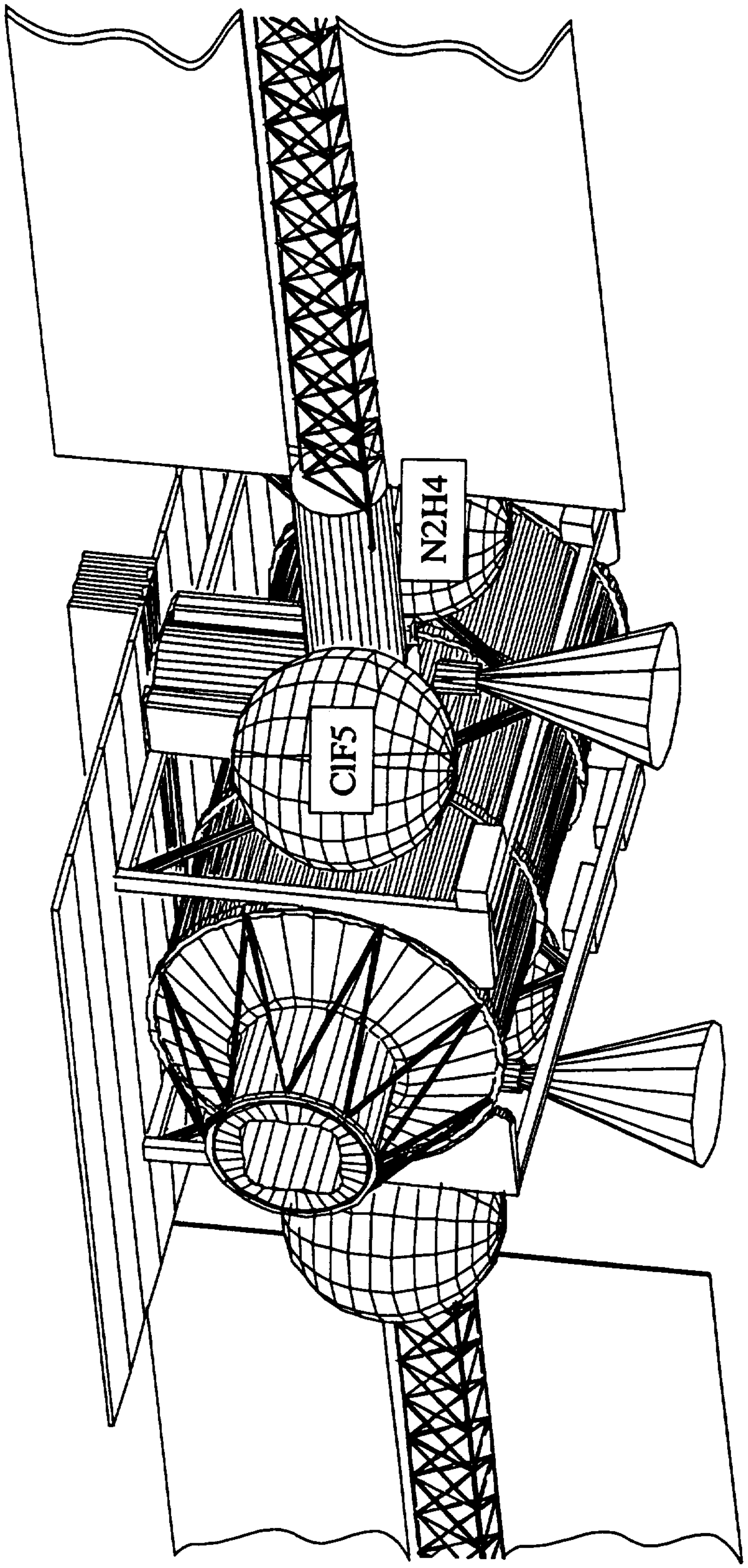

Figure 5-21. Habitat lander using ClF_5/N_2H_4 propulsion.

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SECTION 6.0

LUNAR LANDER PROPULSION SELECTION CRITERIA AND EVALUATION METHODOLOGY

The First Lunar Outpost Propulsion System Trade Study used the analytic hierarchy process (AHP) to evaluate the effectiveness of the reference FLO design and all promising propulsion system concepts in meeting the FLO transportation system requirements. AHP is a structured approach for handling complex problems concerning interrelated study criteria and subjective priorities. The evaluation hierarchy developed for the FLO trade study criteria is presented in figure 6-1. The hierarchy relates cost, schedule, and risk to attributes that are quantifiable.

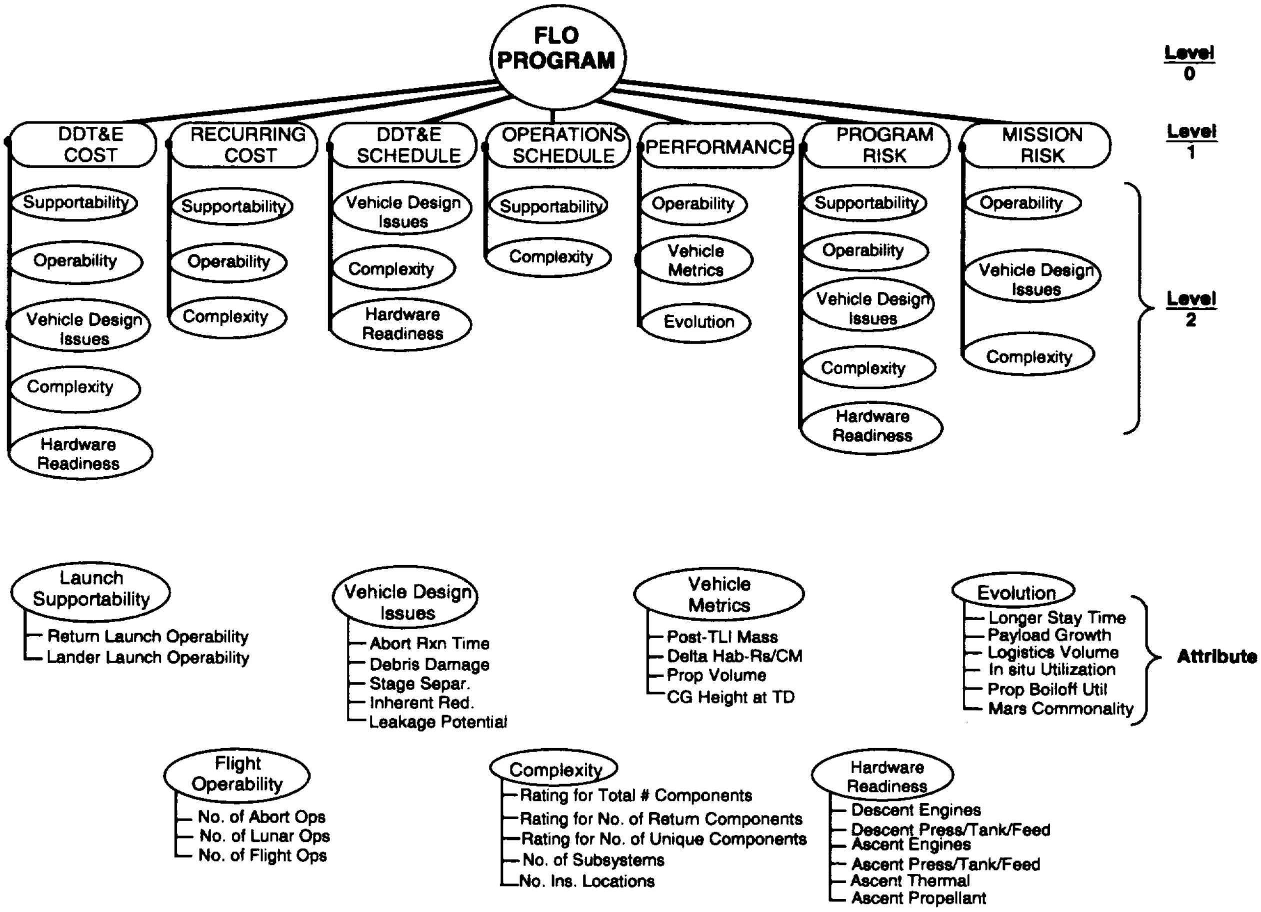

Figure 6-1. FLO propulsion trade study criteria hierarchy.

The criteria in the hierarchy shown in figure 6-1 are weighted using the Analytic Hierarchy Process called "pairwise comparisons." The criteria weights are combined with quantitative evaluations of each propulsion trade option to provide the trade study ranking of the trade options. Confidence is achieved in the trade study ranking by performing a sensitivity analysis of the trade study rankings. The rankings and sensitivity analysis are the basis for the trade study conclusions. This process is shown in figure 6-2.

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Figure 6-2. Trade study process.

The following sections describe the trade study process in more detail. The selection criteria are defined in section 6.1, and a summary of the trade option design data is presented with the definitions. Section 6.2 describes how the AHP calculates the criteria weights and ranks the trade options.

6.1 Selection Criteria Definition

The trade study evaluation criteria were organized into a hierarchy as shown in figure 6-1. The top level (level 0) was considered the objective level. The main objective of the FLO trade study was to pick the lander/return stage propulsion system concept(s) that could best meet the FLO transportation system requirements. Beneath this objective level lies the first level criteria, which were considered to impact the study objective directly. Beneath the first level lie the second-level subcriteria, which were considered to impact the first-level criteria. Input to the second-level subcriteria are the attributes against which all the trade options were evaluated. Each of these attributes had a rating, and every FLO vehicle trade option was assigned one of the attribute ratings for each attribute. These levels are discussed in the following sections. The matrices documenting the pairwise comparisons, and the weights derived at each level within the evaluation hierarchy, are presented in section 7 and appendix D.

6.1.1 Level One Criteria: Cost, Schedule, Performance, and Risk

The level one criteria represent program variables that reflect the overall program environment. The program variables of *cost, schedule, performance* and *risk* are presented in the level one criteria with a distinction between development and operations. The distinction is drawn between development and operations to sensitize the model to the number of FLO missions. The level one program criteria are defined in sections 6.1.1.1 through 6.1.1.7.

6.1.1.1 DDT&E Cost

The *DDT&E cost* is the component of the overall program cost related to the development and qualification of the vehicle hardware, the vehicle software, and the flight facilities in support of the first FLO mission. *DDT&E costs* are typically a function of vehicle design and hardware complexity, vehicle flight operability, and component hardware readiness (HR).

The influence of complexity and HR on *DDT&E cost* may be more obvious than the influence of vehicle design issues and flight operability. For example, during preflight Apollo, the vehicle design issue called FITH increased the *DDT&E cost*. The Lunar Module Series 7B tests at White Sands Test Facility during December 1968 were initiated to ensure thermal and startup transient confidence during stage separation. Because this issue arose outside the normal mission duty cycle testing, it increased the *DDT&E cost* of the program. An additional concern is the effect that vehicle flight operability has on *DDT&E cost*. Avionics and software are proportionally related to the number of mission operations required for a nominal flight, the lunar stay, and any aborts. DDT&E costs attributed to avionics can be driven by numerous operations requiring synchronization and extensive software verification.

6.1.1.2 Recurring Cost

The *recurring cost* is the component of the overall program cost related to mission operations and the production and modification of flight hardware and software. The *recurring cost* is determined by the level of launch support required, the level of mission support required to train the crew and operate the vehicle, and the quantity and complexity of hardware to be manufactured and verified. *Recurring costs* tend to dominate the overall program cost as the number of missions increases.

6.1.1.3 DDT&E Schedule

The *DDT&E schedule* is a measure of the difficulty associated with constructing the manufacturing and processing facilities, and designing/evaluating the vehicle hardware and software with respect to the program goal of a 1999 launch date. The *DDT&E schedule* is influenced by vehicle design issues, vehicle complexity, and component HR.

The inclusion of vehicle *complexity* and component technology readiness level (TRL) into the *DDT&E schedule* may be more obvious than the inclusion of vehicle design issues. The Apollo FITH example described in section 6.1.1.1 threatened to prolong the DDT&E phase of the program. An Apollo lunar landing could have been delayed into the next decade if FITH confidence had not been achieved as quickly as it was.

6.1.1.4 Operational Schedule

The *operational schedule* is a measure of how well a vehicle trade option meets production, assembly, qualification, and launch preparation time requirements for a set of flight hardware. The *operational schedule* is influenced by the launch support required and the vehicle complexity.

6.1.1.5 Performance

Performance is a measure of the vehicle trade option effectiveness in meeting or exceeding overall program requirements. Each of the alternative FLO vehicle trade options is designed to meet a common set of program requirements for crew, payload, and mission abort capabilities. The effectiveness of each vehicle trade option to meet these requirements is measured by evaluating the post-TLI mass, volume, cg height, and the level of activity required to operate the propulsion system. Since all of the vehicle trade options meet the minimum requirements, a higher performing vehicle trade option may be smaller, more compact, or simpler to operate than the other options.

In addition to vehicle metrics such as post-TLI mass and volume, evolution is also included hierarchically under *performance* because evolution is defined as the potential to exceed the initial program requirements. The evolution subcriteria belong in the hierarchical position under *performance* because evolution is frequently traded with the other *performance* subcriteria. For example, scarring or designing a system for evolution may require that the system is suboptimized for the immediate mission. Trading vehicle metrics such as post-TLI mass and vehicle volume with evolution makes the suboptimized situation explicit.

6.1.1.6 Programmatic Risk

Programmatic risk is defined by the uncertainty associated with meeting the FLO cost, schedule, and performance goals during the DDT&E phases of the program. This uncertainty is influenced by vehicle design issues, vehicle component TRL, launch support requirements, and the complexity of the hardware and software.

With respect to vehicle design issues, it was stated in section 6.1.1.1 that the FITH design issue arose late in the Apollo program. Fortunately, these issues were resolved through a successful test program. Even though the test program was successful, the Apollo FITH tests demonstrate the potential for design issues to affect the program by increasing costs and delaying schedule.

6.1.1.7 Mission Risk

Mission risk is defined in this trade study as a combination of the risk associated with not completing all mission objectives successfully, and the risk to the safety of the crew and support personnel associated with all phases of the mission, including aborts. *Mission risk* is influenced by the satisfactory solutions of all vehicle design issues, including the level of redundancy and mission-abort characteristics. Also important is the level of design and operational complexity of the hardware and software.

6.1.2 Lower Level Criteria: Quantifiable Data and Ratings

The issues affecting each level-one criterion are further disseminated into levels of finer detail in the evaluation hierarchy until a level is reached where each trade study vehicle option is assigned a numerical rating. The lower levels contain the subcriteria, the attributes, and the attribute ratings. These levels are generically described first, and the specific categories are then presented. Following the description of each subcriteria is a summary of the trade score range.

Subcriteria: A subcriterion affects one or more criteria in the next higher level. The subcriteria can be found in level 2 as shown in figure 6-1. It is best illustrated in the following example: the subcriterion *Complexity* affects both the *DDT&E COST* and *MISSION RISK* criteria (among others). For this reason, the subcriterion *Complexity* will appear under both of those criteria and could have a different relative contribution to each.

Attribute: An attribute is a quality used to measure a subcriterion. The attributes are designated in figure 6-1. A complete and sufficient set of attributes measures the degree to which a vehicle trade option satisfies a particular subcriterion. Most attributes in this trade study can be measured quantitatively, so that each vehicle option is assigned a "score" based on an engineering evaluation for each attribute.

Attribute Rating: The range of scores for a given attribute is divided further into attribute ratings. These attribute ratings are divided so that significant differences between the vehicle trade options are captured. For example, the subcriterion *complexity* contains a set of attributes consisting of component counts, subsystem counts, and instrumentation location counts. Each of the vehicle trade options are evaluated and assigned one attribute rating for each attribute. Consideration is given to avoiding ranges that place vehicle trade option scores near the transition from one rating to another. In the following section, the attributes for each subcriteria will be defined along with their corresponding attribute ratings.

6.1.2.1 Launch Supportability

The *launch supportability* subcriterion measures the complexity and effort required for ground support of the different propulsion system options evaluated. The level of the support required is measured by using the launch operability index (LOI) developed under contract to NASA by Rocketdyne. This index considers the type of systems typically requiring installation and checkout at Kennedy Space Center before considering the launch and the facilities/scenarios required to maintain them. The result of applying the LOI to lander and return propulsion system options is an overall *launch supportability* rating that can then be used for relative comparisons between trade options. For the special case where the lander and return propulsion systems are not separate, such as on the single-stage vehicle or the stage-and-a-half vehicle, a perfect LOI score was assessed for the active return systems that do not exist separately from the lander systems. Detailed charts describing the LOI are provided in appendix C, and a summary of the ratings each vehicle received for LOI are shown in figure 6-3.

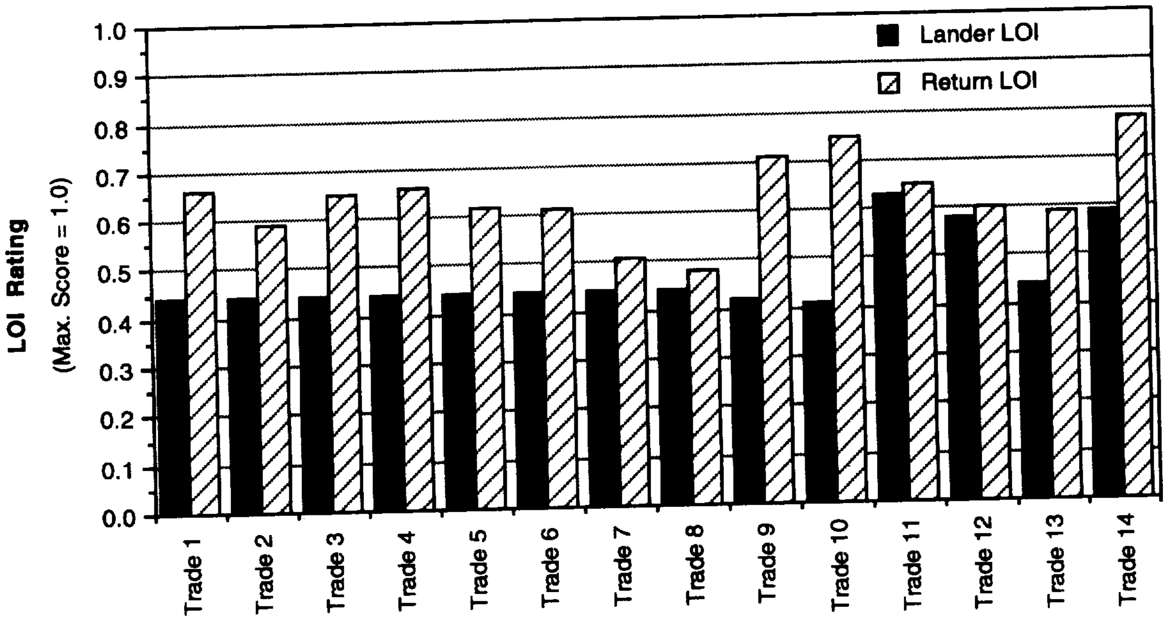


Figure 6-3. LOI trade rating summary.

6.1.2.2 Flight Operability

The *flight operability* subcriterion captures the complexity of the propulsion system as it relates to the number of significant operations required to support the vehicle during a nominal flight scenario, a nominal lunar stay, and during the worst-case abort situation: abort during powered lunar descent. A significant operation is defined as a commanded event causing a specific state change in a schematic component or similar group of components. Each *flight operability* attribute is defined below and is measured with the following attribute ratings:

<u>Number of Abort Operations</u> is the number of operations required to abort the mission successfully during the lunar descent phase. Typical operations counted are "shut down opposing engine," "throttle up remaining engines," "open tank isolation valves," "open engine valves," and "fire pyros to separate lander structure from return structure," etc. This attribute varies from 4 to 12 abort operations required for all of the 14 vehicle options considered. Additionally, whether or not propellant line and engine chilldown is required presented an additional *abort operations* discriminator, which signifies whether nominal operations are required to support an abort. The range of abort operations required is divided into the following attribute ratings:

"Fewer than, or equal to 4 abort operations, no chilldown required"
"Between 5 and 6 abort operations, no chilldown required"
"Greater than, or equal to 7 abort operations, no chilldown required"
"Between 7 and 10 abort operations, chilldown required"
"Greater than, or equal to 11 abort operations, chilldown required"

Number of Flight Operations is the number of all propulsion system operations required to complete the mission successfully and is typically dominated by items such as "open pneumatic pressure regulation system," "open tank isolation valves," "open engine valves," "fire ignitor," etc. This attribute varies from 26 to 97 for all of the 14 vehicle options considered. The range of total mission operations required is divided into the following attribute ratings:

"Fewer than 40 flight operations"
"Between 41 and 60 flight operations"
"Between 61 and 70 flight operations"
"Between 71 and 80 flight operations"
"Between 81 and 90 flight operations"
"Greater than 91 flight operations"

Number of Lunar Operations is the number of operations required to safe and maintain the overall vehicle and the return propulsion system. It is influenced mainly by cryogenic venting operations required during the lunar stay and is also influenced by any post lunar landing activities to deactivate the lander. This attribute varies from 2 to 28 lunar operations required for all of the 14 vehicle options considered. The range is divided into the following attribute ratings:

"Fewer than 8 lunar operations"
"Between 8 and 24 flight operations"
"Greater than 24 flight operations"

A summary of the ratings each vehicle received for the *flight operability* attributes are shown in figure 6-4.

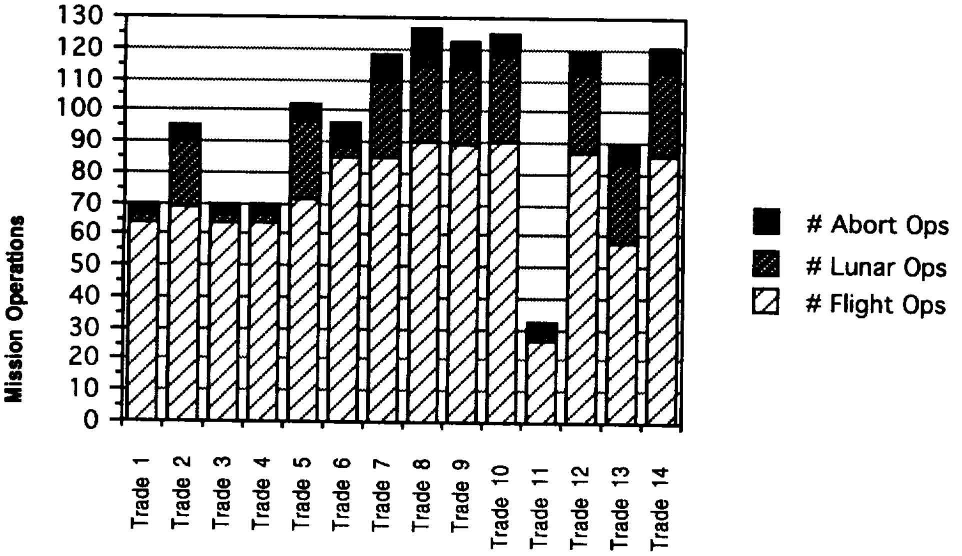


Figure 6-4. Flight operability trade ratings summary.

6.1.2.3 Vehicle Design Issues

The *vehicle design issues* subcriterion captures vehicle system complexities that may increase the uncertainty and risk associated with the DDT&E and Operations phase of the program. *Vehicle design issues* identified in the trade are (1) *abort reaction times* and design unique failure modes such as (2) *debris damage* during lunar descent and (3) *stage separation* difficulties, (4) *inherent redundancy* differences between the vehicles, and (5) *lunar leakage potential*. Each vehicle design issue is defined below and is measured with the following attribute ratings:

Abort Reaction Time varies among the different stage and propellant combinations. The *abort reaction time* is measured as the maximum time required to initiate an Earth return abort during lunar descent and includes the time required to reach 90% of the required abort engine thrust. The different attribute ratings are

"Less than 0.5 sec, without a prechill requirement (<0.5 NP)"
"Between 0.5 and 1.5 sec without a prechill (0.5-1.5 NP)"
"Greater than 1.5 sec without a prechill (>1.5 NP)"
"Less than 1 sec with prechill requirements (<1 P)"
"Between 1 and 1.5 sec with prechill requirements (1-1.5 P)"

Debris Damage concern arises when any vehicle configuration uses the same engines for both lunar descent and ascent propulsion, which could lead to a failure mode consisting of debris damage to the main engines during descent and landing. The attribute ratings are simply

"Yes, there would be a debris damage issue for the return propulsion system (Exposed)."
"No, there would not be a debris damage issue for the return propulsion system (Protected)."

Stage Separation is intended to capture the inherent differences between the various stage configurations as they might appear if a stage separation were required. Of particular importance is the difficulty created by FITH, which is the multiple stage difficulty of firing the engines from a fresh, unused stage down into the exhausted stage. The different attribute ratings are

"No separation required (No sep)"
"Flat interface with no FITH issues regarding separation (FLAT)"
"Structurally flat with return engines protruding into lander stage (eng n hole)"
"Return stage surrounded with structure and disconnects (INTERCONNECTED)"

Redundancy is the attribute intended to capture the variation of component redundancy between stage configurations beyond the minimum fault tolerance required. All vehicle trade options are designed to a minimum level of redundancy, and this redundancy is currently set at zero fault tolerant for mission success (MS), single fault tolerant for crew return, and zero fault tolerant after a descent-abort scenario. When feasible, the designs allow the systems to exceed zero fault tolerance, but the overall propulsion system design is only as redundant as its least redundant component. With this in mind, the following attribute ratings are

"Zero fault MS, Single fault Return, Zero fault Post-descent abort (0, 1, 0)"
"Single fault MS, Single fault Return, Single fault Post-descent abort (1, 1, 1)"

Lunar Leakage Potential is the attribute intended to record concerns regarding the variety of leakage potentials between the vehicles during the lunar stay. Of particular concern are propellants with very small molecules and active seals required for periodic venting during the lunar stay. Of least concern are propellants isolated with pyro valves until required for the Earth return. The different attribute ratings are

> "Any propellant, hermetically sealed: Relatively low potential"
>
> "Medium molecule propellants requiring venting (LO_2 and CH_4): Moderate potential"
>
> "Small molecule propellants requiring venting (LH_2): Relatively high potential"

A summary of the ratings each vehicle received for the Vehicle Design Issue attributes are shown in table 6-I.

Table 6-I. Vehicle Design Issues Trade Rating Summary

	Trade 1	Trade 2	Trade 3	Trade 4	Trade 5	Trade 6	Trade 7
Ascent Prop/Stage Configuration	MMH/N_2O_4	LO_2/N_2H_4	ClF_5/N_2H_4	$M20/N_2H_4$	LO_2/CH_4	MMH/N_2O_4	LO_2/CH_4
Ascent Feed System	Pressure	Pressure	Pressure	high Press.	Pressure	Pump	Pump
Descent Prop	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2
VEHICLE DESIGN ISSUES							
Abort Response Time	<.5 NP	<.5 NP	<.5 NP	<.5 NP	<.5 NP	>1.5 NP	1-1.5 P
Debris Damage Immunity	protected	protected	protected	protected	protected	protected	protected
Stage Separation - Fire-in-hole	eng n hole	flat	flat	flat	flat	eng n hole	eng n hole
Redund. (No. Faults: des,asc,abt)	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1
Leakage Potential	low	moderate	low	low	moderate	low	moderate

	Trade 8	Trade 9	Trade 10	Trade 11	Trade 12	Trade 13	Trade 14
Ascent Prop/Stage Configuration	LO_2/LH_2	Single	Stage 1/2	ClF_5/N_2H_4	LO_2/LH_2	LO_2/LH_2	Stage 1/2
Ascent Feed System	Pump			Pressure	IME used both stage	Pressure	IME stage
Descent Prop	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	ClF_5/N_2H_4		LO_2/LH_2	LO_2/LH_2
VEHICLE DESIGN ISSUES							
Abort Response Time	1.-1.5 P	0.5-1.5 NP	1-1.5 P	<0.5 NP	1-1.5 P	<.5 NP	1-1.5 P
Debris Damage Immunity	protected	exposed	exposed	protected	protected	protected	exposed
Stage Separation - Fire-in-hole	eng n hole	no sep	interconn.	flat	flat	flat	interconn.
Redund. (No. Faults: des,asc,abt)	1,1,1	0,1,0	0,1,0	1,1,1	1,1,1	1,1,1	0,1,0
Leakage Potential	high	high	high	low	high	high	high

6.1.2.4 Complexity

The relative complexities of the propulsion systems considered in the trade study were estimated by comparing the attributes pertaining to the number of system components, the number of subsystems, and the number of instrumentation locations.

At the second FLO propulsion workshop with industry and other NASA centers, suggestions were made to include additional types of system component counts, rather than just counting the "Total Number of Components." The workshop participants recommended that counts be included that capture the following qualities: (1) component commonality, (2) component function, and (3) component type.

Recommendations from the second workshop resulted in the incorporation of the following *complexity* rating counts: "Rating for Total Number of Components," "Rating for Total Number of Return Stage Components," and "Rating for Total Number of Unique Components," in addition to the counts for "Total Number of Subsystems" and "Total Number of Instrumentation Locations" previously used. The additional component ratings relaxed the importance of the "Rating for Total Number of Components" in favor of emphasizing the importance of the *complexity* associated with the return stage function and the benefit to *complexity* associated with commonality. Guidelines were created to define each of the different attribute types to help ensure consistency throughout the trade study.

For the trade study, a component is considered an item that provides an active schematic function. Components are counted for both the lander and return-stage main propulsion systems. Examples include counting a quad check valve as four components, counting individual tanks, valves, regulators, and engines thrust chamber assemblies (TCAs) as one component each. Any mechanical components supporting TCA operation should be counted as one component each. For example, count pumps, turbines, and engine valves as one component each. Items not counted as components include feed lines, filters, orifices, and ground-serviced test ports.

When counting for the attribute "Rating for Total Number of Components," both the lander and return component counts are summed together. When counting for the "Rating for Total Number of Return Stage Components," only those components that are active during the return trip from the lunar surface to Earth are counted. Including this count emphasizes the importance of maintaining simple return-stage propulsion system designs. The attribute for the "Rating for Total Number of Unique Components" counts each different component type once. Since many of the components are similar among the different stages, this attribute captures the commonality of these components throughout the system by counting only the unique components within the system. The components are considered unique if the design requires a separate DDT&E program.

The component counts in this study are modified to include a differentiation between simple components and complex components (i.e., check valves do not equal pumps) by counting them with a *complexity* factor defined below. Three *complexity* factor categories for components were developed to allow each component to be evaluated. Each category employs a multiplication factor to modify the actual component count. The multiplication factor is chosen to equal the category number. This overall *complexity* rating formula is represented by the following equation:

Complexity Rating = (Component Count) * (Complexity Factor)

or

Complexity Rating = (Category #1 Component Count) * (1)
+ (Category #2 Component Count) * (2)
+ (Category #3 Component Count) * (3)

The category definitions are defined below, and then the attributes and their ratings are presented:

Category Definitions

(a) CATEGORY 1: This category contains components that are relatively simple compared to other components existing in the trade study designs. This category primarily includes components that are straightforward to produce and operate passively without requiring an electrical command. To qualify for this category, the component must be simple with very few moving parts. (table 6-I)

(b) CATEGORY 2: This category contains components that have an average level of *complexity*. These components may require an electrical or mechanical command for operation. (table 6-I)

(c) CATEGORY 3: This category contains components that are more complex than any of the other component categories. These components may require long lead times for design, manufacture, and verification, or they may have one of the following physical characteristics: combustion operating temperatures, large sealing force margins, high rotation speeds, large parts count, and/or tight bearing or metal seal tolerances. (table 6-II)

Table 6-II. Component Complexity Factor

	COMPONENTS	COMMENTS
CATEGORY 1	hydraulic accumulators and check valves	few parts, no active control required
CATEGORY 2	solenoid valves, pneumatic valves TVC hydraulic actuators 3-way solenoid valves with vent ports, solenoid activated pilot ball valves, pressure regulators, pyro valves relief valves/burst discs EMA throttle valves, Fill QDs and ignitors	moderate part *complexity* electrical or mechanical commands initiate action
CATEGORY 3	pumps (cryogenic, storable, or hydraulic), turbines, gas generators, heat exchangers, T-0 disconnects, high rpm gear boxes, engine chambers, large tanks, and TVC EMAs	high parts *complexity*, difficult operating conditions, or complicated manufacture

Complexity Rating for Total Number of Components: This rating is calculated in the manner described above. The different attribute scores are

"Less than 300"
"Between 301 and 400"
"Between 401 and 500"
"Between 501 and 600"
"Greater than 601"

Complexity Rating for Number of Return Components: This rating is calculated in the manner described above. The different attribute scores are

"Less than 95"
"Between 95 and 120"
"Between 120 and 200"
"Between 200 and 300"
"Between 300 and 350"
"Greater than 350"

Complexity Rating for Number of Unique Components: This rating is calculated in the manner described above. The different attribute scores are

"Less than 75"
"Between 76 and 100"
"Between 101 and 125"
"Greater than 126"

Number of Subsystems: A subsystem is a group of components using the same fluid to accomplish a function. Typical propulsion system functions include pressurization, propellant storage and distribution, and propellant combustion devices. The ratings are

"Fewer than 10 subsystems"
"Between 10 and 14 subsystems"
"Greater than 14 subsystems"

Number of Instrumentation Locations: An instrumentation location is any place where a transducer, switch indicator, flowmeter, etc., is required to monitor the system. The attribute ratings are

"Fewer than 190 locations"
"Between 190 - 230 locations "
"Between 230 - 300 locations"
"Greater than 300 locations"

A summary of the ratings each vehicle received for the *complexity* attributes are shown in figure 6-5.

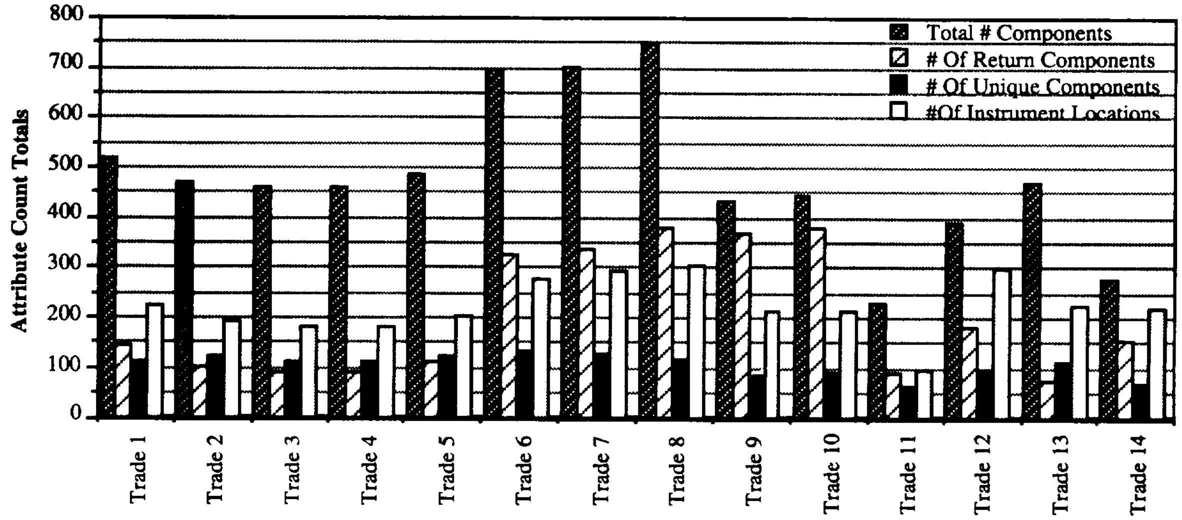


Figure 6-5. *Complexity* Trade Ratings Summary

6.1.2.5 Vehicle Metrics

The *vehicle metrics* subcriteria consists of four different measurements: (1) *vehicle post-TLI mass*, (2) *cargo vehicle mass difference w/crew vehicle*, (3) *total vehicle volume*, and (4) *vehicle cg*. The vehicle post-TLI mass was chosen to represent how well the trade concept meets the crew vehicle HLLV limits. However, to avoid implying that the crew vehicle is always the TLI or HLLV mass driver, the second mass parameter, the mass difference between the habitat (cargo) vehicle and the crew vehicle post-TLI mass is used. The third measurement of performance is the total volume of the propellant tanks, including pressurant. This performance parameter drives the vehicle structural mass, vehicle dimensions and crew egress difficulties. The last vehicle measurement is the crew vehicle cg at lunar touchdown. This measurement reflects the relative stability of the lander vehicle. The attributes used to measure *vehicle metrics* are listed below along with their attribute ratings:

The Vehicle Post-TLI Mass was chosen to represent how well the trade concept meets the crew vehicle HLLV limits. The attribute ratings are

"Less than 80 mt"

"Between 81 - 90 mt"

"Between 91 - 95 mt"

"Greater than 96 mt"

A summary of how each vehicle performed for the post-TLI attribute is shown in figure 6-6.

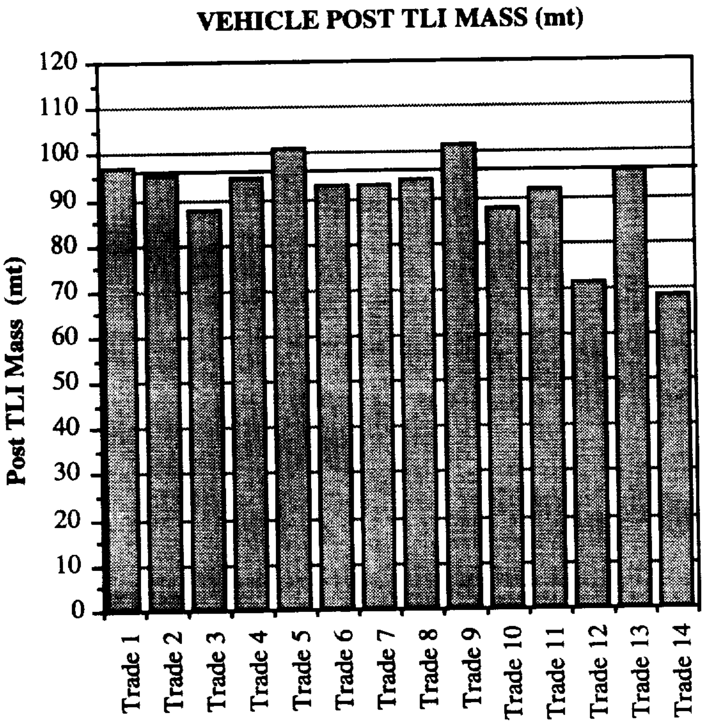


Figure 6-6. Post-TLI mass summary.

<u>The Cargo Vehicle Mass Difference w/Crew Vehicle</u> was chosen to avoid implying that the crew vehicle is always the TLI or HLLV payload mass driver. Additionally, to allow commonality between the crew lander vehicle and the cargo lander vehicle, it is desirable to have similar post-TLI mass sizes. The attribute ratings are

"Negative: Indicating crew vehicle is driver"
"Equal: Indicating vehicles are similarly sized"
"Positive: Indicating habitat vehicle is driver"

<u>Total Volume</u> of the propellant and pressurant tanks is another measurement of performance. This performance parameter drives the vehicle structure mass, dimensions, and crew egress difficulties. The attribute ratings are

"Less than 75 m^3"
"Between 76 - 140 m^3"
"Between 141 - 160 m^3"
"Between 161 - 175 m^3"
"Between 176 - 200 m^3"
"Greater than 200 m^3"

A summary of how each vehicle performed for the volume attribute is shown in figure 6-7.

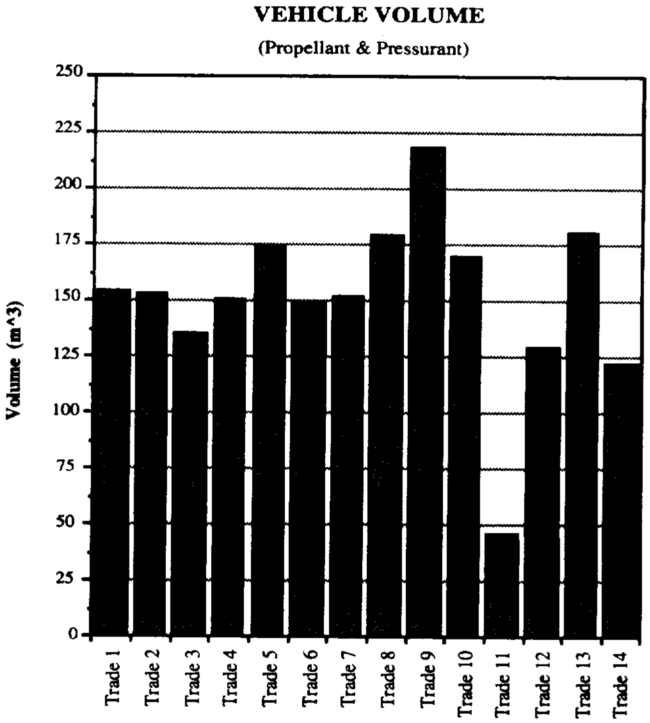


Figure 6-7. Volume summary.

Center of Gravity at touchdown is the last vehicle metric. This measurement reflects the relative stability of the lander vehicle. The attribute ratings for this metric are

"Less than 5 m"
"5 to 6.5 m"
"6.5 to 8 m"
"Greater than 8 m"

6.1.2.6 Hardware Readiness

HR is a measure of the TRL and the expected technology readiness difficulty (TRD). The NASA TRL scale (fig. 6-8) is used to provide consistency in the classification of technical status and is applied to the engines, thermal management, pressurization/feed/tank systems, and propellant combination used in each trade option. The TRD is an estimate of the relative difficulty expected to raise the TRL level to a 9. The HR is calculated by multiplying the TRL times the TRD.

$$HR = (TRL) \times (TRD)$$

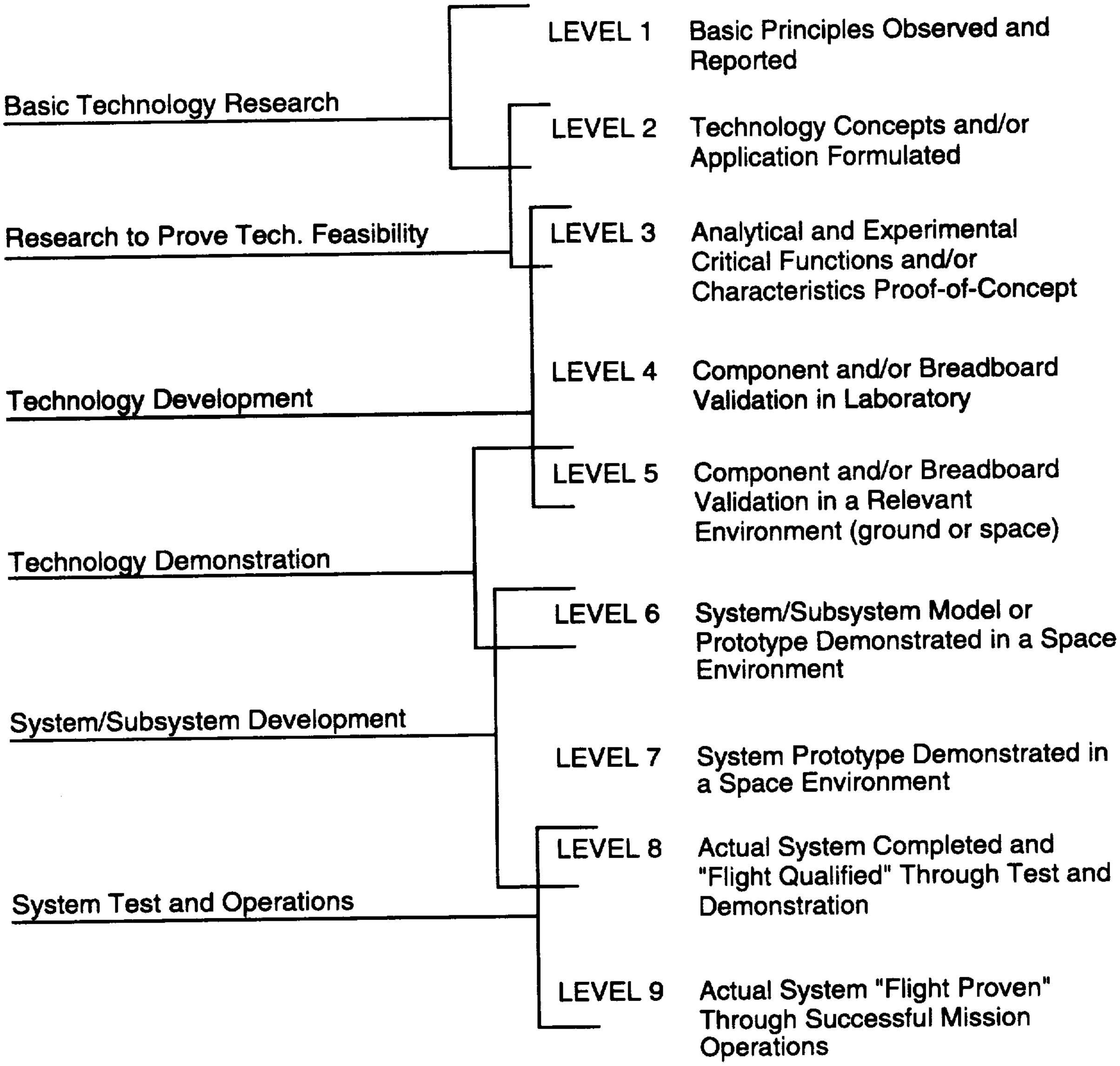


Figure 6-8. NASA technology readiness levels.

Technology Readiness Difficulty is estimated differently for engines, tank/pressurization/feed systems, thermal, and propellants. The following TRD values were used in the trade study to determine hardware readiness level.

Engine

TRD	
1.0	Minimal Mods, Pressure-Fed, Standard Propellants
0.90	Minimal Mods, Pressure-Fed, Low-Experience Propellants
0.90	Moderate Mods, Pressure-Fed, Standard Propellants
0.80	Significant Mods, Pressure-Fed, Standard Propellants
0.75	Significant Mods, Pressure-Fed, Low-Experience Propellants
0.65	Significant Mods, Pressure-Fed, Exotic Propellants
1.0	Minimal Mods to Pump-Fed, Standard Propellants
0.80	Moderate Mods to Pump-Fed, Standard Propellants
0.70	Significant Mods, Pump-Fed, Standard Propellants
0.60	Significant Mods to Pump-Fed, Low-Experience Propellants

Feed/Pressurization/Tank Systems

TRD	
1.0	Exposure to Standard Propellant/Pressurant Combinations
0.9	Exposure to Low Experience Propellant Combinations
0.65	Exposure to Exotic Propellant Combinations

Thermal Systems

TRD	
1.0	MLI or other Insulating Systems
1.0	Heaters
0.8	Vapor-Cooled Shields
0.6	Refrigeration

Propellant

TRD	
1.0	Recent Propellant Manufacturing Experience
0.7	Exotic Propellant, Limited EPA Data for Large Quantities

The HR is calculated by multiplying the TRL times the TRD for each of the following vehicle systems: (1 and 2) Return and Lander Engines, (3 and 4) Return and Lander Feed/Pressurization/Tank Systems, (5 and 6) Return & Lander Propellants, and (7) Return Thermal Systems. (Note that there are no discriminators between the vehicles for Lander Thermal Systems). Each of the seven different systems listed are scored for the attribute HR, and these scores will place the system into one of the following attribute ratings:

"Hardware Readiness = 7-9"
"Hardware Readiness = 6-6.9"
"Hardware Readiness = 4-5.9"
"Hardware Readiness = Less than 4"

A "7-9" rating implies the hardware is ready for phase C/D. A "6-6.9" rating implies that predictable development is required to support phase C/D. A "4-5.9" rating implies that some risk is associated with development to phase C/D. And, a "less than 4" rating implies that significant risk is associated with advanced development, and concerns exist that could preclude the use of the hardware.

A summary table showing the TRL, TRD and HR ratings for each of the trades is provided in table 6-III.

6.1.2.7 Evolution

The *evolution* subcriteria provide positive consideration in the trade study for propulsion systems that have the potential for alternate mission scenarios. The *evolution* subcriteria are categorized using different *evolution* scenarios, and the trade vehicles are evaluated for the degree to which they are able to meet these evolutionary scenarios. The evolutionary scenarios considered in the trade study are (1) Longer Lunar Stay Time, (2) Larger Payloads, (3) Extra Volume for Increased Logistics, (4) In Situ Resource Utilization, (5)Propellant Boiloff Utilization, and (6) Mars Commonality. It should be emphasized that the evolution requirements need more definition, and this affects the ability of this subcriteria to strongly distinguish the evolution potential of the different trade vehicle options.

<u>Longer Lunar Stay Time</u> is measured by placing the return propulsion system for different vehicle trade options into the different lunar stay categories defined below:

Category 1: The propulsion system has an unlimited lunar stay time. The propellants are completely "lunar storable," with no power requirements to maintain temperatures above freezing or below boiling. The propulsion system is mechanically inactive during the lunar stay. Note that none of the trade alternatives fits into this category.

Category 2: The propulsion system essentially has an unlimited lunar stay time, affected linearly only by increasing total energy requirements with increasing lunar stay time. It has low lunar night power requirements and no lunar day power needs. The propulsion system is mechanically inactive during the lunar stay.

Category 3: One propellant is storable as described in attribute ranking 2, above. The other propellant (LO_2 in this trade study) has no heating requirements but must have an increase in MLI or incorporation of vapor-cooled shields for a 6-month stay. For a 1-year stay, a refrigeration or reliquifaction system is recommended, but this would be traded with the weight, complexity, and HR of these systems compared to designing for the expected boiloff. Active venting is required.

Category 4: Both propellants (LO_2 and CH_4 in this trade study) have no heating requirements but require an increase in MLI or incorporation of vapor-cooled shields for a 6-month stay. For a 1-year stay, two separate refrigeration or reliquifaction systems are recommended, but this would be traded with the weight, complexity, and HR of these systems compared to designing for the expected boiloff. Active venting and periodic propellant management are required.

Table 6-III. Hardware Readiness Summary

		Trade 1	Trade 2	Trade 3	Trade 4	Trade 5	Trade 6	Trade 7	Trade 8	Trade 9*	Trade 10*	Trade 11	Trade 12	Trade 13	Trade 14*
Return Stage		Baseline	N_2H_4/ LO_2	N_2H_4/ CPF	M20/ NTO	CH_4/ LO_2	MMH/ NTO	CH_4/ LO_2	LH_2/ LO_2	single	1 and 1/2	N_2H_4/ CPF	LH_2/ LO_2	LH_2/ LO_2	1 and 1/2
Return Stage Pressurization		pressure	pressure	pressure	Press. Opt.	pressure	pump	pump	pump	stage	stage	pressure	IME used on	pressure	IME Stage
Lander Stage		Vehicle	LH_2/ LO_2	LH_2/ LO_2	LH_2/ LO_2	LH_2/ LO_2	LH_2/ LO_2	LH2/ LO_2	LH_2/ LO_2	LH_2/ LO_2	LH_2/ LO_2	both stages	both stages	IME: LH/LOX	LH_2/ LO_2
RETURN ENGINE	TRL	9	5	5	5	5	5	6	7	6	6	5	3	5	3
	Difficulty	1	0.75	0.65	0.8	0.75	0.7	0.6	1	0.8	0.8	0.65	0.7	0.8	0.7
	HR	9	3.75	3.25	4	3.75	3.5	3.6	7	4.8	4.8	3.25	2.1	4	2.1
RETURN TANK/PRESS /FEED	TRL	7	7	5	7	7	7	7	7	7	7	5	3	7	3
	Difficulty	1	1	0.65	1	0.8	1	0.8	1	1	1	0.65	1	1	1
	HR	7	7	3.25	7	5.6	7	5.6	7	7	7	3.25	3	7	3
RETURN THERMAL MANAGEMENT	TRL	7	7	5	7	7	7	6	6	6	6	5	6	6	6
	Difficulty	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	HR	7	7	5	7	7	7	6	6	6	6	5	6	6	6
RETURN PROPELLANT	TRL	9	9	5	9	7	9	7	9	9	9	5	9	9	9
	Difficulty	1	1	0.7	1	1	1	1	1	1	1	0.7	1	1	1
	HR	9	9	3.5	9	7	9	7	9	9	9	3.5	9	9	9
LANDER * ENGINES	TRL	7	7	7	7	7	7	7	7	9	9	5	3	3	9
	Difficulty	1	1	1	1	1	1	1	1	1	1	0.65	0.7	0.7	1
	HR	7	7	7	7	7	7	7	7	9	9	3.25	2.1	2.1	9
LANDER TANK/PRESS /FEED	TRL	7	7	7	7	7	7	7	7	9	7	5	3	3	6
	Difficulty	1	1	1	1	1	1	1	1	1	1	0.65	1	1	1
	HR	7	7	7	7	7	7	7	7	9	7	3.25	3	3	6

* The single-stage and stage-1/2 vehicles are credited with an engine TRL=9, reflecting the fact that there are no separate engines for landing.

Category 5: LO_2/LH_2 cryogenic systems do not require heaters but must have active venting and propellant management during the lunar stay. For a 6-month lunar stay, integrated vapor-cooled shields are required, reducing the LO_2 boiloff by 95% and reducing the LH_2 boiloff by 50% compared to only 2-in. of MLI. For a 1-year lunar stay, two separate refrigeration or reliquifaction systems are required with integrated vapor-cooled shields.

Larger Payload is measured as the post-TLI mass cap (96 mt) minus the habitat TLI vehicle mass plus the post-TLI mass cap minus the Crew Mission TLI Vehicle Mass. The purpose of this attribute is to measure the extra payload benefits for vehicle options should the HLLV be designed for a 96 mt post-TLI requirement. The attribute ranges are

"Less than 0.5 mt"
"Between 0.5 - 1.0 mt"
"Between 1.0 - 1.5 mt"
"Between 1.5 - 2.5 mt"
"Greater than 2.5 mt"

Extra Volume for Increased Logistics is measured by comparing the propellant tank and staging volumes with the shroud limitations of the HLLV. This measurement is strictly a volume comparison and does not consider cg limitations or effects on vehicle design. Three attribute ratings were defined as

"Less than 20 m^3 available"
"Between 20 - 35 m^3 available"
"Greater than 35 m^3 available"

In Situ Resource Utilization compares the different trade options for compatibility with possible in situ resource utilization (ISRU), or lunar mining. Because of the abort-to-orbit during descent requirement, various other abort and operational issues, and the 1999 launch requirements, ISRU was not allowed to affect the vehicle design. This measurement considers only the potential of ISRU. The two attribute rating possibilities so far are

"Yes, in situ resource utilization is possible with this propellant (YES)."
"No, in situ resource utilization is NOT possible with this propellant (NO)."

Propellant Boiloff Utilization compares the vehicle availability of propellant residuals and boiloff for use in functions other than propulsion. Possible boiloff uses considered in this attribute are RCS propellant, power system reactants, ECLSS, and ISRU support. The two attribute rating possibilities so far are

"Yes, propellant boiloff utilization is possible with this propellant (YES)."
"No, propellant boiloff utilization is NOT possible with this propellant (NO)."

Mars Commonality is the last *evolution* subcriteria, and it considers the level of applicability the lunar vehicle has toward a Mars mission. Mars vehicle applicability is based on possible ISRU benefits and aeroshell packaging. Both methane and oxygen can be produced on Mars. The roughly defined attribute ratings are

> "Improves a Mars mission scenario (PROMOTES)."
>
> "Applies to a Mars mission scenario (SOME)"
>
> "Little Commonality with Mars mission scenario (NONE)."

A vehicle that utilizes both LO_2 and CH_4 or provides large benefits to aeroshell packaging is considered to "PROMOTE" Mars commonality. A vehicle that utilizes LO_2 and not CH_4 is considered to provide "SOME" Mars commonality.

A summary table showing the *evolution* attribute ratings for each of the trades is provided in table 6-IV.

Table 6-IV. Evolution Summary

	Trade 1	Trade 2	Trade 3	Trade 4	Trade 5	Trade 6	Trade 7
Ascent Prop/Stage Configuration	MMH/N_2O_4	LO_2/N_2H_4	ClF_5/N_2H_4	$M20/N_2O_4$	LO_2/CH_4	MMH/N_2O_4	LO_2/CH4
Ascent Feed System	Pressure	Pressure	Pressure	high Press.	Pressure	Pump	Pump
Descent Prop	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2
EVOLUTION							
Longer stay time	2	3	2	2	2	2	4
Larger payloads	<0.5	<.5	>2.5	0.5-1.0	<0.5	0.5-1.0	1.5 - 2.5
Logistics volume	<20	20-35	20-35	20-35	20-35	20-35	20-35
In situ resource utilization	no	yes	no	no	yes	no	yes
Boiloff utilization	no	yes	no	no	yes	no	yes
MARS commonality	none	none	promotes	none	promotes	none	promotes

	Trade 8	Trade 9	Trade 10	Trade 11	Trade 12	Trade 13	Trade 14
Ascent Prop/Stage Configuration	LO_2/LH_2	Single	Stage 1/2	ClF_5/N_2H_4	LO_2/LH_2	LO_2/LH_2	Stage 1/2
Ascent Feed System	Pump			Pressure	IME used	Pressure	IME stage
Descent Prop	LO_2/LH_2	LO_2/LH_2	LO_2/LH_2	ClF_5/N_2H_4	both stage	LO_2/LH_2	LO_2/LH_2
EVOLUTION							
Longer stay time	5	5	5	2	4	5	4
Larger payloads	1 - 1.5	<0.5	>2.5	1.5 - 2.5	>2.5	<0.5	>2.5
Logistics volume	20-35	<20	<20	>35	>35	<20	>35
In situ resource utilization	yes	yes	yes	no	yes	yes	yes
Boiloff utilization	yes	yes	yes	no	yes	yes	yes
MARS commonality	some	some	some	promotes	some	none	some

6.1.3 Summary of Design Criteria Evaluation Data

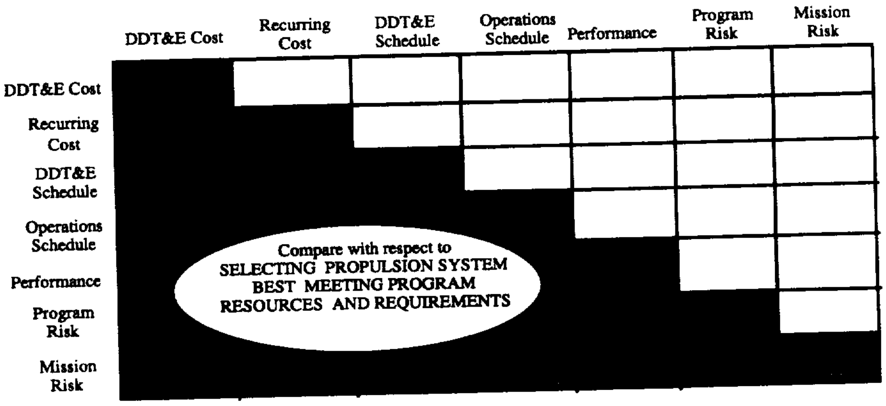
Each trade alternative is rated with the categories described in the previous section. These ratings are the result of the engineering design process. The manner in which these ratings are used to select the best trades is the trade study selection process. The trade study selection process is described in section 6.2.

6.2 Trade Study Selection Process

Using the AHP, criteria weights are derived from pairwise comparisons performed among criteria of the same hierarchical level. At the lowest reaches of the evaluation hierarchy, the vehicle trade options are assigned the appropriate attribute ratings. The attribute ratings received by each vehicle trade option are fed upward through the weighted levels of the hierarchy. This process produces a quantified conclusion, which rates the vehicle trade options. Calculating the conclusions will be presented in section 6.2.3 but only after first describing the pairwise comparison matrix in section 6.2.1 and the manner in which that matrix is used to calculate criteria weights in section 6.2.2. Finally, section 6.2.4 will describe the sensitivity analysis.

6.2.1 The Pairwise Comparison Matrix

The matrix in figure 6-9 is an example matrix used to pairwise compare the first level criteria with respect to the FLO Propulsion System Study goal. This matrix, as all others used for AHP, contains an equal number of rows and columns. Each row and each column contain all of the elements of one level. The elements of one level are compared, one pair at a time, with respect to their importance to the level above. Thus, each open box of the matrix is assigned a score for the relative importance of one element over another with respect to the hierarchy level above. The scores are chosen from the relative comparison scale shown to the right of the matrix in figure 6-9. The scores should reflect the comparison statement, "**ROW** element is <u>#</u> <u>from scale</u> more *important* than **COLUMN** element," or "**ROW** element is <u>#</u> <u>from scale</u> more *preferred* than **COLUMN** element." If the column element is actually more important than the row element, then the value used to describe the comparison should be entered as a negative number. For this trade study, a negative number is distinguished by parentheses.



Compare with respect to
SELECTING PROPULSION SYSTEM
BEST MEETING PROGRAM
RESOURCES AND REQUIREMENTS

ON A SCALE FROM
1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: ROW over COLUMN

Use parenthesis around the number if the importance is actually Column over Row.

Figure 6-9. Pairwise comparison matrix (example: first-level criteria).

6.2.2 Deriving Criteria Weights Using Pairwise Comparisons

The next step is a computation of the priority vector for the matrix to get the relative weights of each element. In mathematical terms,[1] the matrix is completed by making the diagonal of the matrix equal to 1, and since reverse comparisons take place below the diagonal, reciprocals are inserted below the diagonal to complete the square matrix. The eigenvector of the matrix is then calculated and normalized to provide the priority vector. The priority vector contains the weights of each element, and the sum of all the weights adds to 1. It should be noted that the eigenvalue for the matrix can also be used to calculate a consistency ratio, providing feedback to the user on the consistency of the comparisons made in the matrix.

Thus, pairwise comparisons are collected for every level in the hierarchy from which relative weights are derived. This means that the relative weights of the first level criteria with respect to the goal are calculated, as are the relative weights of the subcriteria with respect to each criterion, and on down the hierarchy. For each set of relative weights calculated with respect to the node above, the weights are proportioned using the priority vector to add up to the weight of the node above. Thus, the cumulative value of all the criteria with respect to the goal equals 1.0, and each set of subcriteria has a cumulative weight equal to the criterion directly above it. The sum of all the subcriteria in level two, totaled under every first-level criteria, totals 1.0 as well. Additionally, the subcriteria are evaluated using attributes (the attributes are pairwise compared for their importance to the subcriteria), and the different vehicle options are rated for each attribute in the hierarchy. The result is a weighted hierarchy where the lower level receives a weighted portion of the level just above it. Thus at the attribute level of the hierarchy, where the vehicle evaluations are performed, the sum of all the attribute weights equals 1.0.

6.2.3 Calculating the Trade Study Rankings

The trade study rankings are calculated by combining the weights derived through pairwise comparisons with the evaluations performed on each vehicle trade option. The evaluations performed on each vehicle trade option result in assigning an attribute rating to each vehicle option for each attribute in the study. The maximum attribute weight will be awarded to any option that scores the highest rating available. If an option scores a lower rating than the top rating available, it is assigned only a portion of the total attribute weight available. The portion of the attribute awarded to the vehicle is totaled for all attributes as they appear at the bottom of the hierarchy. Thus, for each attribute in the hierarchy, each vehicle trade option has the potential to score the entire weight of that attribute, and when this score is totaled across the attributes level, a maximum score of 1.0 is possible.

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[1] More information is available in the text by Thomas Saaty, Multicriteria Decision Making: The Analytic Hierarchy Process.

6.2.4 Sensitivity Analysis

The sensitivity of the trade conclusions to any criteria or subcriteria can be analyzed using the sensitivity analysis package available with the software used for this trade study.[2] Sensitivity analyses enable the evaluation of the trade study conclusion under different program level environments. Even though the attribute ratings are relatively inflexible for a particular vehicle and consist of hard numbers and engineering justifications, the program priorities are perhaps more flexible with a changing program environment. As the program environment changes, AHP pairwise comparisons may be reviewed to investigate the effect of the new environment on the trade study conclusions. Sensitivity analysis allows an investigation of "what ifs." It attempts to answer questions such as, "What if the program schedule became more important?" or "What if evolution toward a Mars scenario gains importance?" The sensitivity analysis can show whether the trade conclusion would change under the new program level environment.

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[2] The AHP used in this trade study is performed on software called *Expert Choice* available from Expert Choice, Inc. , 4922 Ellsworth Avenue, Pittsburgh, PA 15213, phone (412) 682-3844.

SECTION 7.0
TRADE STUDY RESULTS

The analytical trade study results were calculated using the selection criteria and evaluation methodology described in section 6.0. This section will present the higher level pairwise comparison matrices and their derived criteria weights. The lower level pairwise comparison matrices and the derived weights are available in appendix D. Following the pairwise comparison results are the analytical results of the trade study. These results consist of a list that ranks the alternative vehicles and the sensitivity analysis of that list.

7.1 Pairwise Comparison Matrices and Derived Criteria Weights

The trade study process, AHP, allows the program management for FLO to control the criteria pairwise comparisons for this trade study, while the vehicle evaluations and conceptual designs are made at the engineering level. The pairwise comparison team consisted of project level personnel from the New Initiatives Office supported by the ExPO, the Systems Engineering Division, and the Propulsion and Power Division at JSC. This team completed the top eight pairwise comparison matrices with consensus. The top eight matrices included the matrix for comparing the level-one criteria with respect to the goal and the seven matrices for comparing the level-two subcriteria with respect to the criteria in the level above. These matrices are presented below with the weights derived from them using AHP.

7.1.1 Level One Weighting

The level one comparison matrix compares the seven program level criteria with respect to the program goal of selecting the main propulsion systems. This matrix emphasizes the hard choices that a program must make regarding cost, schedule, performance, and risk. The matrix and the derived weights are presented in figure 7-1.

	DDT&E Cost	Recurring Cost	DDT&E Schedule	Operations Schedule	Performance	Program Risk	Mission Risk
DDT&E Cost		4	2	5	7	1	(3)
Recurring Cost			(4)	3	5	(5)	(7)
DDT&E Schedule				5	5	(2)	(5)
Operations Schedule					1	(5)	(7)
Performance						(7)	(7)
Program Risk							(2)
Mission Risk							

Compare with respect to
SELECTING PROPULSION SYSTEM
BEST MEETING PROGRAM
RESOURCES AND REQUIREMENTS

ON A SCALE FROM
1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use parenthesis around the number if the importance is actually column over row.

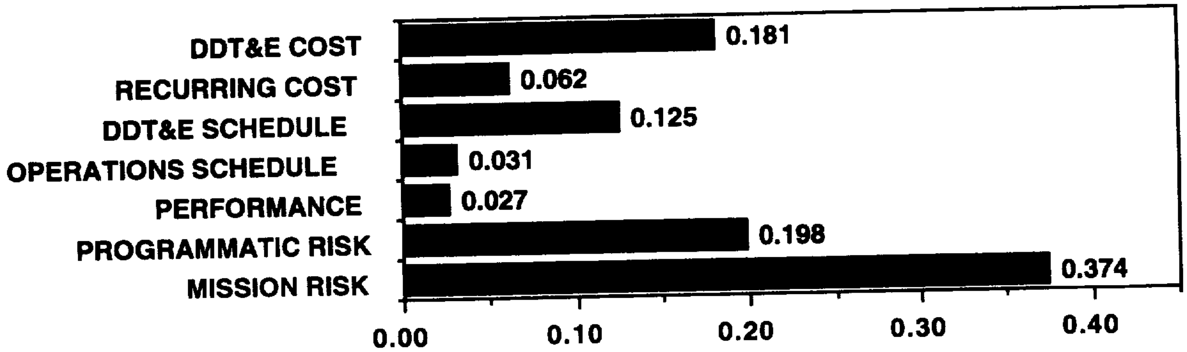


Figure 7-1. First level pairwise comparison matrix and derived weights.

The significant assumptions regarding this matrix and derived weights are listed below:

1. *DDT&E costs* and *schedules* are considered more important than *recurring costs* and *schedules.* This philosophy minimizes the scope of the program, making it more predictable, and keeps the cost of the first missions to a minimum. Past programs have not survived because of their wide scope, with the effect of creating large and unpredictable costs and schedules. Other programs have overemphasized the savings associated with designing for multiple missions. The current program environment suggests clear and achievable short-term goals, and this philosophy is represented in the current pairwise comparisons.

2. *Program risk* and *mission risk* are relatively important, and this is reflected as they appear in the pairwise comparisons. Again, this reflects the current environment where overruns and accidents are not acceptable.

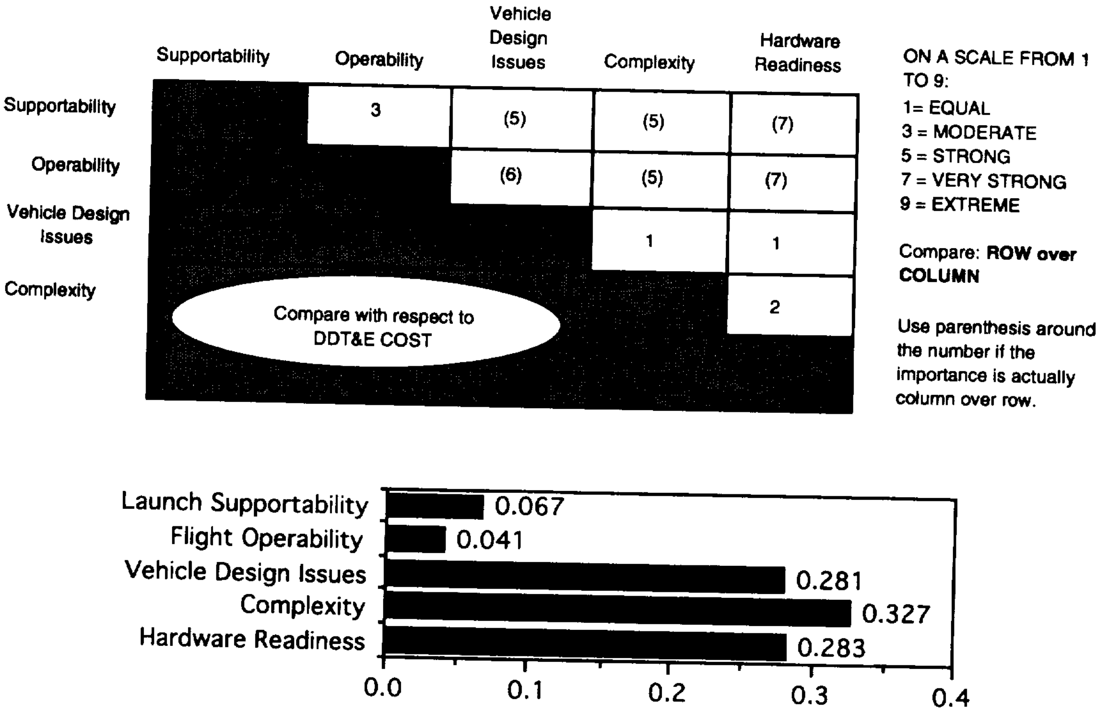
3. The *performance* rates relatively low when pairwise compared to the other criteria. This is because the definition for *performance* is a "measure of the effectiveness of a vehicle trade option in meeting or exceeding program requirements." Since all vehicles meet the minimum program requirements, additional *performance* is not required at the expense of any other program criteria.

7.1.2 Level Two Weighting

The level two comparison matrices compare the subcriteria under each of the seven program level criteria. These subcriteria comparisons are made with respect to the individual criterion in the level directly above. The matrices and derived weights are presented below, along with the basic assumptions and comments that explain each set of comparisons.

7.1.2.1 Subcriteria With Respect to DDT&E Cost

Figure 7-2 shows the pairwise comparisons and derived weights for subcriteria with respect to *DDT&E cost*. The discussion following the figure identifies the key assumptions behind the pairwise comparisons.



	Supportability	Operability	Vehicle Design Issues	Complexity	Hardware Readiness
Supportability		3	(5)	(5)	(7)
Operability			(6)	(5)	(7)
Vehicle Design Issues				1	1
Complexity					2

Compare with respect to DDT&E COST

ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use parenthesis around the number if the importance is actually column over row.

Figure 7-2. Pairwise comparison matrix with respect to *DDT&E cost* and derived criteria weights.

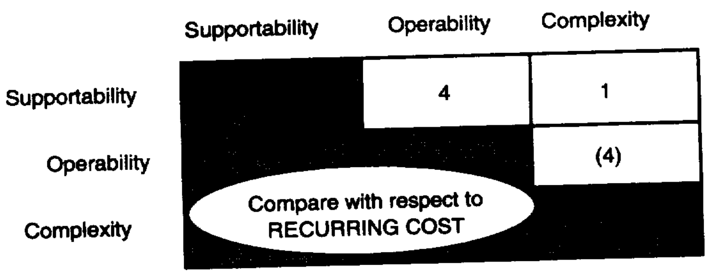
The significant assumptions regarding this matrix and derived weights are listed below:

1. The importance of *launch supportability* on DDT&E cost is minimized by the experience and hardware of previous programs. However, if an emphasis on *recurring cost* were to be established, then the importance of *launch supportability* on DDT&E cost would also be emphasized.

2. The importance of flight operability on DDT&E cost is driven by the avionics requirements associated with abort, lunar stay, and nominal flight. When more operations are required, more synchronization and software verification are also required, and this affects the *DDT&E cost*. However, the innovations associated with *flight operability* can be minimized to reduce *DDT&E cost* based on previous experience with nominal operations and some experience with the abort operations. For this reason, *flight operability* is also minimized in its importance to *DDT&E cost* when compared to *vehicle design issues, complexity* and HR.

7.1.2.2 Subcriteria With Respect to RECURRING COST

Figure 7-3 shows the pairwise comparisons and derived weights for subcriteria with respect to *recurring cost.* The discussion following the figure identifies some of the key assumptions behind the pairwise comparisons.



	Supportability	Operability	Complexity
Supportability		4	1
Operability			(4)
Complexity			

Compare with respect to RECURRING COST

ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use parenthesis around the number if the importance is actually column over row.

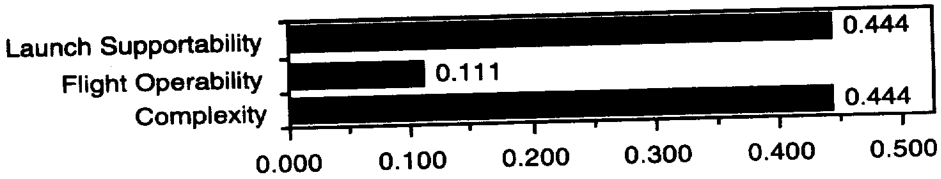


Figure 7-3. Comparison matrix with respect to *recurring cost* and derived criteria weights.

The significant assumptions regarding this matrix and derived weights are listed below:

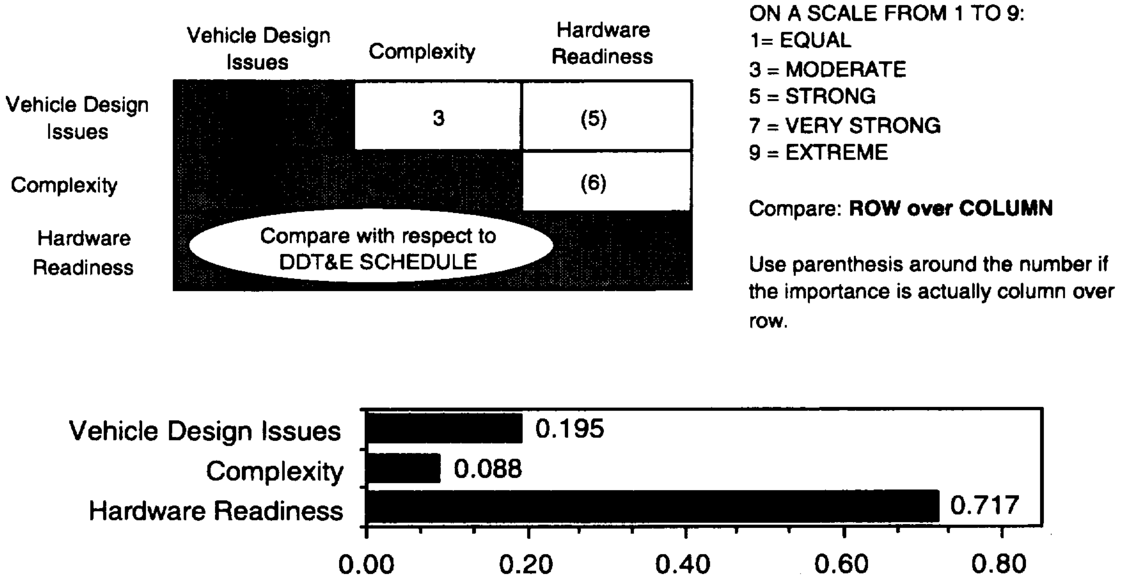
1. The *complexity* of a system affects the number of spares on hand, the amount of effort required to integrate all the parts, and the number of parts to purchase for each mission. For this reason *complexity* compares relatively high.

2. The *launch supportability* of a system also compares high, because ground operations to support a flight are a significant contributor toward the *recurring cost.*

3. *Launch supportability* and *complexity* compared equally with respect to *recurring cost,* because it is believed that a good program balance is achieved when vehicle hardware and the ground infrastructure contribute equally to *recurring cost.*

7.1.2.3 Subcriteria with Respect to DDT&E SCHEDULE

Figure 7-4 shows the pairwise comparisons and derived weights for subcriteria with respect to *DDT&E schedule.* The discussion following the figure identifies the key assumption behind the pairwise comparisons.



	Vehicle Design Issues	Complexity	Hardware Readiness
Vehicle Design Issues		3	(5)
Complexity			(6)
Hardware Readiness			

Compare with respect to DDT&E SCHEDULE

ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

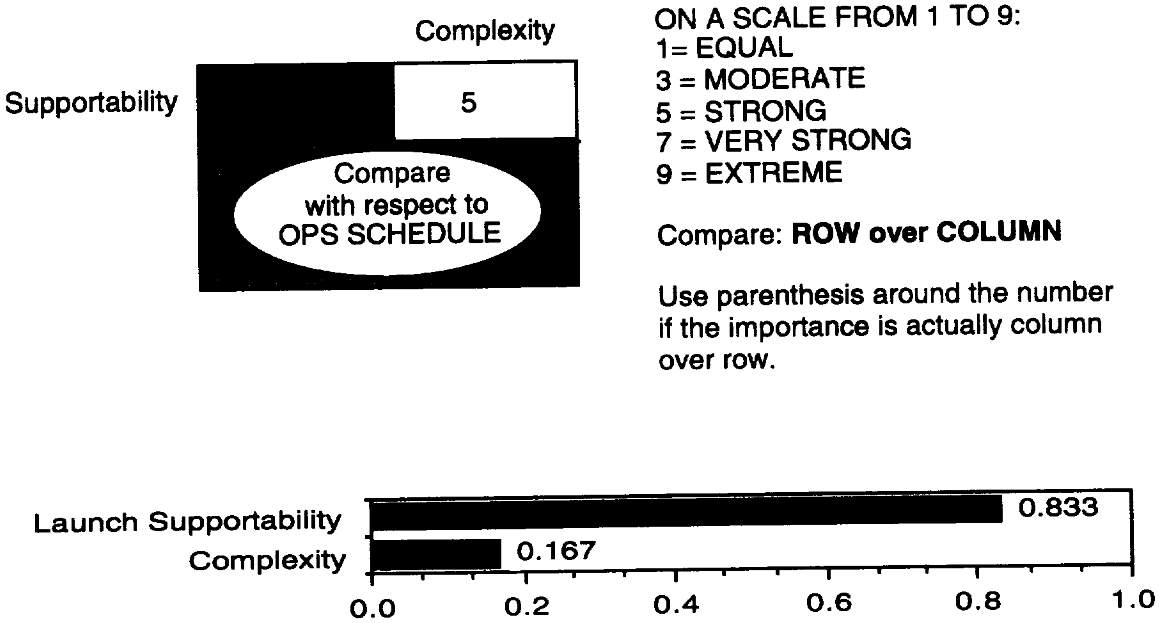
Use parenthesis around the number if the importance is actually column over row.

Figure 7-4. Pairwise comparison matrix with respect to *DDT&E schedule* and derived criteria weights.

The significant assumption regarding this matrix and derived weights is that the HR criteria is considered strongly more important than *complexity* or design issues, since it is believed to drive the *DDT&E schedule.* The other subcriteria, *vehicle design issues,* require effort but without the uncertainty associated with a low HR.

7.1.2.4 Subcriteria with Respect to OPERATIONS SCHEDULE

Figure 7-5 shows the pairwise comparisons and derived weights for subcriteria with respect to *operations schedule*. The discussion following the figure identifies the key assumption behind the pairwise comparisons.



ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

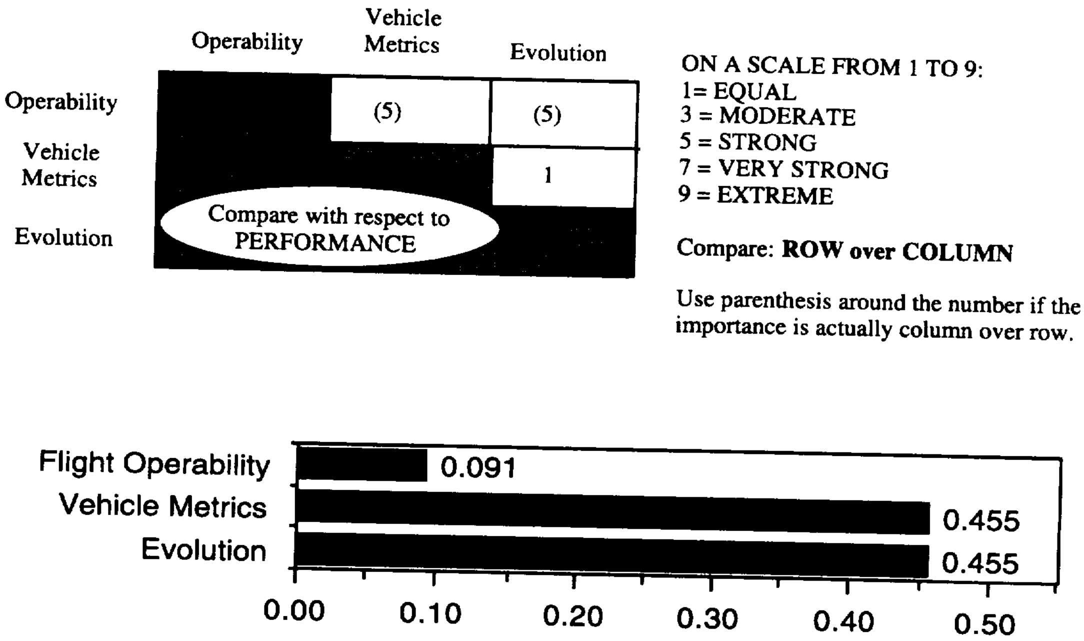
Use parenthesis around the number if the importance is actually column over row.

Figure 7-5. Pairwise comparison matrix with respect to *operations schedule* and derived criteria weights.

The significant assumptions regarding this matrix and derived weights is that the *operations schedule* criteria is a measure of how well a vehicle trade option meets production, assembly, qualification, and launch preparation time requirements for a set of flight hardware. Although *complexity* affects this criterion, *launch supportability* specifically addresses this issue and is considerably more important.

7.1.2.5 Subcriteria with Respect to PERFORMANCE

Figure 7-6 shows the pairwise comparisons and derived weights for subcriteria with respect to *performance* The discussion following the figure identifies some of the key assumptions behind the pairwise comparisons.



ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use parenthesis around the number if the importance is actually column over row.

Figure 7-6. Pairwise comparison matrix with respect to *performance* and derived criteria weights.

The significant assumptions regarding this matrix and derived weights are listed below:

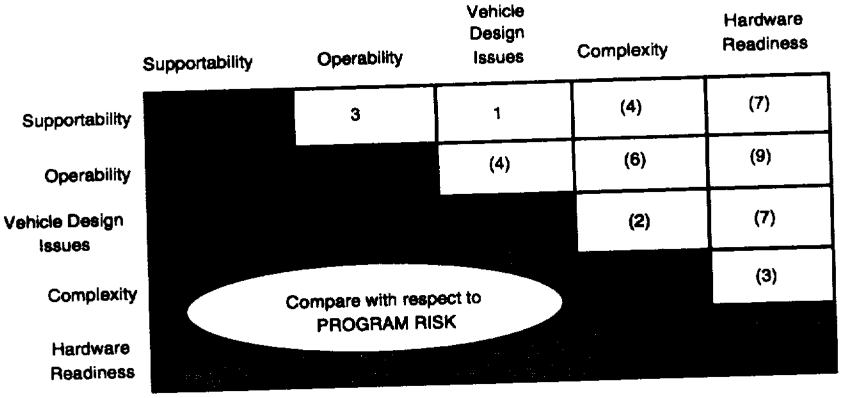
1. *Performance* is a measure of the effectiveness of a vehicle trade option in meeting program requirements. Since all vehicles meet the minimum requirements, this is a measure of how well the vehicle exceeds those requirements.

2. Improving the *vehicle metrics* provides additional program flexibility, and this asset is balanced by improving the vehicle *evolution* characteristics. Thus *evolution* rates equal to *vehicle metrics.*

3. If *evolution* were to become a clearly defined objective, with increased importance, then it could be weighted more heavily here. The FLO program is intended to have clearly defined and predictable objectives that exist within a limited budget. For *evolution* to be considered an important criterion, it should be equally limited and clear in scope.

7.1.2.6 Subcriteria with Respect to PROGRAMMATIC RISK

Figure 7-7 shows the pairwise comparisons and derived weights for subcriteria with respect to *programmatic risk*. The discussion following the figure identifies some of the key assumptions behind the pairwise comparisons.



	Supportability	Operability	Vehicle Design Issues	Complexity	Hardware Readiness
Supportability		3	1	(4)	(7)
Operability			(4)	(6)	(9)
Vehicle Design Issues				(2)	(7)
Complexity					(3)
Hardware Readiness					

Compare with respect to PROGRAM RISK

ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use parenthesis around the number if the importance is actually column over row.

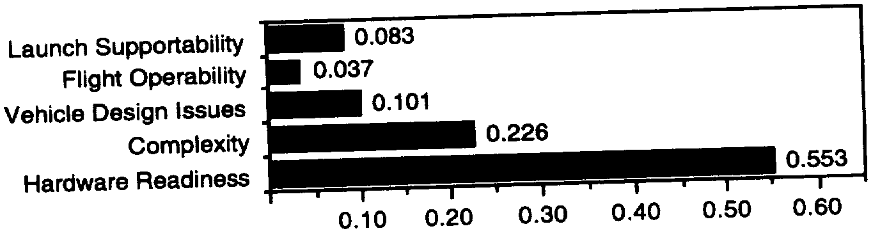


Figure 7-7. Pairwise comparison matrix with respect to *programmatic risk* and derived criteria weights.

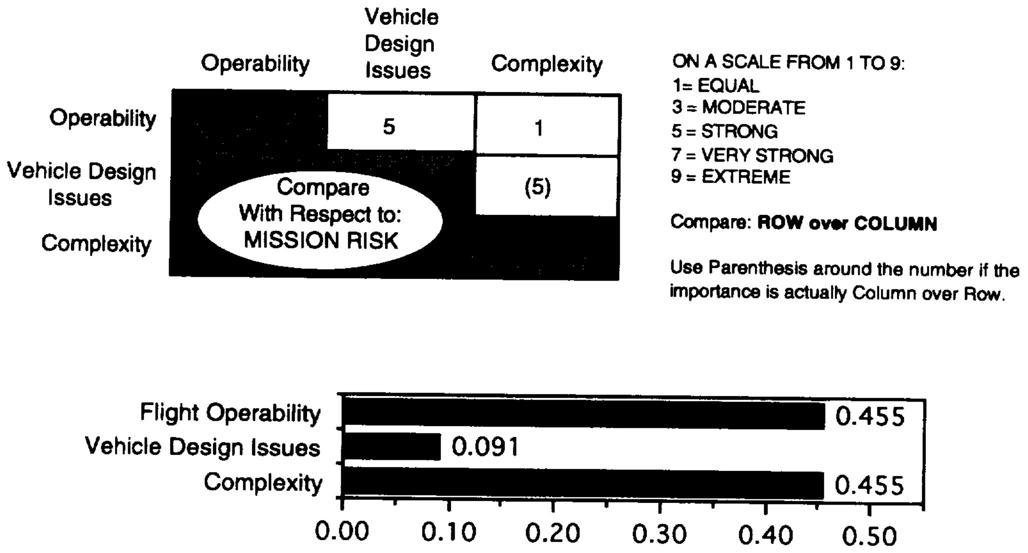
The significant assumptions regarding this matrix and derived weights are listed below:

1. Programmatic risk is most affected by the uncertainty associated with the HR. It is clearly evident from the pairwise comparisons that HR is rated considerably more important than the other criteria. *Complexity* is considered moderately important in the weighting, since it is believed that a complex vehicle can offer headaches and overruns, but that HR has the potential to offer showstoppers.

2. It was generally accepted during the weighting process that all *vehicle design issues* would have solutions to them. This is not to say that those solutions would be easy or agreeable to everyone. However, since HR poses potential showstoppers, it is believed to be comparatively more important to the *programmatic risk* than *vehicle design issues*.

7.1.2.7 Subcriteria with Respect to MISSION RISK

Figure 7-8 shows the pairwise comparisons and derived weights for subcriteria with respect to *mission risk* The discussion following the figure identifies some of the key assumptions behind the pairwise comparisons.



	Operability	Vehicle Design Issues	Complexity
Operability		5	1
Vehicle Design Issues			(5)
Complexity			

Compare With Respect to: MISSION RISK

ON A SCALE FROM 1 TO 9:
1= EQUAL
3 = MODERATE
5 = STRONG
7 = VERY STRONG
9 = EXTREME

Compare: **ROW over COLUMN**

Use Parenthesis around the number if the importance is actually Column over Row.

Figure 7-8. Pairwise comparison matrix with respect to *mission risk* and derived criteria weights.

The significant assumptions regarding this matrix and derived weights are listed below:

1. The more active the hardware is during the mission, the more opportunities exist for failure. If valves are frequently cycled, such as during multiple venting activities, the chances of failure increase. This relation is captured by the high importance attributed to *flight operability* with respect to *mission risk.*
2. Solutions to some *vehicle design issues* may offer more *mission risk* than others, and this is reflected in its relative importance to *mission risk.*
3. *Complexity* is conceptually related to reliability. *Complexity* measures the number and type of components and subsystems and instrumentation. For this reason, *complexity* is a significant contributor toward *mission risk.*

7.1.3 Cumulative Weights of Level-Two Subcriteria with Respect to Goal

The set of pairwise comparisons in section 7.1.2 produced derived criteria weights that agreed with engineering judgment. Another assessment of whether these pairwise comparisons make sense is presented below by calculating the cumulative effect of each subcriterion on the trade study conclusion. For example, the *vehicle design issues* category carries 28.1% of the *DDT&E cost* weight, 19.5% of the *DDT&E schedule* weight, 10.1% of the *programmatic risk* weight, and 9.1% of the *mission risk* weight. The cumulative weight of *vehicle design issues* can be calculated as follows:

Vehicle
Design Issues = 28.1% (*DDT&E cost* weight) + 19.5% (*DDT&E schedule* weight) + 10.1% (*programmatic risk* weight) + 9.1% (*mission risk* weight)

OR,

Vehicle
Design Issues = (0.281 x 0.181) + (0.195 x 0.125) + (0.101 x 0.198) + (0.091 x 0.374)
= 0.129

Similarly, the cumulative weights of the seven different subcriteria are calculated and shown in figure 7-9 below:

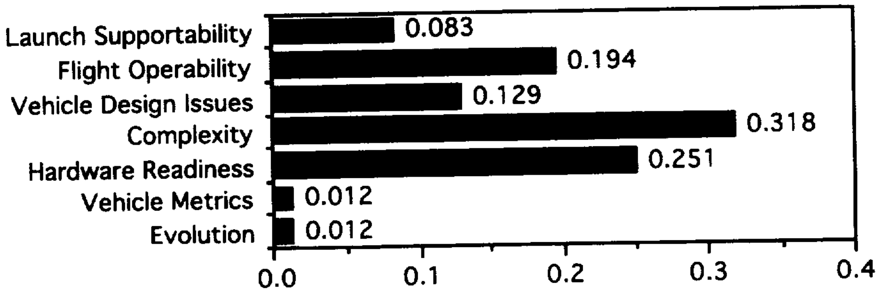


Figure 7-9. Second-level criteria cumulative weights with respect to selecting propulsion system.

The weights above should be questioned for agreement with engineering judgment. Figure 7-9 shows that *complexity* is the most important driver in the trade study for selecting the most design optimum propulsion system. Closely following *complexity* is the HR. The fact that these subcriteria are the drivers for selecting the propulsion system agrees with the engineering judgment that the least complicated vehicle using developed hardware or technology will be the safest, cheapest, most predictable vehicle.

7.2 Analytical Trade Study Results

Using the criteria weights described above and the design data summarized in table 7-I, the trade study results were generated using the AHP process described in section 6.2.3. These results are summarized next in section 7.2.1, and are followed with discussion and sensitivity analyses in section 7.2.2.

Table 7-I. Design Data Summary

		Trade 2	Trade 3	Trade 4	Trade 5	Trade 6	Trade 7	Trade 8	Trade 9	Trade 10	Trade 11	Trade 12	Trade 13	Trade 14
Ascent Prop / Stage Configuration	MMH/ N_2O_4	LO_2/ N_2O_4	ClF_5/ N_2O_4	MMH/ N_2O_4	LO_2/ CH_4	MMH/ N_2O_4	LO_2/ CH4	LO_2/ LH_2	Single	Stage 1/2	ClF_5/ N_2O_4	LO_2/ LH_2	LO_2/ LH_2	Stage 1/2
Ascent Feed System	Pressure	Pressure	Pressure	high Press.	Pressure	Pump	Pump	Pump			Pressure	IME used	Pressure	IME stage
Descent Prop	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	LO_2/ LH_2	ClF_5/N_2O_4	both stage	LO_2/ LH_2	LO_2/LH_2
GROUND SUPPORTABILITY														
Lander Operability Index	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.42	0.41	0.63	0.58	0.44	0.59
Return Operability Index	0.66	0.59	0.65	0.66	0.62	0.61	0.51	0.48	0.71	0.75	0.65	0.6	0.59	0.78
FLIGHT OPERABILITY														
No. of Abort Ops	4	5	4	4	5	8	8	12	8	7	4	7	6	8
No. of Flight Ops	64	69	64	64	71	85	85	90	89	90	26	87	58	86
No. of Lunar Surface Ops/Activity	2	21	2	2	26	2	25	25	25	28	2	25	25	27
VEHICLE DESIGN ISSUES														
Abort Response Time	<0.5 NP	<0.5 NP	<0.5 NP	<0.5 NP	<0.5 NP	1.5 NP	1-1.5 P	1-1.5 P	.5-1.5 NP	1-1.5 P	<0.5 NP	1-1.5 P	<.5 NP	1-1.5 NP
Debris Damage Immunity	protected	protected	protected	protected	protected	protected	protected	protected	exposed	prep exposed	protected	protected	protected	exposed
Stage Separation - Fire-in-hole	eng n hole	flat	flat	flat	flat	eng n hole	eng n hole	eng n hole	no sep	intercon n.	flat	flat	flat	intercon n.
Redund. (No. Faults: des,asc,abt)	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	0,1,0	0,1,0	1,1,1	1,1,1	1,1,1	0,1,0
Leakage Potential	low	moderate	low	low	moderate	low	moderate	high	high	high	low	high	high	high
COMPLEXITY														
Rating for Total No. of Components	516	470	460	460	480	693	701	752	432	440	227	387	466	276
Rating for No. Active Return Comp.	140	100	90	90	110	323	331	382	364	376	90	181	75	154
Rating for No. Unique Components	109	121	109	109	117	130	128	113	80	86	64	96	108	67
Number of Subsystems	11	12	11	11	12	12	13	15	7	7	8	12	11	6
Number of Instrument Locations	222	190	184	184	201	277	293	306	208	208	95	295	222	216
VEHICLE METRICS														
Post TLI Mass (mt)	96.5	95	87.2	94.2	100.1	92.5	92.4	93.5	101.4	87.4	91.2	70.9	95.3	67.9
Volume of Prop Tanks	154.5	152.3	135.4	149.8	173.4	148	152	179	218	169	45.4	128	180	121.9
Delta Habitat - Ascent Mass	-7.3	-5	1.2	-4.8	-9.6	-1.1	-0.9	-4.2	-13.9	2.4	2.5	5.5	-16.4	8.4
CG Height @ TD	7.7	7.3	7	7.4	7.4	7.3	7.3	8.5	6.1	5.9	4.8	7	8.4	5.9
HARDWARE READINESS														
Return Engine	9	3.75	3.25	4	3.75	3.5	3.6	7	4.8	4.8	3.25	2.1	4	2.1
Return Press/Tanks/Feed	7	7	3.25	7	6.3	7	6.3	7	7	7	3.25	3	7	3
Return Thermal Mgmt	7	7	5	7	7	7	6	6	6	6	5	6	6	6
Return Propellant	9	9	3.5	7	7	9	7	9	9	9	3.5	9	9	9
Lander Engines	7	7	7	7	7	7	7	7	9	9	3.25	2.1	7	9
Lander Press/Tank/Feed	7	7	7	7	7	7	7	7	9	7	3.25	3	7	6
EVOLUTION														
Longer stay time	2	3	2	2	4	2	4	5	5	5	2	5	5	5
Larger Payloads	<0.5	<.5	>2.5	0.5-1.0	<0.5	0.5-1.0	1.5 - 2.5	1 - 1.5	<0.5	>2.5	1.5 - 2.5	>2.5	<0.5	>2.5
Logistics Volume	<20	20-35	20-35	20-35	20-35	20-35	20-35	20-35	<20	<20	>35	>35	<20	>35
In situ Resource Utilization	no	yes	no	no	yes	no	yes	yes	yes	yes	no	yes	yes	yes
Boiloff Utilization	no	yes	no	no	yes	no	yes	yes	yes	yes	no	yes	yes	yes
MARS Commonality	none	some	promotes	none	promotes	none	promotes	some	some	some	promotes	some	none	some

7.2.1 Trade Alternative Rankings and Discussion

The design data from the detailed evaluations of each vehicle were entered into AHP using the criteria and weights derived with FLO program management. The design data is summarized in section 5.4 and the detailed data sheets are available in appendix A. The criteria pairwise comparisons and the derived criteria weights are disclosed in section 7.1 and appendix D. The result of combining the criteria weights with the design data is a list ranking the trade alternatives. The ranking is ordered with the system best meeting the program requirements and resources at the top of the ranking. The rankings of the trade study alternatives are summarized in figure 7-10 and table 7-II below.

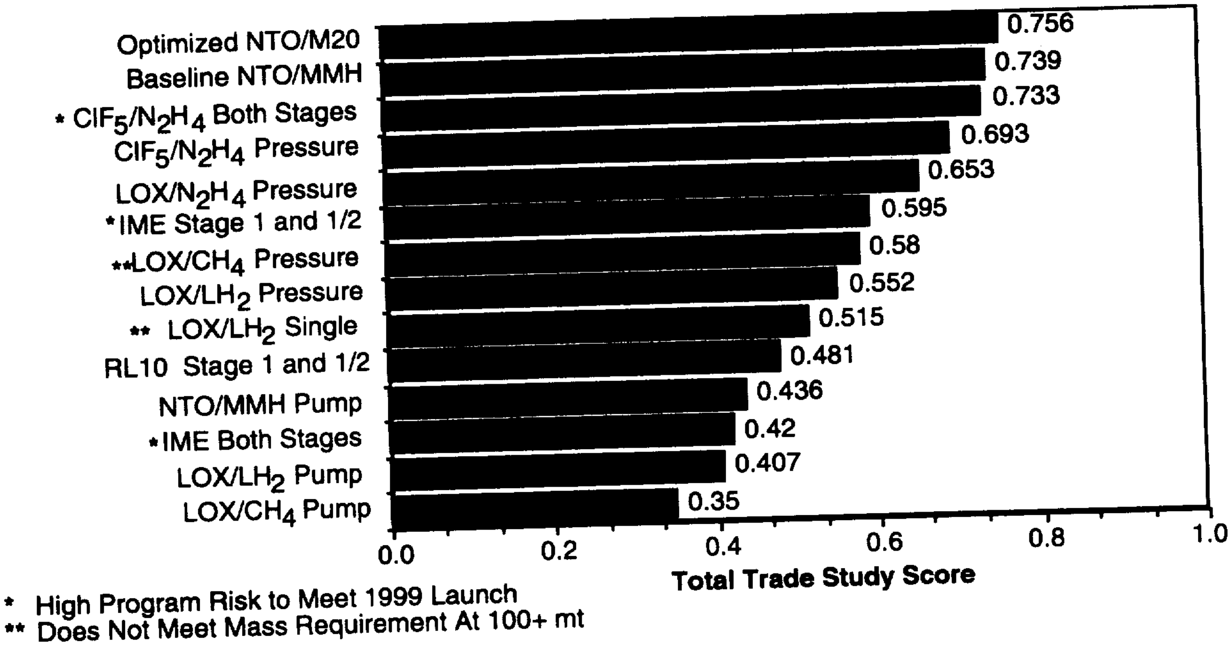


Figure 7-10. Trade study rankings (total possible score of 1.0).

The rankings in table 7-II and figure 7-10 show the optimized N_2O_4/M20 return stage with the baseline LO_2/LH_2 RL10 lander stage as the number one choice for the propulsion system in best meeting the FLO program resources and requirements. This number one ranking assumes that the optimized return stage can be developed by the 1999 launch date, which is considered to be feasible if advanced development is started immediately. If advanced development funding is not available, then the optimized engine might not make the 1999 launch requirement, and the baseline return stage would become the number one choice in meeting the FLO program resources and requirements.

Table 7-II. Trade Study Rankings: (Total Possible Score of 1.0)

Trade No.	Return Stage Description	Return Stage Pressurization	Lander Stage Description	TOTAL
4	Optimized N_2O_4/M20	Pressure	Baseline LO_2/LH_2	.756
1	Baseline N_2O_4/MMH	Pressure	Baseline LO_2/LH_2	.739
11	*ClF_5 on Both Stages	Pressure	ClF_5 Pressure	.733
3	ClF_5/N_2H_4	Pressure	Baseline LO_2/LH_2	.693
2	LO2/N_2H_4	Pressure	Baseline LO_2/LH_2	.653
14	*IME LO_2/LH_2 Stage 1-1/2	Pump	IME Stage 1-1/2	.595
5	**LO_2/CH_4	Pressure	Baseline LO_2/LH_2	.580
13	LO_2/LH_2	Pressure	Baseline LO_2/LH_2	.552
9	LO_2/LH_2 Single Stage	Pump	Single	.515
10	RL10 LO_2/LH_2 Stage 1-1/2	Pump	RL10 Stage 1-1/2	.481
6	N_2O_4/MMH Pump	Pump	Baseline LO_2/LH_2	.436
12	*IME LO_2/LH_2 Both Stages	Pump	IME LO_2/LH_2	.420
8	LO_2/LH_2 Pump	Pump	Baseline LO_2/LH_2	.407
7	LO_2/LH_2 Pump	Pump	Baseline LO_2/LH_2	.350

* High program risk to meet 1999 launch

** Does not meet TLI mass requirement

The ClF_5/N_2H_4 advanced engine designs occupy the number three and number four ranking positions in the trade study. The trade with ClF_5/N_2H_4 on both stages occupies the number three ranking. This high ranking shows the effect of having the low complexity, the low number of operations, and the rapid abort response time provided by a storable, hypergolic, pressure-fed propulsion system on both the lander and return stages of the vehicle. ClF_5/N_2H_4 on both stages is currently restricted from a higher ranking by the HR level. The HR level of ClF_5 is not only low, it would require dedicated and well-funded effort to bring the ClF_5/N_2H_4 propulsion system to maturity by the 1999 launch goal. For the propulsion system with ClF_5/N_2H_4 on both the lander and return stages, this effort would include development of two separate stages, with throttling on the lander stage, and the effort required would be an "Apollo type" effort. The effort for the ClF_5/N_2H_4 on the return stage with RL10s on the lander stage would be simpler without throttling, but funding should start immediately if the 1999 launch date is to be met.

The IME stage-and-a-half trade occupies the sixth ranking in the trade study, even though this trade also may have difficulty meeting the 1999 launch date. This trade ranks high by virtue of its low number of components on the stage-and-a-half design combined with the simplified design of the IME over other pump-fed engines. The IME design does not require redundant engines, because it operates with redundant pumps, turbines, and feed-system components upstream of the engines. The benefits of a low total complexity for the entire vehicle, however, are mitigated by a relatively high complexity for the return stage, compared to the higher ranking storable, pressure-fed stages. The HR is the issue, however, that presents the most difficulty for the IME. There are numerous technology issues, which could preclude the selection of the IME, that should be investigated before selection as a FLO or SEI propulsion system is made.

7.2.2 Trade Rankings Sensitivity Analysis

Sensitivity analysis is a study of the effects of changing criteria weights on the trade study conclusion. The results of this analysis tend to highlight rankings that are sensitive to small changes in weights and allow increased confidence in rankings that are insensitive to criteria weight changes. The method used to perform the sensitivity analysis is to (1) select a set of alternatives smaller than the entire set of trade alternatives, and (2) generate dynamic graphs showing the effect on the trade conclusion by changing criteria weights. This set of trades selected shall be a set of seven or fewer trades for reasons dictated by a software limitation and by the practical need to avoid confusingly large sets of data.

The sensitivity analysis for this study was investigated for changing program level criteria weights. For example, this sensitivity analysis answers the question, "What if the importance of *DDT&E cost* is increased or the importance of *DDT&E schedule* is decreased?" The selection of the trades used in the sensitivity analysis is described in sections 7.2.2.1; the results of that analysis are presented by describing the graphs in Section 7.2.2.2.

7.2.2.1 Selecting the Set of Trades for Sensitivity Analysis

The sensitivity analyses that are presented in this section were intended to address the host of questions regarding the weights of the program-level criteria (first level criteria) and how changes in those weights affect the trade conclusion. To simplify this analysis, the number of trades was reduced from 14 to 6. The particular trades that were eliminated for these sensitivity analyses are presented below:

1. LO_2/N_2H_4 and LO_2/CH_4 pressure-fed return stages (with baseline lander stage) were eliminated from the sensitivity analyses. The ClF_5/N_2H_4 pressure-fed vehicles cover many of the advantages that the two LO_2 vehicles offer. All engines have evolution potential for a Mars mission. There may be other sensitivity analyses that could be run to take a closer look at the pressure-fed return stages, but this analysis is intended to be more general in scope.

2. Pressure-fed LO_2/LH_2 was eliminated by reason of excessive volume.

3. Single-stage LO_2/LH_2 was eliminated because it exceeds the TLI mass limit.

4. Pump-fed N_2O_4/MMH, LO_2/LH_2, and LO_2/CH_4 two-stage vehicles were eliminated because they have numerous parts, numerous operations, low HR levels, and many design difficulties.

5. The IME vehicle on both stages was eliminated in favor of including the IME stage-and-one-half vehicle. The remaining IME Stage 1-1/2 is the most advanced concept in line with the IME philosophy.

7.2.2.2 Sensitivity Analysis of Selected Trades

The following sensitivity graphs focus on the six trades remaining after the down selection described above. They are (1) the baseline, (2) the optimized baseline, (3) the two-stage ClF_5 with ClF_5/N_2H_4 on both stages, (4) the two-stage ClF_5 with RL10 cryogenic engines on the lander stage, (5) the IME Stage 1-1/2, and (6) the RL10 Stage 1-1/2.

The graphical results should be interpreted with the following conventions:

- The graphs show relative rankings as a function of criteria weight. The relative rankings are presented as a normalized percent of the total possible score for each trade in the sensitivity analysis.
- The intersections of the vertical line with the lines representing each trade provide the corresponding rankings of the trades, as read from the top of the vertical line down.
- The position of the vertical line represents the derived criteria weight used to determine the trade rankings.
- Shifting the vertical dotted line to the right or left represents changing the derived weight of the criteria.

These results are presented below. The first graph, figure 7-11, shows the sensitivity of the ranking to changes in the weight of *DDT&E cost.* This graph shows that the trade study rankings are insensitive to changes in the weight of *DDT&E cost.* The reason for this insensitivity can be understood by recognizing that the important subcriteria under *DDT&E cost* are also the important subcriteria driving the overall trade study selection. To verify this reason, see figure 7-1 showing the subcriteria weights that affect *DDT&E cost,* and compare these weights to the cumulative weights of the subcriteria as they affect the trade study conclusions in figure 7.9. By comparing these two figures, it can be seen that *DDT&E cost* shares the same important subcriteria as the cumulative subcriteria list. For example, the most important subcriteria to the trade study conclusions and to *DDT&E cost* are *complexity* and *HR.*

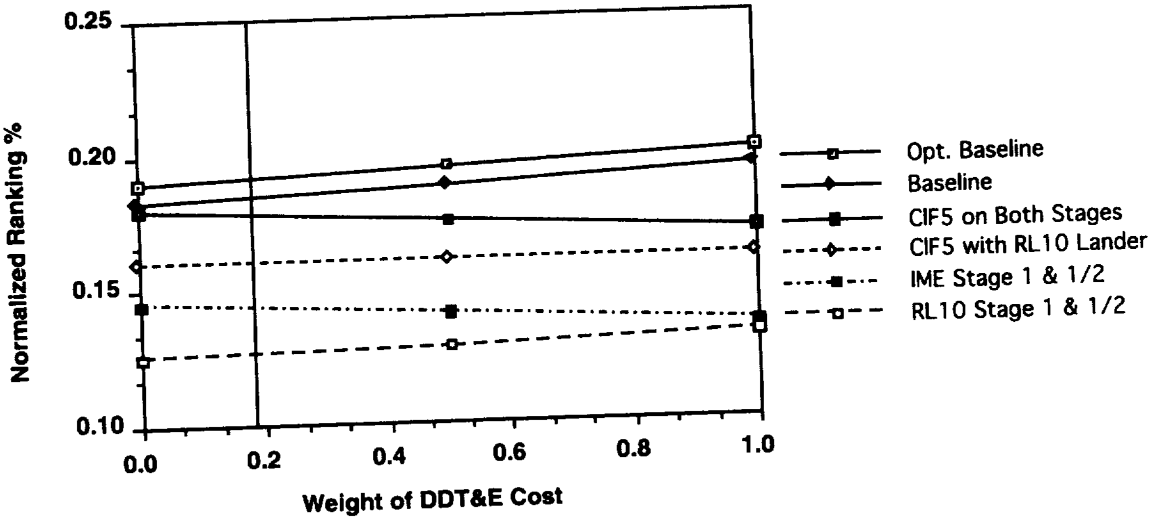


Figure 7-11. Sensitivity of rankings to *DDT&E cost.*

The next graph (fig. 7-12) shows the sensitivity of the trade study rankings to the criteria weight of *recurring cost*. This graph shows that the weight of *recurring cost* would have to be raised from 0.062 to approximately 0.20 before any change in the top ranking would occur. The change that would occur is that the optimized baseline trade would be replaced with the ClF_5/N_2H_4 vehicle having ClF_5 on both stages. This result occurs because the pressure-fed, storable ClF_5/N_2H_4 vehicle is dramatically less complex than any pump-fed cryogenic lander stage. This hardware simplicity, combined with the reduced operations and checkout required for servicing, produces the result that if *recurring cost* were to drive the trade study, ClF_5/N_2H_4 on both stages would be the preferred answer.

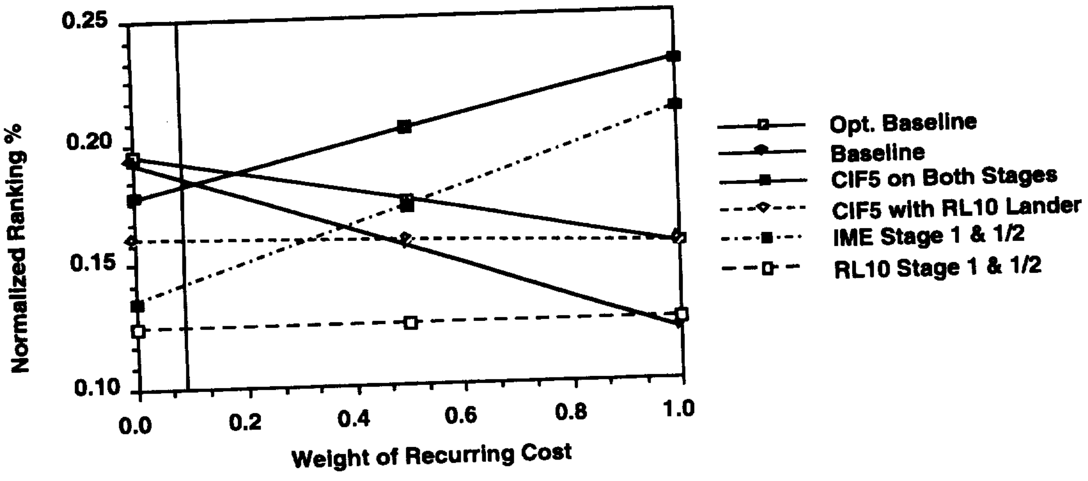


Figure 7-12. Sensitivity of rankings to *recurring cost.*

The next graph (fig. 7-13) shows the sensitivity of the trade study ranking to the criteria weight of *DDT&E schedule*. This graph shows that the weight of *DDT&E schedule* would have to be raised from 0.125 to approximately 0.25 before any change in the top ranking would occur. The result of increasing the weight of *DDT&E schedule* is to change the ranking in favor of the baseline. Note, however, that if the *DDT&E schedule* weight were reduced, the ClF$_5$ vehicle would again approach the top ranking.

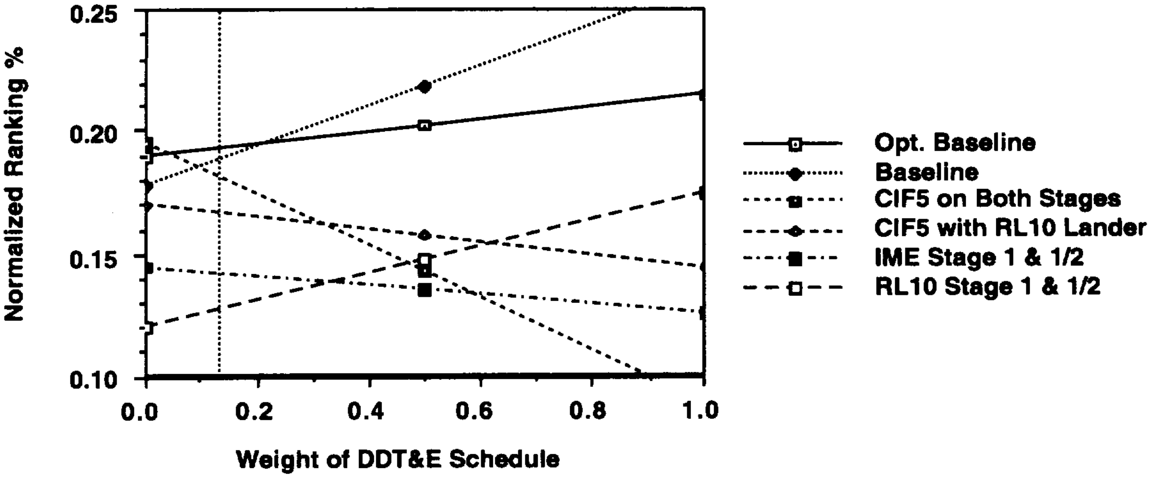


Figure 7-13. Sensitivity of rankings to *DDT&E schedule.*

The next graph (fig. 7-14) shows the sensitivity of the trade study ranking to the criteria weight of the *operational schedule*. This graph shows that the weight of *operational schedule* would have to be raised from 0.031 to approximately 0.15 before any change in the top ranking would occur. The change that occurs by emphasizing the schedule associated with recurring operations is to raise the ranking for ClF$_5$/N$_2$H$_4$ on both stages to the highest position. Note that the IME Stage 1-1/2 becomes the highest ranking when *operations schedule* is considered a major factor in selecting the FLO vehicle (weight > 70%). This is because the IME Stage 1-1/2 trade has a better launch operability index than the ClF$_5$/N$_2$H$_4$ engine, primarily because of the reduced number of stages.

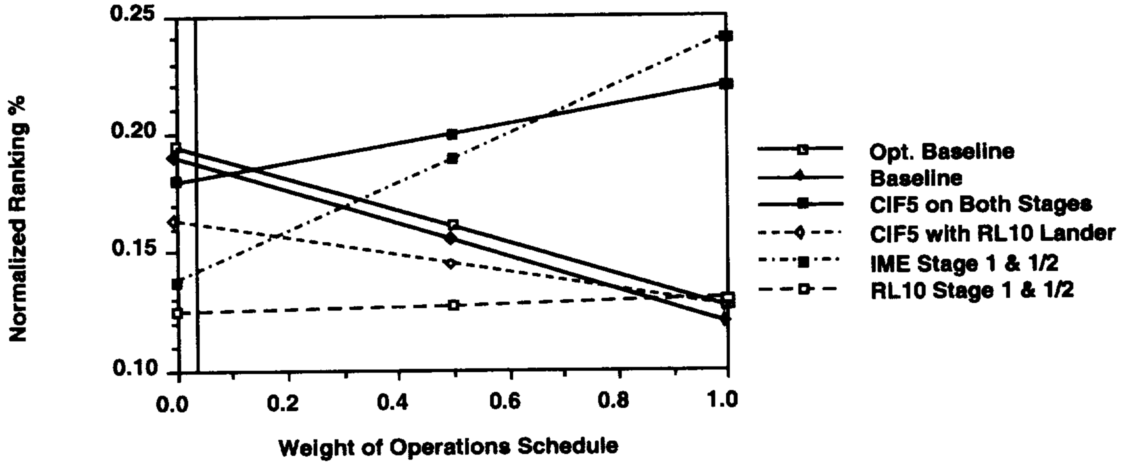


Figure 7-14. Sensitivity of rankings to operational schedule.

The next graph (fig. 7-15) shows the sensitivity of the trade study ranking to the criteria weight of *performance*. This graph shows that the weight of *performance* would have to be raised from 0.027 to approximately 0.19 before any change in the top ranking would occur. Recall that *performance* is defined as the ability to exceed vehicle requirements. *Performance* is measured by looking at the number of operations required to fly the vehicle, the post-TLI mass of the vehicle, and the evolution potential for the vehicle. If criteria weight for *performance* is increased, the lighter trades rank higher. Even though the IME Stage 1-1/2 vehicle is the lightest trade, the ClF_5/N_2H_4 trades also rank high when the weight for *performance* is increased. This is due to the absence of boiloff for longer stay times and the minimized operations with a pressure fed-storable propellant.

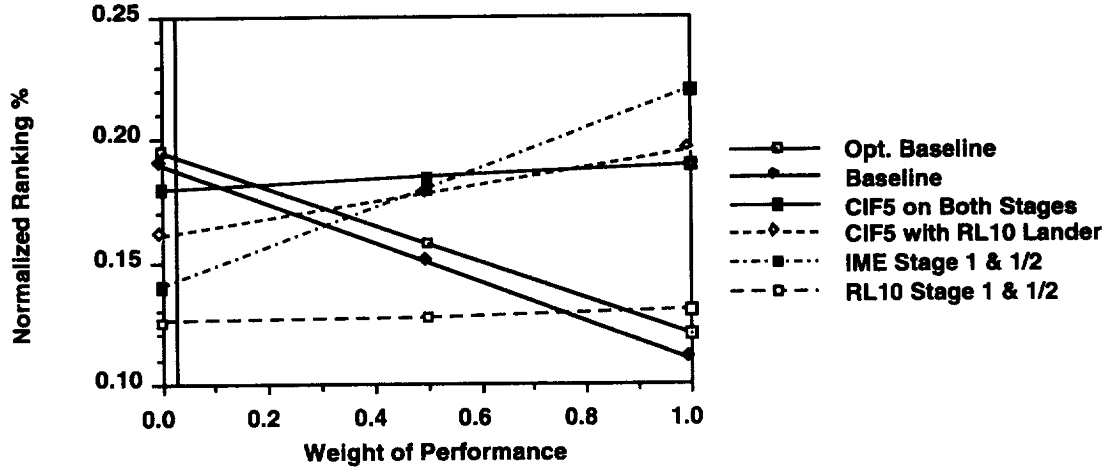


Figure 7-15. Sensitivity of rankings to *performance*.

The next graph (fig. 7-16) shows the sensitivity of the trade study ranking to the criteria weight of *program risk*. This graph shows that the weight of *program risk* would have to be raised from 0.198

C-2

to approximately 0.5 before any change in the top ranking would occur. This increase in criteria weight would put the baseline trade back in the top ranking, mostly because of its higher HR. Similarly, if the weight for *program risk* were reduced, the trade with ClF_5 on both stages would become the highest ranking.

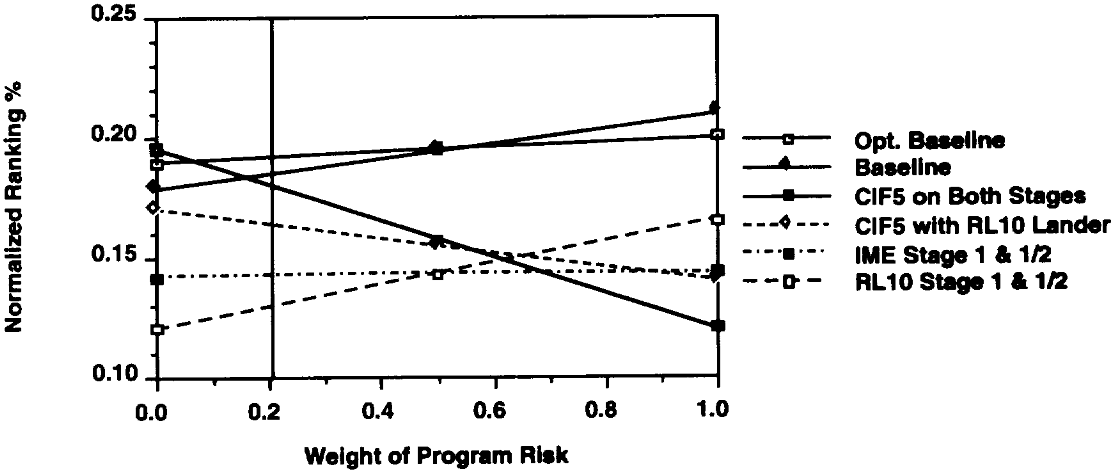


Figure 7-16. Sensitivity of rankings to *program risk.*

The next graph (fig. 7-17) shows the sensitivity of the trade study ranking to the criteria weight of *mission risk*. This graph shows that the weight of *mission risk* would have to be raised from 0.374 to approximately 0.55 before any change in the top ranking would occur. By increasing the weight for *mission risk,* the trade with ClF_5/N_2H_4 on both stages rises to the top of the rankings because it is the simplest and most inactive system. The cryogenic pump-fed trades fall with increased *mission risk* weights, reflecting the more complex hardware and the higher number of operations required for cryogenic fluid management.

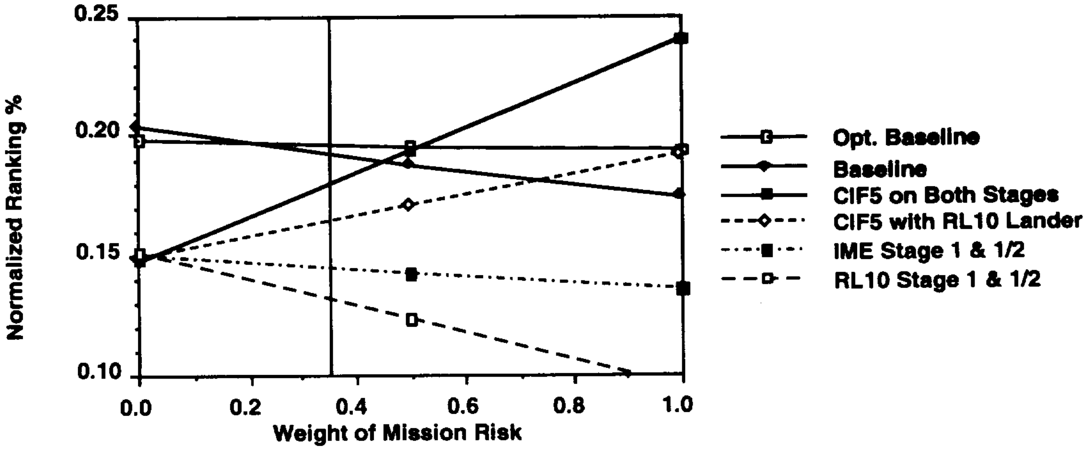


Figure 7-17. Sensitivity of rankings to *mission risk.*

7.2.2.3 Sensitivity Analysis Conclusions

The sensitivity analysis performed on the level-one criteria with respect to the trade study conclusions shows that the results are fairly insensitive to realistic changes in the weighting. All the weights except for *mission risk* need to be at least doubled before a change in the ranking occurs. *Mission risk* has to be raised above 50% from its already dominant 37.4% weight before a change in the conclusions occurs. The conclusions are similarly insensitive to reductions in criteria weights, and this provides confidence in the trade study conclusions.

SECTION 8.0
RECOMMENDATIONS

The results and insensitivities presented in section 7.0 suggest certain recommendations to conclude this trade study report. These recommendations are summarized in the sections below.

8.1 Best Option

The trade study showed that the baseline propulsion system or the optimized baseline propulsion system should be selected for a 1999 launch. The optimized baseline should be chosen to simplify the system if 1993 funds become available for advanced development of a new ascent engine. If startup funds for a 1999 launch are not available soon, then the recommendation is to stay with the baseline propulsion system to meet the 1999 launch goal.

8.2 Recommended Advanced Technology Development

In the event the 1999 launch goal slips, the recommendation is to pursue certain advanced development programs. The completion of an advanced development program for the ClF_5/N_2H_4 engines and the IME engines could significantly change the outcome of this trade study. If ClF_5/N_2H_4 were hardware ready in the required thrust class, it would be considered the best propulsion system for a lunar return vehicle. Similarly, if the IME were available, it could be considered for the lunar lander stage. There would also be a trade for the IME Stage 1-1/2 and the ClF_5/N_2H_4 on the lander stage.

The ClF_5/N_2H_4 option not only benefits FLO but also shows potential for a Mars return vehicle. The high density and small package reduces the size of a Mars aeroshell compared to any other propellant combination. The storability of ClF_5 and hydrazine on the Mars surface provides for a zero boiloff system that is mechanically inactive during the Mars stay. Additionally, ClF_5/N_2H_4 offers the performance necessary to allow the use of a pressure-fed return stage, which offers simplicity and high system confidence. The IME cryogenic pump-fed engines offer the best pump-fed simplicity and performance yet achieved. Its value should not be limited to FLO either and could be applied to space transfer systems and upper stages.

8.3 Trade Study Flexibility to FLO Program Changes

One significance of this trade study approach is the ability to adapt to changing vehicle requirements and changing program environments. For example, the trade rankings presented in this report are a function of the program management environment and reflect the atmosphere of reduced cost, predictable goals, and high mission safety with low risks. If the program environment changes, this will affect the criteria weights, and this in turn will change the trade rankings to conform to the new program environment. The process of revisiting the assumptions used to derive criteria weights and investigating the effect on the rankings is made relatively simple with AHP.

APPENDIX A

This appendix contains the detailed data sheets for each of the 14 trade study propulsion systems, presented in order from Trade #1 through Trade #14. The detailed data sheets summarize the evaluations for each of the trade study propulsion systems for each of the parameters that were measured.

TRADE #1
NTO/MMH PRESSURE FED RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A1.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index

#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLANTS (3)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) FLUIDS (2) ONLY, EXPENDABLE, NO LEAKAGE, LOADED LONG BEFORE COMMIT(10)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (7)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN LOI= .66

LANDER STAGE Launch Operability Index

#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITH OUTREMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI= .44

A1.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Hypergolic Engine Valves
1	Separate From Lander Stage Structure
4	TOTAL NUMBER OF ABORT OPERATIONS

APPENDIX A
Trade #1 NTO/MMH

 # OF FLIGHT OPERATIONS — *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)
- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

11 Mid-Course Correction
- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

9 LOI Burn
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System

- Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
- Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Lander Stage Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

6 Return Stage Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Hypergolic Engine Valves
- Separate From Lander Stage Structure
- Close Engine Valves
- Close Pressurization Iso valves

4 TEI Burn

- Activate Tank Pressurization Iso valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

4 1 Mid-Course Correction

- Activate Tank Pressurization valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

64 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
0	No Lunar Operations Until Liftoff
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
2	TOTAL NUMBER OF LUNAR OPERATIONS

A1.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	Not Clean, Some Obstruction Creates "Fire-in-the-Hole" Concerns. The 3 ascent engines protrude down into a hole in the Lander Stage.
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A1.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
8	1	2 Sets of Quad Check Valves
4	2	2 Sets of series redundant Pressure Regulators
2	2	Pressure Reg Iso Valves
5	2	Pyro Isolation Valves
1	3	Helium Tank
2	3	Fuel Tanks
2	3	Oxidizer Tanks
2	3	Heat Exchangers
24	2	Biprop Valves
2	2	Burst Disc/Relief Valves
5	2	Fill quick disconnects
6	3	EMA TVC actuators
3	3	Engines
66		Total Return Stage Component Count
		LANDER STAGE
2	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)

2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
6	3	LH2 Tanks with diffusers and start buckets
2	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
173		Lander Stage Component Count
239		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

516	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
140	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
109	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engines
4	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation/Autogenous PressSystem
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
11	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
5	Temperature Transducers
9	Pressure Transducers
48	Valve Position Indicators (2 per Prop Feed Valve only)
62	
	LANDER STAGE
	Pressurization/Feed/Vent Systems
11	Temperature Transducers
9	Pressure Transducers
24	Valve Position Indicators (2 per prop prevalve and f/d)
24	Liquid level sensors (3 per tank)
64	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
222	TOTAL INSTRUMENT LOCATIONS COUNT

A1.5 VEHICLE METRICS

96.5 mt	Post TLI Mass
154.5	Propellant Volume (m^3)
-7.3 mt	Δ Habitat - Return Stage Mass
7.7 m	CG Height at Touchdown

A1.6 HARDWARE READINESS (HR)

TRL	*X*	*DIFFICULTY*	*=*	*HR*	
					RETURN STAGE
9		1		9	Engines
7		1		7	Tanks/Press/Feed
7		1		7	Thermal Management
9		1		9	Propellant
					LANDER STAGE
7		1		7	Engines
7		1		7	Tanks/Press/Feed

A1.7 EVOLUTION

LONGER STAY TIME	Unlimited Except By Heater Power
LARGER PAYLOADS	None
INSITU RESOURCE UTILIZATION	None
PROPELLANT BOILOFF UTILIZATION	None
MARS COMMONALITY	minimal

TRADE #2
LOX / N2H4 PRESSURE FED RETURN
LOX / LH2 PUMP FED ENGINE LANDER

A2.1. GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLANTS (3)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) SINGLE GROUND PURGE (9)
#10) MAIN ENGINES GIMBALLED WITH EMA
#11) SINGLE FLUID LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT (4)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN STAGE LOI=.59

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATIC ACTUATORS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI=.44

A2.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Engine Valves
1	Fire Ignitors
1	Separate From Lander Stage Structure
5	TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)
- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

11 Mid-Course Correction
- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

9 LOI Burn
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System

  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Lander Stage Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

Lander Stage

2
- Vent LOX tank in transit

7 Return Stage Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Engine Valves
- Fire Ignitors
- Separate From Lander Stage Structure
- Close Engine Valves
- Close Pressurization valves

5 TEI Burn

- Open Pressurization valves
- Open Engine Valves
- Fire Ignitors
- Close Engine Valves
- Close pressurization valves

5 1 Mid-Course Correction

- Open Pressurization valves
- Open Engine Valves
- Fire Ignitors
- Close Engine Valves
- Close Pressurization valves

69 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
19	Vent LOX tank
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
21	TOTAL NUMBER OF LUNAR OPERATIONS

A2.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	FLAT, Clean, The single Return Stage engine does not protrude down into a hole in the Lander Stage.
LUNAR LEAKAGE	Moderate
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A2.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
8	1	2 Sets of Quad Check Valves
4	2	2 Sets of series redundant Pressure Regulators
2	2	Pressure Reg Iso Valves
5	2	Pyro Isolation Valves
1	3	Helium Tank
2	3	Fuel Tanks
2	3	Oxidizer Tanks
1	3	Heat Exchangers
2	2	T-0 Fill/drain valves
1	3	T-0 Disconnect
4	2	GOX vent valves
3	2	Fill quick disconnects
2	2	Burst Disc/Relief Valves
2	3	EMA TVC actuators
8	2	Biprop Engine Valves
2	2	Ignitors
1	3	Engine
50		Total Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves

APPENDIX A
TRADE #2 LOX/N2H4

4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
221		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

470 COMPLEXITY RATING FOR TOTAL # OF COMPONENTS
100 COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE
121 COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Lox Tank vent system
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engines
5	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
12	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
6	Temperature Transducers
7	Pressure Transducers
6	Liquid Level Sensors (3 per tank)
20	Valve Position Indicators
39	
	LANDER STAGE
15	Tank Liquid level sensors
8	Pressure Transducers
8	Temperature Transducers
24	Valve Position Indicators
55	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
190	TOTAL INSTRUMENT LOCATIONS COUNT

A2.5 VEHICLE METRICS

95.0 mt	Post TLI Mass
152.3	Propellant Volume (m^3)
-5 mt	Δ Habitat - Return Stage Mass
7.3 m	CG Height at Touchdown

A2.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
5	0.75	3.75	Engines
7	1	7	Tanks/Press/Feed
7	1	7	Thermal Management
9	1	9	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed

A2.7 EVOLUTION

LONGER STAY TIME	Req Heater Power, some O2 boiloff, category 3
LARGER PAYLOADS	Some capability, but less than 5.0 mt
LOGISTICS VOLUME	Between 20 - 35 m^3
INSITU RESOURCE UTILIZATION	Yes, O2 from lunar soil
PROPELLANT BOILOFF UTILIZATION	Yes, O2
MARS COMMONALITY	possible

TRADE #3
CIF5/N2H4 PRESSURE FED RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A3.1. GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLENTS (1)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) FLUIDS (2) ONLY, EXPENDABLE, NO LEAKAGE, LOADED LONG BEFORE COMMIT(10)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (7)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN STAGE LOI= .65

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITH OUTREMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI= .44

A3.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Hypergolic Engine Valves
1	Separate From Lander Stage Structure
4	TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)
- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

11 Mid-Course Correction
- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

9 LOI Burn
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System

    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

6 Ascent Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Hypergolic Engine Valves
- Separate From Lander Stage Structure
- Close Engine Valves
- Close Pressurization Iso valves

4 TEI Burn

- Activate Tank Pressurization Iso valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

4 1 Mid-Course Correction

- Activate Tank Pressurization valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

64 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
0	No Lunar Operations Until Liftoff
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
2	TOTAL NUMBER OF LUNAR OPERATIONS

A3.2 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	FLAT, Clean, The single Return Stage engine does not protrude down into a hole in the Lander Stage.
LUNAR LEAKAGE	Hermetically Sealed.
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A3.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
8	1	2 Sets of Quad Check Valves
4	2	2 Sets of series redundant Pressure Regulators
2	2	Pressure Reg Iso Valves
5	2	Pyro Isolation Valves
1	3	Helium Tank
2	3	Fuel Tanks
2	3	Oxidizer Tanks
2	3	Heat Exchangers
24	2	Biprop Valves
2	2	Burst Disc/Relief Valves
5	2	Fill quick disconnects
6	3	EMA TVC actuators
3	3	Engines
66		Total Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)

2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
237		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

460	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
90	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
109*	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engine
4	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
11	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
6	Temperature Transducers
7	Pressure Transducers
20	Valve Position Indicators
33	
	LANDER STAGE
15	Tank Liquid level sensors
8	Pressure Transducers
8	Temperature Transducers
24	Valve Position Indicators
55	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
184	TOTAL INSTRUMENT LOCATIONS COUNT

A3.5 VEHICLE METRICS

87.2 mt	Post TLI Mass
135.4	Propellant Volume (m^3)
1.2 MT	Δ Habitat - Return Stage Mass
7.0 m	CG at Touchdown

A3.6 HARDWARE READINESS (HR)

TRL	*X*	*DIFFICULTY*	*=*	*HR*	
					RETURN STAGE
5		0.65		3.25	Engines
5		0.65		3.25	Tanks/Press/Feed
5		1		5	Thermal Management
5		0.7		3.5	Propellant
					LANDER STAGE
7		1		7	Engines
7		1		7	Tank/Press/Feed

A3.7 EVOLUTION

LONGER STAY TIME	Unlimited Except By Heater Power, Category 2
LARGER PAYLOADS	Yes
LOGISTICS VOLUME	Between 20 - 35 mt
INSITU RESOURCE UTILIZATION	None
PROPELLANT BOILOFF UTILIZATION	None
MARS COMMONALITY	minimal

TRADE #4
NTO/M20 PRESSURE FED OPTIMIZED SINGLE ENGINE RETURN STAGE LOX / LH2 PUMP FED LANDER STAGE

A4.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLENTS (3)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) FLUIDS (2) ONLY, EXPENDABLE, NO LEAKAGE, LOADED LONG BEFORE COMMIT(10)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (10)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN STAGE LOI=.66

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI=.44

A4.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Hypergolic Engine Valves
1	Separate From Lander Stage Structure
4	TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS — *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)
- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

11 Mid-Course Correction
- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

9 LOI Burn
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System

- Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
- Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
    - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
    - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

6 Ascent Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Hypergolic Engine Valves
- Separate From Lander Stage Structure
- Close Engine Valves
- Close Pressurization Iso valves

4 TEI Burn

- Activate Tank Pressurization Iso valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

4 1 Mid-Course Correction

- Activate Tank Pressurization valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

64 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
0	No Lunar Operations Until Liftoff
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
2	TOTAL NUMBER OF LUNAR OPERATIONS

A4.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	FLAT, Clean, The single Return Stage engine does not protrude down into a hole in the Lander Stage.
DEBRIS DAMAGE IMMUNITY	Immune, since Lander Stage Protected & Unused
LUNAR LEAKAGE	Return Propellant is Hermetically Sealed During Lunar Stay

A4.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
8	1	2 Sets of Quad Check Valves
4	2	2 Sets of series redundant Pressure Regulators
2	2	Pressure Reg Iso Valves
5	2	Pyro Isolation Valves
1	3	Helium Tank
2	3	Fuel Tanks
2	3	Oxidizer Tanks
2	3	Heat Exchangers
8	2	Biprop Valves
2	2	Burst Disc/Relief Valves
5	2	Fill quick disconnects
2	3	EMA TVC actuators
1	3	Engines
44		Total Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)

APPENDIX A
TRADE #4 NTO/MMH HI-EFF

2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
215		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

460	COMPLEXITY RATING FOR TOTAL # OF COMPONENTS
90	COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE
109*	COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engine
4	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
11	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURNSTAGE
6	Temperature Transducers
7	Pressure Transducers
20	Valve Position Indicators
33	
	LANDER STAGE
15	Tank Liquid level sensors
8	Pressure Transducers
8	Temperature Transducers
24	Valve Position Indicators
55	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
184	TOTAL INSTRUMENT LOCATIONS COUNT

A4.5 VEHICLE METRICS

94.2 mt	Post TLI Mass
149.8 m3	Propellant Volume (m^3)
-4.8 mt	Δ Habitat - Return Stage Mass
7.4 m	CG at Touchdown

A4.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
5	0.8	4	Engines
7	1	7	Tanks/Press/Feed
7	1	7	Thermal Management
7	1	7	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed

A4.7 EVOLUTION

LONGER STAY TIME	Unlimited Except By Heater Power, Category 2
LARGER PAYLOADS	none
LOGISTICS VOLUME	Between 20 - 35 m^3
INSITU RESOURCE UTILIZATION	None
PROPELLANT BOILOFF UTILIZATION	None
MARS COMMONALITY	minimal

TRADE #5
LOX / CH4 PRESSURE FED RETURN
LOX / LH2 PUMP FED ENGINE LANDER

A5.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) SPACE STORABLE, NON-TOXIC PROPELLANTS (7)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) SINGLE GROUND PURGE (9)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) TWO FLUID CH4 AND LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT (4)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN STAGE LOI=.62

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLENT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) DISTRIBUTED HYDRAULIC ACTUATORS (3)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI=

A5.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Engine Valves
1	Fire Ignitors
1	Separate From Lander Stage Structure
5	TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)
- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

11 Mid-Course Correction
- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

9 LOI Burn
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System

    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

4 Descent Vent LOX tank in transit

7 Ascent Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Engine Valves
- Fire ignitors
- Separate From Lander Stage Structure
- Close Engine Valves
- Close Pressurization Iso valves

5 TEI Burn

- Activate Tank Pressurization Iso valves
- Open Engine Valves
- Fire Ignitors
- Close Engine Valves
- Close Tank Pressurization valves

5 1 Mid-Course Correction

- Activate Tank Pressurization valves
- Open Hypergolic Engine Valves
- Close Engine Valves
- Close Tank Pressurization valves

71 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
24	Vent LOX tank
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
26	TOTAL NUMBER OF LUNAR OPERATIONS

A5.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	Flat interface is possible
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused
LUNAR LEAKAGE	Moderate opportunity for leakage during Lunar stay due to active static seals with large molecule propellants.

A5.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
8	1	2 Sets of Quad Check Valves
4	2	2 Sets of series redundant Pressure Regulators
2	2	Pressure Reg Iso Valves
5	2	Pyro Isolation Valves
1	3	Helium Tank
2	3	Fuel Tanks
2	3	Oxidizer Tanks
4	2	T-0 Fill/drain valves
2	3	T-0 Disconnect
4	2	GOX vent valves
4	2	CH4 vent valves
1	2	Fill quick disconnects
2	2	Burst Disc/Relief Valves
2	3	EMA TVC actuators
8	2	Biprop Engine Valves
2	2	Ignitors
1	3	Engine
54		Total Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves

APPENDIX A
TRADE #5 LOX/CH4

4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
14	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
225		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

480 COMPLEXITY RATING FOR TOTAL # OF COMPONENTS
110 COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE
117* COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Lox Tank vent system
1	Tanks and Feed System
1	Thermal Control Vents
1	Main Engines
5	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
12	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	DESCRIPTION
	RETURN STAGE
7	Temperature Transducers
7	Pressure Transducers
12	Liquid Level Sensors (3 per tank)
24	Valve Position Indicators
50	
	LANDER STAGE
15	Tank Liquid level sensors
8	GHe Temperature Transducers
8	Pressure Transducers
24	Valve Position Indicators
55	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
201	TOTAL INSTRUMENT LOCATIONS COUNT

A5.5 VEHICLE METRICS

100.1 mt	Post TLI Mass
173.4	Propellant Volume (m^3)
9.6 mt	Δ Habitat - Return Stage Mass
7.4 m	CG Height at Touchdown

A5.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
5	0.75	3.75	Engines
7	0.9	6.3	Tanks/Press/Feed
7	1	7	Thermal Management
7	1	7	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed

A5.7 EVOLUTION

LONGER STAY TIME	Req Heater Power, some O2 boiloff
LARGER PAYLOADS	Some capability
LOGISTICS VOLUME	Between 20 -35 m^3
INSITU RESOURCE UTILIZATION	Yes, O2 from lunar soil
PROPELLANT BOILOFF UTILIZATION	Yes, O2
MARS COMMONALITY	possible CH4 from Mars atmosphere could promote Mars propulsion evolution.

TRADE #6
NTO/MMH PRESSURE FED RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A6.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index

#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 Hypergolic Bipropellents (3)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 All EMA Actuators (8)
#8 No Heatshield (10)
#9 Pneumatic Storage, Multiple Purge (2)
#10 Main Engine Gimballed With EMA (5)
#11 Fluids Only, Expendable, No Leakage, Loaded Long Before Commit (10)
#12 Ambient Helium - Closed Loop Flow Control Valve (6)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Few Static Seals Only Used In Fluid Systems (10)
#16 Little Physical Integration (3)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Gas Generator Bipropellant (6)
RETURN STAGE LOI=.61

LANDER STAGE Launch Operability Index

#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 Hypergolic Bipropellents (3)
#4 Expendable (10)
#5 Single Using Toxic Propellant, Auxiliary Propulsion (4)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 EMA And Active Pneumatics (4)
#8 Local Shielding of Critical Components (6)
#9 Pneumatic Storage, Multiple Purge (2)
#10 Engines Provide Power for Engine Actuator (2)
#11 Multi-Fluid, Retract At Commit, Service Mast Required (2)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Little Physical Integration (3)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Expander, LH2 Autogenous, Throttle (4.5)
RETURN LOI=.44

A6.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Open Pressurant & Pneumatic System • Initiate pryotechnic isolation valves
1	Open Tank Propellant Feed System • Initiate propellant pyrotechnic isolation valves
1	Open engine-pair pneumatic isolation valves
4	Start Engines • Open turbine start valve (GHe spin-up)

- Open gas generator propellant valves
- Open engine propellant valves
- Close turbine start valve

1 Separate From Lander Stage Structure

8 TOTAL NUMBER OF LANDER STAGE ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)

- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

12 Mid-Course Correction

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Pair Isolation Valves
  - Open 3-way solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 LOI Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Pair Isolation Valves
  - Open 3-way solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve

- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

13 Ascent Burn

- Open Pressurant & Pneumatic System
  - Initiate pryotechnic isolation valves
- Open Tank Propellant Feed System
  - Initiate propellant pyrotechnic isolation valves
- Open engine-pair pneumatic isolation valves

---Start Engines---

- Open turbine start valve (GHe spin-up)
- Open gas generator propellant valves
- Open engine propellant valves
- Seperate Stages w/ pyro valve initiation
- Close turbine start valve

---Shutdown Engine---

- Close gas generator propellant valves
- Open engine/line/gas generator purge valves

- Close tank pneumatic isolation valves
- Close engine propellant valves
- Close engine/line/gas generator purge valves

10 TEI Burn

- Open engine-pair pneumatic isolation valves
  ---Start Engines---
- Open turbine start valve (GHe spin-up)
- Open gas generator propellant valves
- Open engine propellant valves
- Close turbine start valve
  ---Shutdown Engine---
- Close gas generator propellant valves
- Open engine/line/gas generator purge valves
- Close tank pneumatic isolation valves
- Close engine propellant valves
- Close engine/line/gas generator purge valves

10 Mid-Course Correction

- Open engine-pair pneumatic isolation valves
  ---Start Engines---
- Open turbine start valve (GHe spin-up)
- Open gas generator propellant valves
- Open engine propellant valves
- Close turbine start valve
  ---Shutdown Engine---
- Close gas generator propellant valves
- Open engine/line/gas generator purge valves
- Close tank pneumatic isolation valves
- Close engine propellant valves
- Close engine/line/gas generator purge valves

85 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
0	RETURN STAGE
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	

2 TOTAL NUMBER OF LUNAR OPERATIONS

A6.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Zero Fault Tolerant for Lander Stage. Single Fault Tolerant for Ascent and Post Abort.
ABORT REACTION TIME	• 2.0 sec max. • 0.5 sec to activate propulsion system and achieve acceptable engine inlet pressures • 1.5 sec to achieve 90% thrust from engine start
STAGE SEPARATION	Not Clean, Some Obstruction Creates "Fire-in-the-Hole" Concerns
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A6.4 COMPLEXITY

# OF COMPONENTS	COMPLEXITY CATEGORY	DESCRIPTION
		RETURN STAGE
2	3	N2O4 Tanks
2	3	MMH Tanks
8	2	GHe Solenoid Valves
8	2	EMA Tank Isolation Valves
6	2	Pyro Valves, normally closed
5	2	Fill Quick Disconnects
2	2	Burst Disk/Relief Valves
2	2	Relief Valves, GHe
1	3	GHe Tank, 4500 psia
4	2	GHe Regulators, 50 psia
2	2	GHe Regulators, 310 psia
14	1	GHe Check Valves
4	3	Engine Chambers (Four XLR-132's)
4	3	N2O4 Pumps
4	3	MMH Pumps
4	3	Turbines
4	3	Gas Generators
24	2	Solenoid Valves, normally closed
12	2	Pneumatic Valves
12	2	3-Way Solenoid Valves w/ vent ports
20	2	GHe Check Valves
8	3	Electro-Mechanical Actuators (EMA's)
152		
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators

4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
323		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

693	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
323	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
130*	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engines
5	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
12	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
	Engine Systems (4 XLR-132's)
12	Temperature Transducers
32	Pressure Transducers
0	Tachometers
32	Valve Position Indicators (2 per valve)
76	
	Pressurization/Feed/Vent Systems
10	Temperature Transducers
12	Pressure Transducers
16	Valve Position Indicators (2 per valve)
12	Fluid Level Indicators (3 per tank)
50	
	LANDER STAGE
	Pressurization/Feed/Vent Systems
8	Temperature Transducers
8	Pressure Transducers
15	Fluid Level Indicators (3 per tank)
24	Valve Position Indicators (2 per valve)
55	

	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	

277 TOTAL INSTRUMENT LOCATIONS COUNT

A6.5 VEHICLE METRICS

92.5 mt	Post TLI Mass
147.9	Propellant Volume (m^3)
-2.3 mt	Δ Habitat - Return Stage Mass
7.3 m	CG Height at Touchdown

A6.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
5	0.7	3.5	Engines
7	1	7	Tanks/Press/Feed
7	1	7	Thermal Management
9	1	9	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed

A6.7 EVOLUTION

LONGER STAY TIME	Unlimited Except By Heater Power
LARGER PAYLOADS	Depends on HLLV
LOGISTICS VOLUME	Between 20 - 35 m^3
INSITU RESOURCE UTILIZATION	None
PROPELLANT BOILOFF UTILIZATION	None
MARS COMMONALITY	minimal

TRADE #7
LOX/LCH4 PUMP FED RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A7.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LO2 With Hydrocarbon Fuel (7)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 EMA And Active Pneumatics (4)
#8 No Heatshield (10)
#9 Pneumatic Storage, Multiple Purge (2)
#10 Engines Provide Power for Engine Actuator (2)
#11 Multi-Fluid, Retract At Commit, Service Mast Required (2)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Little Physical Integration (3)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Expander, LH2 Autogenous, Throttle (4.5)
RETURN LOI=.51

LANDER STAGE Launch Operability Index
#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 Hypergolic Bipropellents (3)
#4 Expendable (10)
#5 Single Using Toxic Propellant, Auxiliary Propulsion (4)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 EMA And Active Pneumatics (4)
#8 Local Shielding of Critical Components (6)
#9 Pneumatic Storage, Multiple Purge (2)
#10 Engines Provide Power for Engine Actuator (2)
#11 Multi-Fluid, Retract At Commit, Service Mast Required (2)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Little Physical Integration (3)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Expander, LH2 Autogenous, Throttle (4.5)
LANDER LOI=.44

A7.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Open Pneumatic System • Open pneumatic regulation system solenoid valves
1	Open Tank Isolation Valves • Open corresponding 3-way solenoid valves
1	Prepressurize Propellant Tanks

  - Open LCH4 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves

1 Open Engine Prevalves

- Open fuel prestart 3-way solenoid valve
- Open oxidizer prestart 3-way solenoid valve

1 Open Engine Valves

- Open start 3-way solenoid valve

1 Fire Ignitor

1 Open GCH4 Autogenous Pressurization Valves

1 Separate From Lander Stage Structure

8 TOTAL NUMBER OF LANDER STAGE ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)

- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

12 Mid-Course Correction

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Pair Isolation Valves
  - Open 3-way solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 LOI Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves

    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open Engine Pair Isolation Valves
    - Open 3-way solenoid valves
  - Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
  - Open Engine Valves
    - Open start 3-way solenoid valve
  - Fire Ignitor
  - Open GH2 Autogenous Pressurization Valves
  - Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
  - Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
  - Close GH2 Autogenous Pressurization Valves
  - Close Tank Pressurization System
    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close LH2 pressurant regulation system and vent descent tanks by opening relief solenoid valves
  - Close LO2 pressurant regulation system and vent descent tanks by opening relief solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

13 Ascent Burn

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks

  - Open LCH4 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Pair Isolation Valves
  - Open 3-way solenoid valves
- Open Engine Prevalves
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GCH4 Autogenous Pressurization Valves
- Separate From Lander Stage Structure
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GCH4 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close LCH4 pressurant regulation system and vent ascent tanks by opening relief solenoid valves
  - Close LO2 pressurant regulation system and vent descent tanks by opening relief solenoid valves

10 TEI Burn

- Prepressurize Propellant Tanks
  - Open LCH4 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GCH4 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GCH4 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LCH4 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

10 Mid-Course Correction

- Prepressurize Propellant Tanks
  - Open LCH4 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves

  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GCH4 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GCH4 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LCH4 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent 3-way solenoid valves

85 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
	RETURN STAGE PROPULSION SYSTEM
1	Activate Ascent Tank Vent Control System • Vent tank abort pressurant
22	Lunar Surface Thermal Vent Activities • Operate Active Vent System • Open Solenoid Vent Valves • Close Solenoid Vent Valves
23	

25 TOTAL NUMBER OF LUNAR OPERATIONS

A7.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Zero Fault Tolerant for Lander Stage Single Fault Tolerant for Ascent and Post Abort
ABORT REACTION TIME	1.3 sec to achieve 90% thrust from engine start
STAGE SEPARATION	Not Clean, Some Obstruction Creates "Fire-in-the-Hole" Concerns
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused
LUNAR LEAKAGE	Moderate relative potential for Lunar leakage with active static seals and large molecule propellant

7.5.0 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
2	3	LO2 Tanks
2	3	LCH4 Tanks
20	2	GHe Solenoid Valves (normally colsed 14, open 6)
8	2	GCH4 Solenoid Valves
4	2	GO2 Solenoid Valves
4	2	Pnematic Valves
6	2	3-Way Solenoid Valves w/ vent ports
2	2	LO2 Fill and Drain Pneumatic Valves
2	2	CH4 Fill and Drain Pneumatic Valves
1	3	LO2 T-0 Disconnects
1	3	CH4 T-0 Disconnects
2	2	Burst Disk/Relief Propellant Valves
3	3	GHe Tank, 4500 psia
8	1	GCH4 Check Valves
4	2	GHe Regulators, 50 psia
2	2	GHe Regulators, 310 psia
4	2	Relief Valves, GHe, 55 psia
2	2	Relief Valves, GHe, 315 psia
4	3	RL10M-1 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
8	2	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatic Valves
12	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
161		Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets

APPENDIX A
TRADE #7 LOX/CH4, PUMP

4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
332		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

701	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
331	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
128	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	LCH4 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
6	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
13	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
	Pressurization/Feed/Vent Systems
4	Temperature Transducers
14	Pressure Transducers
12	Fluid Level Indicators (3 per tank)
16	Valve Position Indicators (2 per valve)
46	

	Engine Systems (4 RL10M-1's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
	LANDER STAGE
	Pressurization/Feed/Vent Systems
8	Temperature Transducers
8	Pressure Transducers
15	Fluid Level Indicators (3 per tank)
24	Valve Position Indicators (2 per valve)
55	
	Engine Systems (4 RL10A-3-3A's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
293	TOTAL INSTRUMENT LOCATIONS COUNT

A7.5 VEHICLE METRICS

92.4 mt	Post TLI Mass
152.3	Propellant Volume (m^3)
-3.5 mt	Δ Habitat - Return Stage Mass
7.3 m	CG Height at Touchdown

A7.6 HARDWARE READINESS (HR)

TRL	*X*	*DIFFICULTY*	*=*	*HR*	
					RETURN STAGE
6		0.6		3.6	Engines
7		0.9		6.3	Tanks/Press/Feed
6		1		6	Thermal Management
7		1		7	Propellant
					LANDER STAGE
7		1		7	Engines
7		1		7	Tanks/Press/Feed

A7.7 EVOLUTION

LONGER STAY TIME	Yes. Limited by boiloff and HLLV
LARGER PAYLOADS	Depends on HLLV
LOGISTICS VOLUME	Between 20 - 35 m^3
INSITU RESOURCE UTILIZATION	LO2 production could supply return oxidizer.
PROPELLANT BOILOFF UTILIZATION	LO2 for power or crew use and RCS propellant use.
MARS COMMONALITY	Possible CH4 from Mars atmosphere would tend to promote Mars propulsion evolution

TRADE #8
LOX/LH2 PUMP FED RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A8.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED,PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) ONLY TWO PROPELLANTS, LOX/LH2 (4)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (7)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE , RECIRC PUMP(3)
RETURN LOI= 0.48

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI= 0.44

A8.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
7	Prechill Return Stage Prior to Lander Stage Operation • Open Pneumatic System • Open pneumatic regulation system solenoid valves • Open Tank Isolation Valves • Open corresponding 3-way solenoid valves • Prepressurize Propellant Tanks

    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Recirc Pump pneumatic valves
    - Open corresponding 3-way solenoid valve
- Start Recirc Pump, Operate 10 min. prior to Lander Stage Activation
- Shut down Recirc Pump
- Close Recirc Pump pneumatic valves
    - Close corresponding 3-way solenoid valve

5 Start Engines

- Open Engine Prevalves
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
    - Open start 3-way solenoid valve
- Fire Ignitor
- Fire Pyro stage separation bolts
- Open GH2 Autogenous Pressurization Valves

12 TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)

- Settle Ullage (RCS or Other)
- Operate Active Vent System
    - Open Solenoid Vent Valves
    - Close Solenoid Vent Valves

0 Mid-Course Correction (Performed by RCS)

7 Prechill Return Stage Prior to Lander Stage Operation

- Open Pneumatic System
    - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
    - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open recirc pump 3-way solenoid valve
- Start Recirc Pump, Operate 10 min. prior to Lander s Stage Activation
- Shut down Recirc Pump
- Close Recirc Pump pneumatic valves
    - Close corresponding 3-way solenoid valve

9 LOI Burn

- Open Pneumatic System
    - Open pneumatic regulation system solenoid valves
- Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
    - Open start 3-way solenoid valve

- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves

8 Descent Burn

- Open Engine Prevalves (Childown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

LUNAR RETURN STAGE OPS

7 Prechill Return Stage

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open recirc pump 3-way solenoid valve
- Start Recirc Pump, Operate 10 min. prior to Lander s Stage Activation
- Shut down Recirc Pump
- Close Recirc Pump pneumatic valves
  - Close corresponding 3-way solenoid valve

8 Perform Lunar Ascent Burn

- Open Engine Prevalves
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Fire Pyro stage separation bolts
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve

- Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves

9 Perform TEI Burn

- Open Engine Prevalves
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

68 TOTAL NUMBER OF FLIGHT OPERATIONS

 # OF LUNAR OPERATIONS — *NOMINAL SCENARIO*

LUNAR LANDER STAGE

1 Bleed off Oxidizer Residuals

1 Bleed off Fuel Residuals

LUNAR RETURN STAGE

1 Safe Return Stage for Lunar Stay

- Vent Tank Abort Pressure

22 Lunar Surface Thermal Vent Activities

- Open Solenoid Vent Valves
- Close Solenoid Vent Valves

25 TOTAL NUMBER OF LUNAR OPERATIONS

A8.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Zero Fault Tolerant for Lander Stage Single Fault Tolerant for Ascent and Post Abort
ABORT REACTION TIME	1.3 Second With 10 min. prechill Preparation
STAGE SEPARATION	Some Protrusion of engines in lander stage creates "Fire-in-the-Hole" Concerns, structurally flat interface
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A8.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		RETURN STAGE
3	3	GHe Tanks (4500 psia)

22	2	GHe Solenoid Valves (Normally Closed 14, Open 8)
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	Check Valves One Dual Set/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Pneumatic ISO Valves
2	2	Recirc Pump Pneumatic ISO Valves
2	3	Recirc Pumps
8	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps
4	3	Engine Turbines
4	3	High rpm Gear Box
8	2	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatic Valves
12	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
177		Return Stage Component Count
		LANDER STAGE
3	3	GHe Tanks (4500 psia)
10	2	GHe Solenoid Valves
6	1	GHe check vales
8	2	GH2 Solenoid Valves
4	2	GOX Solenoid Valves
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single stage (GHe, 50 psia)
2	2	Regulators, single stage (GHe 450 psia)
8	1	One Dual Set Check valve/RL10 (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
8	2	Engine/Tank Pre valves
4	2	3-Way Solenoid Valves with vent ports
4	3	LH2 Tanks with diffusers and start buckets
1	3	LOX Tanks with diffusers and start buckets
4	3	RL10 Throttling Engine Chambers
4	3	Oxidizer Turbopumps
4	3	Fuel Turbopumps

4	3	Engine Turbines
4	3	High rpm Gear Box
8	3	Engine Cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Ignitors
12	2	Pneumatically Actuated Engine FeedValves
20	2	3-Way Solenoid Valves with vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
171		Lander Stage Component Count
348		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

752	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
382	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
113	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Recirc Pump System
1	Main Engine System (includes actuator and throttling systems
8	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	
15	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
15	Tank Liquid level sensors
8	Pressure Transducers
2	Tachometers
8	Temperature Transducers
26	Valve Position Indicators
59	

	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
	LANDER STAGE
15	Tank Liquid level sensors
8	Pressure Transducers
8	Temperature Transducers
24	Valve Position Indicators
55	
	Engine Systems (4 RL10's)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators
32	Valve Position Indicators
96	
306	TOTAL INSTRUMENT LOCATIONS COUNT

A8.5 VEHICLE METRICS

93 mt	Post TLI Mass
139	Propellant Volume (m^3)
-7.5 mt	Δ Habitat - Return Stage Mass
8.5 m	CG Height at Touchdown

A8.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed
6	1	6	Thermal Management
9	1	9	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tanks/Press/Feed

A8.7 EVOLUTION

LONGER STAY TIME	6 Month requires extra propellant, MLI & 1 year requires refrigeration, Category 5
LARGER PAYLOADS	1.0 - 1.5 mt Capability
INSITU RESOURCE UTILIZATION	Potential
PROPELLANT BOILOFF UTILIZATION	Potential
MARS COMMONALITY	Some

TRADE #9
SINGLE STAGE LOX/LH2
VEHICLE PARAMETERS

A9.1 GROUND SUPPORTABILITY

RETURN Launch Operability Index

#1 No Compartments (10)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LH2, LO2 (4)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 No Actuators (10)
#8 No Heatshield (10)
#9 Pneumatic Storage, Multiple Purges Or Pneumatic Valve Control (2)
#10 No Throttling, Same as Lander System (10)
#11 Fluids Filled Through Lander Ground Interface (10)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Little Physical Integration (3)
#17 No Ground Support Equipment Required (10)
#18 Same Engine System as Lander (10)

RETURN LOI=.71

LANDER Launch Operability Index

#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LO2 / LH2 and Hydrazinr Monopropellants (3)
#4 Expendable (10)
#5 Single Using Toxic Propellant, Auxiliary Propulsion (4)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 EMA And Active Pneumatics (4)
#8 Local Shielding of Critical Components (6)
#9 Pneumatic Storage, Multiple Purges Or Pneumatic Valve Control (2)
#10 Engines Provide Power for Engine Actuator (2)
#11 Multi-Fluid, Retract At Commit, Service Mast Required (2)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Little Physical Integration (3)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Expander, LH2 Autogenous, Throttle (4.5)

LANDER LOI=.42

A9.2 FLIGHT OPERABILITY

# OF DESCENT ABORT OPERATIONS	*WORST CASE SCENARIO*
ABORT TO ORBIT	
1	Prepressurize ascent propellant tanks with GHe
1	Shut down engine with detected fault and opposing engine (close six 3-way solenoid valves)
1	Throttle up remaining two engines
1	Open ascent pressurization solenoid valves
1	Open ascent propellant tank pneumatic isolation valves

1 Close descent pressurization solenoid valves
1 Close descent propellant tank pneumatic isolation valves
1 Drop landing legs (command pyros to fire)
8 TOTAL NUMBER OF DESCENT ABORT OPERATIONS

 # OF FLIGHT OPERATIONS — *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

20 Transit Thermal Vent Activities (10 times)

- Settle Ullage (RCS or Other)
- Operate Active Vent System
  - Open Solenoid Vent Valves
  - Close Solenoid Vent Valves

0 Mid-Course Correction (Performed by RCS)

11 LOI Burn

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve

- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

11 Ascent Burn

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and ascent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and ascent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

11 TEI Burn

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve

- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

0 Mid-Course Correction (Performed by RCS)

64 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	DESCENT PROPULSION SYSTEM
1	Bleed off LO2 Residuals
1	Bleed off LH2 Residuals
2	
	ASCENT PROPULSION SYSTEM
1	Activate Ascent Tank Vent Control System • Vent tank abort pressurant
22	Lunar Surface Thermal Vent Activities • Operate Active Vent System • Open Solenoid Vent Valves • Close Solenoid Vent Valves
23	
25	TOTAL NUMBER OF LUNAR OPERATIONS

A9.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Zero Fault Tolerant for Lunar Landing; Single Fault Tolerant for Crew Return; Zero Fault Tolerant Post-Abort
ABORT REACTION TIME	1.0 sec max. for shutdown of opposing engines and throttle up of remaining engines 2.4 sec max. to switch from descent tank to ascent tank use.
STAGE SEPARATION	No stage seperation is required. Landing gear is dropped during ascent.
DEBRIS DAMAGE IMMUNITY	Damage to descent stage does affect ascent propulsion system. (May remove engine-out capability for ascent)

A9.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		COMMON COMPONENTS
6	3	GHe Tanks (4500 psia)
14	2	Solenoid Valves, normally closed (GHe)
2	2	Solenoid Valves, normally closed (GH2)

APPENDIX A
TRADE #9 SINGLE STAGE

4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single-stage (GHe, 50 psia)
2	2	Regulators, single-stage (GHe, 450 psia)
8	1	Check Valves, one dual set (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
4	2	3-Way Solenoid Valves w/ vent ports
4	2	Solenoid Valves, normally open (GHe)
4	3	RL-10 Throttling Engine Chambers
4	3	Oxidizer turbopumps
4	3	Fuel turbopumps
4	3	Engine turbines
4	3	High rpm Gear Box
4	3	Hydrogen cooldown vent valves
8	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Igniters
4	2	Pneumatic Valves
12	2	3-Way Solenoid Valves w/ vent ports
12	2	Engine TVC Hydraulic Actuators
8	2	Hydraulic Accumulator
4	1	Hydraulic Relief Valves
4	2	Low pressure pump and recirc chamber
4	3	High Pressure Pump
4	3	
145		
		DESCENT COMPONENTS
6	3	LH2 Tanks w/ diffusers & start buckets (2.6 m dia.)
2	3	LO2 Tanks w/ diffusers & start buckets (2.6 m dia.)
2	2	3-Way Solenoid Valves w/ vent ports
2	2	Solenoid Valves, normally open (GHe)
4	2	Pneumatic valves, tank isolation
6	2	Solenoid Valves, normally closed (GH2)
6	2	Solenoid Valves, normally closed (GO2)
2	2	Burst discs/Relief Valves
30		
		ASCENT COMPONENTS
1	3	LH2 Tanks w/ diffuser & start bucket (4.0 m dia.)
1	3	LO2 Tanks w/ bubbler & start bucket (3.0m dia.)
2	2	3-Way Solenoid Valves w/ vent ports
2	2	Solenoid Valves, normally open (GHe)
4	2	Pneumatic valves, tank isolation
6	2	Solenoid Valves, normally closed (GH2)
6	2	Solenoid Valves, normally closed (GO2)
2	2	Burst discs/Relief Valves
24		
199		TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

432 COMPLEXITY RATING FOR TOTAL # OF COMPONENTS
364 COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE
80* COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS

# OF SUBSYSTEMS	DESCRIPTION
	STAGE MAIN PROPULSION
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	DESCRIPTION
	COMMON SYSTEMS
5	Temperature Transducers
13	Pressure Transducers
8	Valve Position Indicators (2 per valve)
26	
	ENGINE SYSTEMS (4 RL-10s)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
	DESCENT PROPULSION SYSTEM
12	Temperature Transducers
10	Pressure Transducers
8	Valve Position Indicators (2 per valve)
24	Fluid Level Indicators (3 per tank)
54	
	ASCENT PROPULSION SYSTEM
6	Temperature Transducers
10	Pressure Transducers
2	Delta P Transducers
8	Valve Position Indicators (2 per valve)
6	Fluid Level Indicators (3 per tank)
32	
208	TOTAL INSTRUMENT LOCATIONS COUNT

A9.5 VEHICLE METRICS

101.4 mt	Post TLI Mass
218 m^3	Propellant Volume
-13.9 mt	Δ Habitat - Lunar Ascent Mass
6.1 m	CG Height at Touchdown

A9.6 HARDWARE READINESS (HR)

TRL	X	DIFFICULTY	=	HR	
					ASCENT STAGE
6		0.6		3.6	Engines
7		0.9		6.3	Tanks/Press/Feed
6		1		6	Thermal Management
9		1		9	Propellant

			DESCENT STAGE
9	1	9	Engines (Credited with 9 since already accounted with Return stage engines)
9	1	9	Tanks/Press/Feed (Credited with 9 since already accounted with Return stage

A9.7 EVOLUTION

LONGER STAY TIME	No. Concept currently exceeds 93 mt limit for 45 day stay, Category 5
LARGER PAYLOADS	No. Concept currently exceeds 93 mt limit for cargo version
INSITU RESOURCE UTILIZATION	LO2 production could supply Earth return oxidizer
PROPELLANT BOILOFF UTILIZATION	LO2 for power or crew use. LH2 for CO2 reduction or CH4 production. Both for RCS propellant use.
MARS COMMONALITY	Possible

TRADE #10
1.5 STAGE ALL CRYO VEHICLE

A10.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1 No Compartments (10)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LH2, LO2 (4)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 No Actuators (10)
#8 No Heatshield (10)
#9 Pneumatic Storage, Multiple Purges Or Pneumatic Valve Control (2)
#10 No Throttling, Same as Lander System (10)
#11 Fluids Filled Through Lander Ground Interface (10)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Fully Integrated(10)
#17 No Ground Support Equipment Required (10)
#18 Same Engine System as Lander (10)
RETURN LOI=.75

LANDER STAGE Launch Operability Index
#1 Compartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LO2 / LH2 and Hydrazinr Monopropellants (3)
#4 Expendable (10)
#5 Single Using Toxic Propellant, Auxiliary Propulsion (4)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 EMA And Active Pneumatics (4)
#8 Local Shielding of Critical Components (6)
#9 Pneumatic Storage, Multiple Purges Or Pneumatic Valve Control (2)
#10 Engines Provide Power for Engine Actuator (2)
#11 Multi-Fluid, Retract At Commit, Service Mast Required (2)
#12 Autogenous And Ambient Helium-Closed Loop Control Valve (5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 No Integration (1)
#17 Special GSE With Maintanance Required (3)
#18 Pump Fed Expander, LH2 Autogenous, Throttle (4.5)
LANDER LOI=.41

A10.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO (ENGINE OUT)*
1	Shutdown opposing engine
1	Throttle up other engines
1	Open ascent tank feed system
1	open ascent tank pressurization system
1	close descent tank pressurization system
1	close descent feed system
1	fire pyros to drop descent stage
7	TOTAL NUMBER OF ABORT OPERATIONS

 # OF FLIGHT OPERATIONS *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

- 20 Transit Thermal Vent Activities (10 times)
  - Settle Ullage (RCS or Other)
  - Operate Active Vent System
    - Open Solenoid Vent Valves
    - Close Solenoid Vent Valves
- 0 Mid-Course Correction (Performed by RCS)
- 11 LOI Burn
  - Open Pneumatic System
    - Open pneumatic regulation system solenoid valves
  - Open Tank Isolation Valves
    - Open corresponding 3-way solenoid valves
  - Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
  - Open Engine Valves
    - Open start 3-way solenoid valve
  - Fire Ignitor
  - Open GH2 Autogenous Pressurization Valves
  - Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
  - Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
  - Close GH2 Autogenous Pressurization Valves
  - Close Tank Pressurization System
    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- 10 Descent Burn
  - Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and tank pressurization solenoid valves
  - Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
  - Open Engine Valves
    - Open start 3-way solenoid valve
  - Fire Ignitor
  - Open GH2 Autogenous Pressurization Valves
  - Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
  - Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
  - Close GH2 Autogenous Pressurization Valves
  - Close Tank Pressurization System

    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close Tank Isolation Valves
    - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

12 Ascent Burn

- Open Pneumatic System
  - Open pneumatic regulation system solenoid valves
- Open Tank Isolation Valves
  - Open corresponding 3-way solenoid valves
- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Fire pyros for disconnects and descent stage
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 TEI Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve

- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

10 1 Mid-Course Correction

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

73 TOTAL NUMBER OF FLIGHT OPERATIONS

 # OF LUNAR OPERATIONS *NOMINAL SCENARIO*

RETURN STAGE

26
- vent operations

LANDER STAGE

1 Bleed off Oxidizer Residuals
1 Bleed off Fuel Residuals
2
28 TOTAL NUMBER OF LUNAR OPERATIONS

A10.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Zero Fault Tolerant for Lunar Landing; Single Fault Tolerant for Ascent, Zero Fault Tolerant Post-Abort
ABORT REACTION TIME	1.3Second With Preparation
STAGE SEPARATION	Not Clean, Some Obstruction Creates "Fire-in-the-Donut" Concerns
DEBRIS DAMAGE IMMUNITY	The Return Engines are Exposed at Lunar Landing

A10.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*DESCRIPTION*
		COMMON COMPONENTS
6	3	GHe Tanks (4500 psia)
14	2	Solenoid Valves, normally closed (GHe)
2	2	Solenoid Valves, normally closed (GH2)
4	2	Relief Valves (GHe, 60 psia)
2	2	Relief Valves (GHe, 500 psia)
4	2	Regulators, single-stage (GHe, 50 psia)
2	2	Regulators, single-stage (GHe, 450 psia)
8	1	Check Valves, one dual set (GH2)
2	2	LH2 Fill and Drain Pneumatic Valves
2	2	LO2 Fill and Drain Pneumatic Valves
1	3	LH2 T-0 Disconnect
1	3	LO2 T-0 Disconnect
1	2	GHe Fill Quick Disconnect
4	2	3-Way Solenoid Valves w/ vent ports
4	2	Solenoid Valves, normally open (GHe)
4	3	RL-10 Throttling Engine Chambers
4	3	Oxidizer turbopumps
4	3	Fuel turbopumps
4	3	Engine turbines
4	3	High rpm Gear Box
8	2	Hydrogen cooldown vent valves
4	2	EMA Operated Fuel Throttle Valves
4	2	EMA Operated OX Valves
4	2	Igniters
12	2	Pneumatic Valves
12	2	3-Way Solenoid Valves w/ vent ports
8	2	Engine TVC Hydraulic Actuators
4	1	Hydraulic Accumulator
4	2	Hydraulic Relief Valves
4	3	Low pressure pump and recirc chamber
4	3	High Pressure Pump
145		
		DESCENT COMPONENTS
6	3	LH2 Tanks w/ diffusers & start buckets (2.6 m dia.)
2	3	LO2 Tanks w/ diffusers & start buckets (2.6 m dia.)
2	2	3-Way Solenoid Valves w/ vent ports
2	2	Solenoid Valves, normally open (GHe)
2	2	Pneumatic valves, tank isolation
6	2	Solenoid Valves, normally closed (GH2)
6	2	Solenoid Valves, normally closed (GO2)
2	2	Burst discs/Relief Valves
28		
		ASCENT COMPONENTS
2	3	Cryogenic disconnects
2	3	Gas phase disconnects
1	3	LH2 Tanks w/ diffuser & start bucket (4.0 m dia.)
1	3	LO2 Tanks w/ bubbler & start bucket (3.0m dia.)
2	2	3-Way Solenoid Valves w/ vent ports
2	2	Solenoid Valves, normally open (GHe)
4	2	Pneumatic valves, tank isolation
6	2	Solenoid Valves, normally closed (GH2)
6	2	Solenoid Valves, normally closed (GO2)
2	2	Burst discs/Relief Valves
28		

201 TOTAL PROPULSION SYSTEM COMPONENT COUNT

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

440	**COMPLEXITY RATING FOR TOTAL # OF COMPONENTS**
376	**COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE**
86	**COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS**

# OF SUBSYSTEMS	*DESCRIPTION*
	1.5 STAGE
1	LH2 Tank Pressurant Regulation and Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	COMMON SYSTEMS
5	Temperature Transducers
13	Pressure Transducers
8	Valve Position Indicators (2 per valve)
26	
	ENGINE SYSTEMS (4 RL-10s)
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
	DESCENT PROPULSION SYSTEM
12	Temperature Transducers
10	Pressure Transducers
8	Valve Position Indicators (2 per valve)
24	Fluid Level Indicators (3 per tank)
54	
	ASCENT PROPULSION SYSTEM
6	Temperature Transducers
10	Pressure Transducers
2	Delta P Transducers
8	Valve Position Indicators (2 per valve)
6	Fluid Level Indicators (3 per tank)
32	
208	TOTAL INSTRUMENT LOCATIONS COUNT

A10.5 VEHICLE METRICS

83 mt	Post TLI Mass
168	Propellant Volume (m^3)
2.4 mt	Δ Habitat - Lunar Return Mass
5.9 m	CG Height at Touchdown

A10.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
6	0.6	3.6	Engines
7	1	7	Tanks/Press/Feed
6	1	6	Thermal Management
9	1	9	Propellant
			LANDER STAGE
9	1	9	Engines (Credited with 9 since already accounted with Return stage engines)
7	1	7	Tanks/Press/Feed

A10.7 EVOLUTION

LONGER STAY TIME	Limited
LARGER PAYLOADS	Depends on HLLV
INSITU RESOURCE UTILIZATION	Lunar LOX Possibilities
PROPELLANT BOILOFF UTILIZATION	Possible
MARS COMMONALITY	minimal

TRADE #11
ClF5/N2H4 PRESSURE FED RETURN STAGE
ClF5/N2H4 PRESSURE FED LANDER STAGE

A11.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLANTS (1)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) FLUIDS (2) ONLY, EXPENDABLE, NO LEAKAGE, LOADED LONG BEFORE COMMIT(10)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (7)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
RETURN LOI= .65

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) HYPERGOLIC BIPROPELLENTS (1)
#4) EXPENDABLE (10)
#5) RCS INTEGRATED WITH MAIN (8.5)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) FLUIDS (2) ONLY, EXPENDABLE, NO LEAKAGE, LOADED LONG BEFORE COMMIT(10)
#12) AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (6)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS (7)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED BIPROPELLANT (9)
LANDER STAGE LOI= .65

A11.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Hypergolic Engine Valves
1	Separate From Lander Stage Structure
4	TOTAL NUMBER OF ABORT OPERATIONS

# OF FLIGHT OPERATIONS	*NOMINAL SCENARIO*
	TRANSIT TO MOON FLIGHT OPERATIONS
0	Transit Thermal Vent Activities
5	Mid-Course Correction
	• Activate Tank Pyro Iso Valves
	• Open Tank Pressurization Valves
	• Open Hypergollic Engine Valves
	• Close Engine Valves
	• Close Tank Pressurization Valves
4	LOI Burn
	• Open Tank Pressurization Valves
	• Open Hypergollic Engine Valves
	• Close Engine Valves
	• Close Tank Pressurization Valves
4	Descent Burn
	• OpenTank Pressurization Valves
	• Open Hypergollic Engine Valves
	• Close Engine Valves
	• Close Tank Pressurization Valves
	LUNAR RETURN STAGE OPS
6	Ascent Burn
	• Activate Engine - Tank Pyro Iso Valves
	• Activate Tank- Pressurization Pyro Iso Valves
	• Open Hypergolic Engine Valves
	• Separate From Descent Stage Structure
	• Close Engine Valves
	• Close Pressurization Iso valves
4	TEI Burn
	• Open Tank Pressurization Iso valves
	• Open Hypergolic Engine Valves
	• Close Engine Valves
	• Close Tank Pressurization valves
4	1 Mid-Course Correction
	• Open Tank Pressurization valves
	• Open Hypergolic Engine Valves
	• Close Engine Valves
	• Close Tank Pressurization valves
26	TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
0	No Lunar Operations Until Liftoff
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
2	TOTAL NUMBER OF LUNAR OPERATIONS

A11.3 VEHICLE DESIGN ISSUES

<u>INHERENT REDUNDANCY</u>	Lander Stage: Single Fault Tolerant for feed system component failure. Engine structural failure notcredible. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural failure not credible. Engine mechanical valves are redundant.

ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	FLAT, Clean, The single Return Stage engines does not protrude down into a hole in the Lander Stage.
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused

A11.4 COMPLEXITY

# OF COMPONENT	COMPLEXITY CATEGORY	# x Category	DESCRIPTION
			RETURN STAGE
8	1	8	2 Sets of Quad Check Valves
4	2	8	2 Sets of series redundant Pressure Reg.
2	2	4	Pressure Reg Iso Valves
5	2	10	Pyro Isolation Valves
1	3	3	Helium Tank
2	3	6	Fuel Tanks
2	3	6	Oxidizer Tanks
2	3	6	Heat Exchangers
8	2	16	Biprop Valves
2	2	4	Burst Disc/Relief Valves
5	2	10	Fill quick disconnects
2	3	6	EMA TVC actuators
1	3	3	Engines
44	31	90	
			LANDER STAGE
8	1	8	2 Sets of Quad Check Valves
4	2	8	Sets of series redundant Pressure Regulators
2	2	4	Pressure Reg Iso Valves
5	2	10	Pyro Isolation Valves
1	3	3	Helium Tank
3	3	9	Fuel Tanks
3	3	9	Oxidizer Tanks
2	3	6	Heat Exchangers
16	2	32	Biprop Valves
2	2	4	Burst Disc/Relief Valves
5	2	10	Fill quick disconnects
4	3	12	EMA TVC actuators
8	2	16	EMA THROTTLE VALVES
2	3	6	Engines
65	33	137	

TOTAL PROPULSION SYSTEM COMPONENT COUNT = 109

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

COMPLEXITY RATING FOR TOTAL # OF COMPONENTS = 227
COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE = 90
COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS * = 64

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engine
4	
	LANDER STAGE
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engine
4	
8	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
5	Temperature Transducers
7	Pressure Transducers
2	Thrust Control Indicators
20	Valve Position Indicators
34	
	LANDER STAGE
6	Tank Liquid level sensors
8	Pressure Transducers
7	Temperature Transducers
4	Thrust Control Indicators
36	Valve Position Indicators
61	
95	TOTAL INSTRUMENT LOCATIONS COUNT

A11.5 VEHICLE METRICS

90.7 mt	Post TLI Mass
46.1	Propellant Volume (m^3)
2.5 mt	Δ Habitat - Return Stage Mass
4.8m	CG Height at Touchdown

A11.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
5	0.65	3.25	Engines
5	0.65	3.25	Tanks/Press/Feed
5	1	5	Thermal Management
5	0.65	3.25	Propellant
			LANDER STAGE
7	1	7	Engines
7	1	7	Tank/Press/Feed
5	1	5	Thermal Management
6	.65	3.25	Propellant

A11.7 EVOLUTION

LONGER STAY TIME	Unlimited Except By Heater Power
LARGER PAYLOADS	Yes
INSITU RESOURCE UTILIZATION	None
PROPELLANT BOILOFF UTILIZATION	None
MARS COMMONALITY	High performance, small aeroshell package

TRADE #12
OPTIMIZED IME RETURN STAGE
OPTIMIZED IME LANDER STAGE

A12.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED,PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) ONLY TWO PROPELLANTS, LOX/LH2 (4)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA (8)
#8) NO HEATSHIELD (10)
#9) NO PNEUMATIC SYSTEM (10)
#10) DIFFERENTIAL THROTTLING - FIXED MAIN ENGINES (10)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENEOUS - FIXED ORIFICE CONTROL (8)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) ENGINES ARE INTEGRATED WITH SYSTEM, POSSIBLE POWER INTEG. (7)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER/PRE-BURNER CYCLE PUMP FED, THROTTLE (3.5)
RETURN LOI=.60

LANDER STAGE Launch Operability Index
#1) COMPARTMENT COMPLETELY CLOSED,PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) ONLY TWO PROPELLANTS, LOX/LH2 (4)
#4) EXPENDABLE (10)
#5) RCS INTEGRATED WITH LANDER STAGE (8.5)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA (8)
#8) NO HEATSHIELD (10)
#9) NO PNEUMATIC SYSTEM (10)
#10) DIFFERENTIAL THROTTLING - FIXED MAIN ENGINES (10)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENEOUS - FIXED ORIFICE CONTROL (8)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) ENGINES ARE INTEGRATED WITH SYSTEM, POSSIBLE POWER INTEG. (7)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER/PRE-BURNER CYCLE PUMP FED, THROTTLE (3.5)
LANDER STAGE LOI=.58

A12.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Open Tank Iso Valves
1	Open Pump Iso Valves
1	Open Manifold Iso Valves
1	Open Engine Valves
1	Fire Igniter
1	Open Autogeneous Pressurization Valves

1	Separate From Lander Stage Structure
7	TOTAL NUMBER OF ABORT OPERATIONS

# OF FLIGHT OPERATIONS	*NOMINAL SCENARIO*
	TRANSIT TO MOON FLIGHT OPERATIONS
20	Transit Thermal Vent Activities (10 times)
11	Mid-Course Correction
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves]
	• Fire Igniter
	• Open Autogeneous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close GH2 Autogenous Pressurization Valves
11	LOI Burn
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves]
	• Fire Igniter
	• Open Autogeneous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close GH2 Autogenous Pressurization Valves
11	Descent Burn
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves]
	• Fire Igniter
	• Open Autogeneous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close GH2 Autogenous Pressurization Valves
	LUNAR RETURN STAGE OPS
12	Perform Lunar Ascent Burn
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves]
	• Fire Igniter
	• Fire Pyro Stage Separation Bolts
	• Open Autogeneous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close GH2 Autogenous Pressurization Valves
11	Perform TEI Burn

- Open Tank Iso Valves
- Open Pump Iso Valves
- Open Manifold Iso Valves
- Open Engine Valves]
- Fire Igniter
- Open Autogeneous Pressurization Valves
- Close Engine Valves
- Close Tank Iso Valves
- Close Pump Iso Valves
- Close Manifold Iso Valves
- Close GH2 Autogenous Pressurization Valves

11 Mid-Course Correction

- Open Tank Iso Valves
- Open Pump Iso Valves
- Open Manifold Iso Valves
- Open Engine Valves]
- Fire Igniter
- Open Autogeneous Pressurization Valves
- Close Engine Valves
- Close Tank Iso Valves
- Close Pump Iso Valves
- Close Manifold Iso Valves
- Close GH2 Autogenous Pressurization Valves

87 TOTAL NUMBER OF FLIGHT OPERATIONS

 # OF LUNAR OPERATIONS *NOMINAL SCENARIO*

LUNAR LANDER STAGE
1 Bleed off Oxidizer Residuals
1 Bleed off Fuel Residuals

LUNAR RETURN STAGE
1 Safe Return Stage for Lunar Stay
- Vent Tank Abort Pressure

22 Lunar Surface Thermal Vent Activities
- Open Solenoid Vent Valves
- Close Solenoid Vent Valves

25 TOTAL NUMBER OF LUNAR OPERATIONS

A12.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Return and Lander Stages: Single Fault Tolerant for feed system component failure. Engine structural failure not credible. Single Fault Tolerant Post-Abort
ABORT REACTION TIME	1.5 to 2.0 Seconds for Pump Ramping
STAGE SEPARATION	Clean, The Return Stage Does Not Protrude Down Into A Hole In The Lander Stage.
DEBRIS DAMAGE IMMUNITY	Immune, since Return Stage Protected & Unused
LEAKAGE POTENTIAL	LH2 , NOT hermetically sealed

A12.4 COMPLEXITY

# OF COMPONENTS	COMPLEXITY CATEGORY	# x Category	DESCRIPTION
			RETURN STAGE
8	2	16	GH2 Solenoid Valves
8	2	16	GO2 Solenoid Valves
1	2	2	GH2 Relief Valve
1	2	2	GO2 Relief Valve
1	2	2	GH2 Burst Disc
1	2	2	GO2 Burst Disc
4	2	8	LH2 EMA Valves
4	2	8	LOX EMA Valves
4	2	8	LH2 Solenoid Valves
6	2	12	LOx Solenoid Valves
2	2	4	GH2 Solenoid Valves
2	2	4	3-Way Solenoid Valves with vent ports
2	3	6	LH2 Tanks
2	3	6	LOX Tanks
4	2	8	Modulating Valves
2	3	6	Oxidizer Turbopumps
2	3	6	Hydrogen Turbopumps
2	3	6	Heat Exchangers
12	2	24	Engine Valves
12	2	24	Engine Throttling Valves
3	3	9	Engine Chambers
83	48	181	
			LANDER STAGE
8	2	16	GH2 Solenoid Valves
8	2	16	GO2 Solenoid Valves
1	2	2	GH2 Relief Valve
1	2	2	GO2 Relief Valve
1	2	2	GH2 Burst Disc
1	2	2	GO2 Burst Disc
4	2	8	LH2 EMA Valves
4	2	8	LOX EMA Valves
4	2	8	LH2 Solenoid Valves
6	2	12	LOx Solenoid Valves
2	2	4	GH2 Solenoid Valves
2	2	4	3-Way Solenoid Valves with vent ports
4	3	12	LH2 Tanks
2	3	6	LOX Tanks
4	2	8	Modulating Valves
2	3	6	Oxidizer Turbopumps
2	4	8	Hydrogen Turbopumps
2	3	6	Heat Exchangers
16	2	32	Engine Valves
16	2	32	Engine Throttling Valves
4	3	12	Engine Chambers
94	48	206	

TOTAL PROPULSION SYSTEM COMPONENT COUNT = 177
COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

COMPLEXITY RATING FOR TOTAL # OF COMPONENTS = 387
COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE = 181
COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS* = 96

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN STAGE
1	LH2 Tank Autogenous Pressurization System
1	LO2 Tank Autogeneous Pressurization System
1	Tank Vent Control System
1	Tanks and Feed System
1	Turbo-Pump System
1	Main Engine System (includes actuator and throttling systems
6	
	LANDER STAGE
1	LH2 Tank Autogenous Pressurization System
1	LO2 Tank Autogeneous Pressurization System
1	Tank Vent Control System
1	Tanks and Feed System
1	Turbo-Pump System
1	Main Engine System (includes actuator and throttling systems
6	
12	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN STAGE
8	Pressure Transducers
4	Tachometers
8	Temperature Transducers
76	Valve Position Indicators
96	
	Engine Systems
6	Temperature Transducers
3	Pressure Transducers
12	Thrust Control Indicators
24	Valve Position Indicators
45	
	LANDER STAGE
8	Pressure Transducers
10	Temperature Transducers
76	Valve Position Indicators
94	
	Engine Systems (4 RL10's)
8	Temperature Transducers
4	Pressure Transducers
16	Thrust Control Indicators
32	Valve Position Indicators
60	
295	TOTAL INSTRUMENT LOCATIONS COUNT

A12.5 VEHICLE METRICS

70.1 mt	Post TLI Mass
127.1 m3	Propellant Volume (m^3)
5.5 mt	Δ Habitat - Return Stage Mass
7.0 m	CG Height at Touchdown

A12.6 HARDWARE READINESS (HR)

TRL	*X DIFFICULTY*	*= HR*	
			RETURN STAGE
4	.7	2.8	Engines
7	1	7	Tanks/Press/Feed
7	1	7	Thermal Management
9	1	9	Propellant
			LANDER STAGE
4	.7	2.8	Engines
7	1	7	Tanks/Press/Feed
7	1	7	Thermal Management
9	1	9	Propellant

A12.7 EVOLUTION

LONGER STAY TIME	6 Month requires extra propellant, MLI & 1 year requires refrigeration, Category 5
LARGER PAYLOADS	High Performance Provides ≥2.5 mt
INSITU RESOURCE UTILIZATION	yes, use LO2 manuf. from lunar soil
PROPELLANT BOILOFF UTILIZATION	Yes, Use for power or RCS
MARS COMMONALITY	High Isp performance, however boiloff in Mars atmosphere is high and large aeroshell is required due to LH2 tankage.

TRADE #13
PRESSURE FED LH2/LOX RETURN STAGE
LOX / LH2 PUMP FED LANDER STAGE

A13.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index

#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) ONLT TWO PROPELLANTS, LOX/LH2 (4)
#4) EXPENDABLE (10)
#5) NO AUXILARY PROPULSION (10)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) ALL EMA ACTUATORS (8)
#8) NO HEATSHIELD (10)
#9) NO GROUND PURGE (10)
#10) MAIN ENGINES GIMBALLED WITH EMA (5)
#11) MULTI-FLUID LH2/LO2 T-0 INTERFACE, NOLEAKAGE, RETRACT AT COMMIT (2)
#12) COLD HELIUM, HEAT EXCHANGER - CLOSED LOOP FLOW CONTROL VALVE (4)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITHOUT REMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) PRESSURE FED LH2/LOX (9)
RETURN LOI= .59

LANDER STAGE Launch Operability Index

#1) COMPARTMENT COMPLETELY CLOSED, PANEL ACCESS (3)
#2) FUNCTIONAL CHECKS AUTOMATED, LEAK CHECKS MANUAL (1.5)
#3) LO2/LH2 , AND MONOPROPELLANT (3)
#4) EXPENDABLE (10)
#5) SINGLE USING TOXIC PROP, AUXIALLRY PROPULSION (4)
#6) ORDANANCE MULTIPLE LAUNCH SITE INSTALLATION CLEARING REQ (4)
#7) EMA AND ACTIVE PNEUMATICS (4)
#8) NO HEATSHIELD (10)
#9) PNEUMATIC STORAGE, MULTIPLE PURGE (2)
#10) MAIN ENGINES GIMBALLED WITH HYD ACT., ENGINE PROVIDES POWER (2)
#11) MULTI FLUID LH2/LO2 T-0 INTERFACE, NO LEAKAGE, RETRACT AT COMMIT (2)
#12) AUTOGENOUS AND AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE (5)
#13) NO PRECONDITIONING REQUIRED (10)
#14) ACCESS WITH OUTREMOVAL OF OTHERS, SOME SUPPORT EQUIP (7)
#15) STATIC AND DYNAMIC SEALS (3)
#16) LITTLE PHYSICAL INTEGRATION (3)
#17) SPECIAL GSE WITH MAINTANANCE REQUIRED (3)
#18) EXPANDER CYCLE PUMP FED , THROTTLE (4.5)
LANDER STAGE LOI= .44

A13.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Activate Engine - Tank Pyro Iso Valves
1	Activate Tank- Pressurization Pyro Iso Valves
1	Open Engine Valves
1	Open TankPressurization Iso Valves
1	Fire Ignitors
1	Separate From Lander Stage Structure
6	TOTAL NUMBER OF ABORT OPERATIONS

APPENDIX A
TRADE #13 LO2/LH2 PRES. FED

 # OF FLIGHT OPERATIONS — *NOMINAL SCENARIO*

TRANSIT TO MOON FLIGHT OPERATIONS

- 4 Transit Thermal Vent Activities (2 times)
- 4 Mid-Course Correction
  - 11 Open Pneumatic System
    - Open pneumatic regulation system solenoid valves
  - Open Tank Isolation Valves
    - Open corresponding 3-way solenoid valves
  - Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
  - Open Engine Valves
    - Open start 3-way solenoid valve
  - Fire Ignitor
  - Open GH2 Autogenous Pressurization Valves
  - Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
  - Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
  - Close GH2 Autogenous Pressurization Valves
  - Close Tank Pressurization System
    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- 11 LOI Burn
  - Open Pneumatic System
    - Open pneumatic regulation system solenoid valves
  - Open Tank Isolation Valves
    - Open corresponding 3-way solenoid valves
  - Prepressurize Propellant Tanks
    - Open LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Open LO2 pressurant regulation system and descent tank pressurization solenoid valves
  - Open Engine Prevalves (Chilldown Engine)
    - Open fuel prestart 3-way solenoid valve
    - Open oxidizer prestart 3-way solenoid valve
  - Open Engine Valves
    - Open start 3-way solenoid valve
  - Fire Ignitor
  - Open GH2 Autogenous Pressurization Valves
  - Close Engine Valves (Shutdown Engine)
    - Close and vent start 3-way solenoid valve
  - Close Engine Prevalves
    - Close and vent fuel prestart 3-way solenoid valve
    - Close and vent oxidizer prestart 3-way solenoid valve
  - Close GH2 Autogenous Pressurization Valves
  - Close Tank Pressurization System

    - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
    - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves

10 Descent Burn

- Prepressurize Propellant Tanks
  - Open LH2 pressurant regulation system and tank pressurization solenoid valves
  - Open LO2 pressurant regulation system and tank pressurization solenoid valves
- Open Engine Prevalves (Chilldown Engine)
  - Open fuel prestart 3-way solenoid valve
  - Open oxidizer prestart 3-way solenoid valve
- Open Engine Valves
  - Open start 3-way solenoid valve
- Fire Ignitor
- Open GH2 Autogenous Pressurization Valves
- Close Engine Valves (Shutdown Engine)
  - Close and vent start 3-way solenoid valve
- Close Engine Prevalves
  - Close and vent fuel prestart 3-way solenoid valve
  - Close and vent oxidizer prestart 3-way solenoid valve
- Close GH2 Autogenous Pressurization Valves
- Close Tank Pressurization System
  - Close and vent LH2 pressurant regulation system and descent tank pressurization solenoid valves
  - Close and vent LO2 pressurant regulation system and descent tank pressurization solenoid valves
- Close Tank Isolation Valves
  - Close and vent corresponding 3-way solenoid valves

LUNAR RETURN STAGE OPS

8 Ascent Burn

- Activate Engine - Tank Pyro Iso Valves
- Activate Tank- Pressurization Pyro Iso Valves
- Open Tank Pressurization Iso Valves
- Open Engine Valves
- Fire Ignitors
- Separate From Descent Stage Structure
- Close Engine Valves
- Close Pressurization Iso valves

5 TEI Burn

- Open Tank Pressurization Iso valves
- Open Engine Valves
- Fire Ignitors
- Close Engine Valves
- Close Tank Pressurization valves

5 1 Mid-Course Correction

- Open Tank Pressurization valves
- Open Engine Valves
- Fire Ignitors
- Close Engine Valves
- Close Tank Pressurization valves

58 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	RETURN STAGE
23	Cryo vent cycles
	LANDER STAGE
1	Bleed off Oxidizer Residuals
1	Bleed off Fuel Residuals
2	
25	TOTAL NUMBER OF LUNAR OPERATIONS

A13.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Lander Stage: Zero Fault Tolerant for engine failure except during terminal phase of descent, one fault tolerant for feed system component failure. Return Stage: Single Fault Tolerant for Ascent and Post Abort. Engine structural filure not credible. Engine mechanical valves are redundant.
ABORT REACTION TIME	Less Than 0.5 Second Without Preparation
STAGE SEPARATION	Not Clean, Some Obstruction Creates "Fire-in-the-Hole" Concerns. The ascent engine protrudes down into a hole in the Lander Stage .
DEBRIS DAMAGE IMMUNITY	Immune, since Return Lander Protected & Unused
LEAKAGE POTENTIAL	HIGH Potential Due to LH2 Presence

A13.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*# x Category*	*DESCRIPTION*
			RETURN LANDER
8	1	8	2 Sets of Quad Check Valves
2	2	4	1 Set of series redundant Pressure Regulators
2	2	4	Pressure Reg Iso Valves
4	2	8	Pyro Isolation Valves
2	3	6	Helium Tanks
2	3	6	Fuel Tanks
2	3	6	Oxidizer Tanks
8	2	16	Biprop Valves
2	2	4	Burst Disc/Relief Valves
2	2	4	Fill quick disconnects
2	3	6	EMA TVC actuators
1	3	3	Engine
37	28	75	
			LANDER STAGE
3	3	9	GHe Tanks (4500 psia)
10	2	20	GHe Solenoid Valves
6	1	6	GHe check vales
8	2	16	GH2 Solenoid Valves
4	2	8	GOX Solenoid Valves
4	2	8	Relief Valves (GHe, 60 psia)
2	2	4	Relief Valves (GHe, 500 psia)
4	2	8	Regulators, single stage (GHe, 50 psia)

2	2	4	Regulators, single stage (GHe 450 psia)
8	1	8	One Dual Set Check valve/RL10 (GH2)
2	2	4	LH2 Fill and Drain Pneumatic Valves
2	2	4	LO2 Fill and Drain Pneumatic Valves
1	3	3	LH2 T-0 Disconnect
1	3	3	LO2 T-0 Disconnect
1	2	2	GHe Fill Quick Disconnect
8	2	16	Engine/Tank Pre valves
4	2	8	3-Way Solenoid Valves with vent ports
6	3	18	LH2 Tanks with diffusers and start buckets
2	3	6	LOX Tanks with diffusers and start buckets
4	3	12	RL10 Throttling Engine Chambers
4	3	12	Oxidizer Turbopumps
4	3	12	Fuel Turbopumps
4	3	12	Engine Turbines
4	3	12	High rpm Gear Box
8	3	24	Engine Cooldown vent valves
4	2	8	EMA Operated Fuel Throttle Valves
4	2	8	EMA Operated OX Valves
4	2	8	Ignitors
12	2	24	Pneumatically Actuated Engine FeedValves
20	2	40	3-Way Solenoid Valves with vent ports
8	2	16	Engine TVC Hydraulic Actuators
4	1	4	Hydraulic Accumulator
4	2	8	Hydraulic Relief Valves
4	3	12	Low pressure pump and recirc chamber
4	3	12	High Pressure Pump
174	80	391	

TOTAL PROPULSION SYSTEM COMPONENT COUNT = 211

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

COMPLEXITY RATING FOR TOTAL # OF COMPONENTS = 466
COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE = 75
COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS = 108

# OF SUBSYSTEMS	*DESCRIPTION*
	RETURN LANDER
1	Tank Pressurization
1	Tanks and Feed System
1	Thermal Control -Electrical Heaters
1	Main Engines
4	
	LANDER STAGE
1	LH2 Tank Pressurant Regulation/Autogenous PressSystem
1	LO2 Tank Pressurant Regulation System
1	Pneumatic Pressurant Regulation and Pressurization System
1	Tank Vent Control System
1	LH2 Tank Propellant Gaging Systems
1	Tanks and Feed System
1	Main Engine System (includes actuator and throttling systems
7	

11 TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	*DESCRIPTION*
	RETURN LANDER
5	Temperature Transducers
9	Pressure Transducers
48	Valve Position Indicators (2 per Prop Feed Valve only)
62	
	LANDER LANDER
	Pressurization/Feed/Vent Systems
11	Temperature Transducers
9	Pressure Transducers
24	Valve Position Indicators (2 per prop prevalve and f/d)
24	Liquid level sensors (3 per tank)
64	
	Engine Systems
16	Temperature Transducers
36	Pressure Transducers
4	Tachometers
8	Thrust Control Indicators (2 per TC)
32	Valve Position Indicators (2 per valve)
96	
222	TOTAL INSTRUMENT LOCATIONS COUNT

A13.5 VEHICLE METRICS

99.6 mt	Post TLI Mass
189.4 m3	Propellant Volume (m^3)
-16.4 mt	Δ Habitat - Return Stage Mass
8.4 m	CG HEIGHT @ TD

A13.6 HARDWARE READINESS (HR)

TRL	*X*	*DIFFICULTY*	*=*	*HR*	
					RETURN STAGE
6		.8		4.8	Engines
7		1		7	Tanks/Press/Feed
7		1		7	Thermal Management
9		1		9	Propellant
					LANDER STAGE
7		1		7	Engines
7		1		7	Tanks/Press/Feed
7		1		7	Thermal Management
9		1		9	Propellant

A13.7 EVOLUTION

LONGER STAY TIME	significant modifications
LARGER PAYLOADS	None
INSITU RESOURCE UTILIZATION	Yes, use LO2 from lunar soil
PROPELLANT BOILOFF UTILIZATION	Use for power or eclss
MARS COMMONALITY	none, low performance, large aeroshell required.

TRADE #14
OPTIMIZED IME STAGE 1/2

A14.1 GROUND SUPPORTABILITY

RETURN STAGE Launch Operability Index
#1 Comprartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LH2, LO2 (4)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launch Site Installation Clearing Required (4)
#7 All EMA(8)
#8 No Heatshield (10)
#9 No Pneumatic System (10)
#10 Differential Throttling - Fixed Main Engines(10)
#11 Multi-Fluid LH2/LO2 T-0 Interface, No Leakage, Retract At Commit(2)
#12 Autogenous - Closed Loop Flow Control Valve (5.5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Dynamic Seals Used (3)
#16 Return Stage fully integrated into Lander Stage, RCS integrated (10)
#17 Special GSE With Maintenance Required(3)
#18 Same Engine System as Lander (10)
RETURN LOI=.78

LANDER STAGE Launch Operability Index
#1 Comprartment Completely Closed, Panel Access (3)
#2 Functional Checks Automated, Leak Checks Manual (1.5)
#3 LH2, LO2 (4)
#4 Expendable (10)
#5 No Auxiliary Propulsion (10)
#6 Ordance Multiple Launc Site Installation Clearing Required (4)
#7 All EMA(8)
#8 No Heatshield (10)
#9 No Pneumatic System (10)
#10 Differential Throttling - Fixed Main Engines(10)
#11 Multi-Fluid LH2/LO2 T-0 Interface, No Leakage, Retract At Commit2)
#12 Autogenous - Closed Loop Flow Control Valve (5.5)
#13 No Preconditioning Required (10)
#14 Access without Removal Of Others, Some Support Equip (7)
#15 Extensive Use Of Static Seals In All Fluid Systems, Few Dynamic Seals Used (3)
#16 Integration of power and RCS (7)
#17 Special GSE With Maintenance Required(3)
#18 Pump fed cryogenic engine (4.5)
LANDER LOI= .59

A14.2 FLIGHT OPERABILITY

# OF ABORT OPERATIONS	*WORST CASE SCENARIO*
1	Isolate Landing Stage Prop Tanks
1	Separate From Landing Stage Prop Tanks
1	Open Tank Iso Valves
1	Open Pump Iso Valves
1	Open Manifold Iso Valves
1	Open Engine Valves
1	Fire Igniter
1	Open Autogeneous Pressurization Valves
8	TOTAL NUMBER OF ABORT OPERATIONS

# OF FLIGHT OPERATIONS	*NOMINAL SCENARIO*
	TRANSIT TO MOON FLIGHT OPERATIONS
20	Transit Thermal Vent Activities (10 times)
11	Mid-Course Correction
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves
	• Fire Igniter
	• Open Autogenous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close Autogenous Pressuirzation Valves
11	LOI Burn
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves
	• Fire Igniter
	• Open Autogenous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close Autogenous Pressuirzation Valves
11	Descent Burn
	• Open Tank Iso Valves
	• Open Pump Iso Valves
	• Open Manifold Iso Valves
	• Open Engine Valves
	• Fire Igniter
	• Open Autogenous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close Autogenous Pressuirzation Valves
	LUNAR RETURN STAGE OPS
11	Ascent Burn
	• Isolate Landing Stage Prop Tanks
	• Separate From Landing Stage Prop Tanks
	• Open Manifold Iso Valves
	• Open Engine Valves
	• Fire Igniter
	• Open Autogenous Pressurization Valves
	• Close Engine Valves
	• Close Tank Iso Valves
	• Close Pump Iso Valves
	• Close Manifold Iso Valves
	• Close Autogenous Pressuirzation Valves
11	TEI Burn
	• Isolate Landing Stage Prop Tanks
	• Separate From Landing Stage Prop Tanks
	• Open Manifold Iso Valves
	• Open Engine Valves
	• Fire Igniter

- Open Autogenous Pressurization Valves
- Close Engine Valves
- Close Tank Iso Valves
- Close Pump Iso Valves
- Close Manifold Iso Valves
- Close Autogenous Pressuirzation Valves

11 Mid-Course Correction

- Open Tank Iso Valves
- Open Pump Iso Valves
- Open Manifold Iso Valves
- Open Engine Valves
- Fire Igniter
- Open Autogenous Pressurization Valves
- Close Engine Valves
- Close Tank Iso Valves
- Close Pump Iso Valves
- Close Manifold Iso Valves
- Close Autogenous Pressuirzation Valves

86 TOTAL NUMBER OF FLIGHT OPERATIONS

# OF LUNAR OPERATIONS	*NOMINAL SCENARIO*
	LANDER STAGE PROPULSION SYSTEM
1	Bleed off LO2 Residuals
1	Bleed off LH2 Residuals
1	Isolate Lander Stage Propellant Tanks
1	Separate From Lander Stage Propellant Tanks
4	
	RETURN STAGE PROPULSION SYSTEM
1	Safe Return Stage For Lunar Stay
22	Lunar Surface Thermal Vent Activities
23	
27	TOTAL NUMBER OF LUNAR OPERATIONS

A14.3 VEHICLE DESIGN ISSUES

INHERENT REDUNDANCY	Return and Lander Stages: Single fault tolerant for feed system component failure. Engine structural failure not credible. One Fault Tolerant Post Abort
ABORT REACTION TIME	1.5 to 2.0 seconds for pump ramping 2.4 sec max. to switch from descent tank to ascent tank.
STAGE SEPARATION	Descent tank seperation is required. Landing gear is also dropped during ascent.
DEBRIS DAMAGE IMMUNITY	Damage to Lander Stage does affect Return Stage propulsion system. (May remove engine-out capability for ascent)
Lunar Leakage Potential	LH2, Not hermetically sealed

A14.4 COMPLEXITY

# OF COMPONENTS	*COMPLEXITY CATEGORY*	*# x Cat*	*DESCRIPTION*
			COMMON COMPONENTS
4	2	8	Autogenous Pressurization System Solenoid Valves
2	2	4	LH2 Fill and Drain Pneumatic Valves
2	2	4	LO2 Fill and Drain Pneumatic Valves
1	3	3	LH2 T-0 Disconnect
1	3	3	LO2 T-0 Disconnect
4	3	12	Engine Chambers
16	2	32	Engine Solenoid Valves
16	2	32	Engine Throtlle Valves
4	2	8	Igniters
4	2	8	Turbo-Pumps
4	2	8	Turbo-Pump Isolation Valves
4	2	8	Manifold Isolation Valves
2	2	4	Gaseous Cryo Three Way Valves
6	2	12	Gaseous Cryo Solenoid Valves
4	2	8	Modulating Valves
74	33	154	
	LANDER STAGE COMPONENTS		
6	3	18	LH2 Tanks
2	3	6	LO2 Tanks
4	2	8	Tank Iso Valves (normally open)
2	2	4	Tank iso Valve (normally closed)
4	2	8	Tank Separation mechanism
8	2	16	Tank Solenoid Vent Valves
6	2	12	Autogenous Press. System Solenoid Valves
2	2	4	Tank Press System EMA valves (normally open)
2	2	4	Burst discs/Relief Valves
36	20	80	
	RETURN STAGE COMPONENTS		
1	3	3	LH2 Tanks
1	3	3	LO2 Tanks
4	2	8	Tank iso Valve (normally closed)
8	2	16	Tank Solenoid Vent Valves
4	2	8	Autogenous Press. System Solenoid Valves
2	2	4	Burst discs/Relief Valves
20	14	42	

TOTAL PROPULSION SYSTEM COMPONENT COUNT = 130

COMPLEXITY RATING = (Category #1 Count) X 1 + (Category #2 Count) X 2 + (Category #3 Count) X 3

COMPLEXITY RATING FOR TOTAL # OF COMPONENTS = 276
COMPLEXITY RATING FOR # OF ACTIVE RETURN STAGE = 154
COMPLEXITY RATING FOR # OF UNIQUE COMPONENTS = 67

# OF SUBSYSTEMS	*DESCRIPTION*
	STAGE MAIN PROPULSION
1	LH2 Tank Autogenous Pressurization System
1	LO2 Tank Pressurant Regulation System
1	Tank Vent Control System
1	Tanks and Feed System
1	Turbo-pump System
1	Main Engine System
6	
6	TOTAL PROPULSION SUBSYSTEM COUNT

# OF INSTRUMENTATION LOCATIONS	DESCRIPTION
	COMMON SYSTEMS
8	Temperature Transducers
14	Pressure Transducers
4	Tachometers
36	Valve Position Indicators (2 per valve)
62	
	ENGINE SYSTEMS
8	Temperature Transducers
4	Pressure Transducers
16	Thrust Control Indicators
32	Valve Position Indicators (2 per valve)
60	
	LANDER STAGE PROPULSION SYSTEM
8	Temperature Transducers
4	Pressure Transducers
44	Valve Position Indicators
56	
	RETURN STAGE PROPULSION SYSTEM
2	Temperature Transducers
4	Pressure Transducers
32	Valve Position Indicators
38	
216	TOTAL INSTRUMENT LOCATIONS COUNT

A14.5 VEHICLE METRICS

67.9 mt	Post TLI Mass
121.7 m^3	Propellant Volume
8.4 mt	Δ Habitat - Return Stage Mass
5.9 m	CG HEIGHT @ TD

A14.6 HARDWARE READINESS (HR)

TRL	X DIFFICULTY	= HR	
			RETURN STAGE
4	0.7	2.8	Engines/Press/Feed
7	1	7	Tanks
6	1	6	Thermal Management
9	1	9	Propellant
			LANDER STAGE
9	1	9	Engines (Credited with 9 since already accounted with Return stage engines)
9	1	9	Tanks/Press/Feed (Credited with 9 since already accounted with Return stage

A14.7 EVOLUTION

LONGER STAY TIME	Requires mods for 6 months, Category 5
LARGER PAYLOADS	Yes
INSITU RESOURCE UTILIZATION	Yes, Use Lunar soil to make LO2
PROPELLANT BOILOFF UTILIZATION	Yes, Use for power, eclss
MARS COMMONALITY	High performance, but high boiloff in mars atmosphere, and large aeroshell required

APPENDIX B

This appendix contains the listing of the computer model used to calculate the performance parameters utilized in the trade study. The commercial software, *TK Solver*, was used to run the performance computer model. The detailed output data sheets for each of the 14 trade study propulsion systems is presented in order following the performance model listing. The detailed output data sheets contain the general and specific inputs and outputs for each trade.

APPENDIX B
PERFORMANCE MODEL

TWO STAGE PERFORMANCE MODEL (TK SOLVER SOFTWARE)

RULES

```
"---DESCENT STAGE MASS BREAKDOWN---
PRPSYS1=FESYS1+TNKST1+TNKS1+ENGS1+PTNK1+73
TNKST1=.3*TNKS1
SPPT1=STRUCT1+PROT1+POWER1+AV1+LGEAR
LGEAR=(VEHCL-MBURN1-BOIL1)*.03
PSYS1=PTNK1+HEMASS1
GROWTH1=GROWTH%*(PRPSYS1+SPPT1)
STAGE1=PRPSYS1+SPPT1+GROWTH1+FLUIDS1+HEMASS1+200

"---ASCENT STAGE MASS BREAKDOWN---
PRPSYS2=FESYS2+TNKST2+TNKS2+ENGS2+PTNK2
TNKST2=.3*TNKS2
SPPT2=STRUCT2+PROT2+POWER2+AV2+ECLSS
PSYS2=PTNK2+HEMASS2
GROWTH2=GROWTH%*(PRPSYS2+SPPT2)
STAGE2=PRPSYS2+SPPT2+GROWTH2+FLUIDS2+HEMASS2+CREWMOD

"---PROPELLANT STUFF---
PROP1=MBURN1+RESID1
PROP2=MBURN2+RESID2
RESID1=MBURN1*RESERVE
RESID2=MBURN2*RESERVE
TOTPROP=FU1+FU2+OX1+OX2

"---BOILOFF STUFF---
BOILFU1=54509*4*NFUTNK1*1.3*ATOTFU1/FUVAP1
BOILOX1=54509*4*NOXTNK1*1.3*ATOTOX1/OXVAP1
BOIL1=BOILFU1+BOILOX1
BOILFU2=HTRATEF*STIME*NFUTNK2*1.3*ATOTFU2/FUVAP2
BOILOX2=HTRATEO*STIME*NOXTNK2*1.3*ATOTOX2/OXVAP2
BOIL2=BOILFU2+BOILOX2

"---ROCKET EQUATION STUFF---
EXP(DELV1/(ISP1*G))=(FU1+OX1-
BOIL1+STAGE1+STAGE2+PAYLOAD+FU2+OX2)/(STAGE1+STAGE2+PAYLOAD+FU1+OX1-BOIL1-
MBURN1+FU2+OX2)
EXP(DELV2/(ISP2*G))=(FU2+OX2-BOIL2+STAGE2+RETCARGO)/(STAGE2+RETCARGO+FU2+OX2-
BOIL2-MBURN2)

"---VEHICHLE CALC
VEHCL=STAGE1+STAGE2+PAYLOAD+TOTPROP

"---DESCENT TANKS---
FU1=PROP1/(1+MR1)+BOILFU1+APRSFU1
OX1=PROP1*MR1/(MR1+1)+BOILOX1
CALL PROPTNK(FU1,FURAD1,FURHO1,PPRES1,NFUTNK1,METSIG1,METRHO1,TMIN1;FUVOL1,
                LENFU1,ATOTFU1,FUTNK1,FUTNKV1)
CALL PROPTNK(OX1,OXRAD1,OXRHO1,PPRES1,NOXTNK1,METSIG1,METRHO1,TMIN1;OXVOL1,
                LENOX1,ATOTOX1,OXTNK1,OXTNKV1)
MLI1=(NOXTNK1*ATOTOX1*.493)+(NFUTNK1*ATOTFU1*.766)
TNKS1=(OXTNK1*NOXTNK1)+(FUTNK1*NFUTNK1)+MLI1

"---ASCENT TANKS---
FU2=PROP2/(1+MR2)+BOILFU2
OX2=PROP2*MR2/(MR2+1)+BOILOX2
```

APPENDIX B
PERFORMANCE MODEL

```
CALL OTNK(FU2,FURAD2,FURHO2,PPRES2,NFUTNK2,METSIG2,METRHO2;FUVOL2,LENFU2,
          ATOTFU2,FUTNK2,FUTNKV2)
CALL OTNK(OX2,OXRAD2,OXRHO2,PPRES2,NOXTNK2,METSIG2,METRHO2;OXVOL2,LENOX2,
          ATOTOX2,OXTNK2,OXTNKV2)
MLI2=0
TNKS2=(OXTNK2*NOXTNK2)+(FUTNK2*NFUTNK2)+MLI2

"---PRESSURIZATION STUFF
CALL PRESS(FUVOL1,OXVOL1,PPRES1,.1,TEMPFU1,TEMPOX1;PTNK1,HEMASS1)
CALL PRESS(FUVOL2,OXVOL2,PPRES2,1,TEMPFU2,TEMPOX2;PTNK2,HEMASS2)
CALL AUTOPRS(FUTNKV1,2,PPRES1,TEMPFU1,NFUTNK1;APRSFU1)

"---STRUCTURE CALCS
CALL STRUCT(LENFU1, LENOX1, DIA1;STRUCT1)
CALL STRUCT(LENFU2, LENOX2, DIA2;STRUCT2)
```

SUBROUTINES (Procedures)

PROPTNK	Procedure	8;5	PROPTNK - CALCS TANK STUFF
PRESS	Procedure	6;2	PRESS - PRESSURIZATION STUFF
STRUCT	Procedure	3;1	STRUC - STRUCTURE ESTIMATOR
AUTOPRS	Procedure	5;1	AUTOPRS - AUTOGENOUS STUFF
OTNK	Procedure	7;5	OTNK - CALCS O-WRAP TANK STUFF

PROCEDURE: **PROPTNK - CALCS TANK STUFF**

Parameter Variables:	G
Input Variables:	PROP,TNKRAD,PROPRHO,PPRES,NUMTNKS,METSIG,METRHO,TMIN
Output Variables:	PROPVOL,TNKLEN,ATOT,TNKMASS,TNKVOL

Statements:

```
"-------CONSTANTS
SF=1.9
ALRHO=METRHO
ALSIG=METSIG
ACCEL=4
KT=1.2

"---TANK CALCS
PROPVOL=PROP/PROPRHO
TNKVOL=PROPVOL*1.05/NUMTNKS
DOMVOL=(4*PI()*TNKRAD^3)/3
CYLLEN=(TNKVOL-DOMVOL)/(PI()*TNKRAD^2)
TNKLEN=2*TNKRAD+CYLLEN
TOTPRES=PPRES+PROPRHO*G*TNKLEN*ACCEL
TWALL=SF*TOTPRES*TNKRAD/ALSIG
TDOM=SF*TOTPRES*TNKRAD/(2*ALSIG)
IF TWALL<TMIN THEN TWALL=TMIN
IF TDOM<TMIN THEN TDOM=TMIN
ACYL=2*PI()*TNKRAD*CYLLEN
ADOM=4*PI()*TNKRAD^2
ATOT=ACYL+ADOM
MDOM=ADOM*TDOM*ALRHO
MCYL=ACYL*TWALL*ALRHO
TNKMASS=KT*(MDOM+MCYL)
```

PROCEDURE: **PRESS - PRESSURIZATION STUFF**
Parameter Variables:
Input Variables: FUVOL,OXVOL,PPRES,FACT,TEMPFU,TEMPOX
Output Variables: PTNK,HEMASS
Statements:

```
PROPVOL=(FACT*FUVOL+OXVOL)*1.05
TEND=300*(400/4000)^((1.66-1)/1.66)
HEMASSFU=PPRES*FUVOL*FACT/(TEMPFU*2077)
HEMASSOX=PPRES*OXVOL/(TEMPOX*2077)
RESIDHE=400*(PROPVOL/9)/(2077*TEND)
HEMASS=HEMASSFU+HEMASSOX+RESIDHE
VM3=HEMASS*300*2077/(2.75E7)
PTNK=1.5*(2.75E7*VM3)*4/1000000
```

PROCEDURE: **STRUC - STRUCTURE ESTIMATOR**
Parameter Variables:
Input Variables: LENFU,LENOX,DIA
Output Variables: STRUCT
Statements:

```
IF LENOX<LENFU THEN LEN=LENFU ELSE LEN=LENOX
AM2=PI()*DIA*LEN
MLB=1.27*(AM2*10.76)^1.1506
STRUCT=.45359*MLB
```

PROCEDURE: **AUTOPRS - AUTOGENOUS STUFF**
Parameter Variables:
Input Variables: TNKVOL,MW,TNKPRES,TEMP,NUMTNKS
Output Variables: PRESM
Statements:

```
M1=MW*TNKPRES*TNKVOL/(1.206*TEMP*6870)
PRESM=M1*NUMTNKS
```

PROCEDURE: **OTNK - CALCS O-WRAP TANK STUFF**
Parameter Variables: G
Input Variables: PROP,TNKRAD,PROPRHO,PPRES,NUMTNKS,METSIG,METRHO
Output Variables: PROPVOL,TNKLEN,ATOT,TNKMASS,TNKVOL
Statements:

```
"-------CONSTANTS
SF=1.9
ALRHO=METRHO
ALSIG=METSIG
ACCEL=4
KT=1.2
TMIN=.001143

"---TANK CALCS
PROPVOL=PROP/PROPRHO
TNKVOL=PROPVOL*1.05/NUMTNKS
DOMVOL=(4*PI()*TNKRAD^3)/3
CYLLEN=(TNKVOL-DOMVOL)/(PI()*TNKRAD^2)
TNKLEN=2*TNKRAD+CYLLEN
TOTPRES=PPRES+PROPRHO*G*TNKLEN*ACCEL
ACYL=2*PI()*TNKRAD*CYLLEN
ADOM=4*PI()*TNKRAD^2
ATOT=ACYL+ADOM
```

APPENDIX B
PERFORMANCE MODEL

```
LINMASS=ATOT*8.89E-4*ALRHO
IF TOTPRES*SF<5.5E6 THEN TOTPRES=5.5E6/SF
WMASS=TOTPRES*TNKVOL*SF*4.017/1.1E6
TNKMASS=LINMASS+WMASS
```

APPENDIX B
Trade #1 NTO/MMH

MMH/NTO PRESS TRADE #1
(O-WRAP TANKS FOR ASCENT)

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	45687.874	kg	DESCENT USED PROPELLANT MASS
	MBURN2	18378.824	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	150.24829	kg	DESCENT FUEL BOILOFF
	BOILOX1	103.79954	kg	DESCENT OX BOILOFF
	BOILFU2	.00342781	kg	ASCENT FUEL BOILOFF
	BOILOX2	.00252214	kg	ASCENT OX BOILOFF
	LGEAR	1515.8767	kg	LANDING GEAR MASS
	APRSFU1	427.83002	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICLE STUFF
	TOTPROP	66670.582	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	96471.144	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1			--DESCENT STAGE DIA--
6	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.25	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.25	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
258	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS

APPENDIX B
Trade #1 NTO/MMH

131	AV2	kg	ASCENT AVIONICS MASS
238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
320	ISP2	sec	ASCENT ISP
1.91	MR2		ASCENT MIXTURE RATIO
880	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1447	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
250	PPRES2	PSI	ASCENT PROP TANK PRESSURE
3.863	DIA2		--ASCENT STAGE DIA--
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
.75	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.8	OXRAD2	m	ASCENT OX TANK RAD
1.13E9	METSIG2		ASCENT TANK METAL SIGMA
4456	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.000635	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
300	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4760.9403	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	686.79037	kg	DESCENT TANK STRUCTURE
TNKS1	2289.3012	kg	DESCENT PROPELLANT TANKS
SPPT1	4738.1443	kg	DESCENT SUPPORT MASS
STRUCT1	2538.2676	kg	DESCENT STRUCTURE MASS
STAGE1	12794.638	kg	DESCENT STAGE MASS
GROWTH1	1899.8169	kg	DESCENT GROWTH BUDGET
PTNK1	544.84867	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	145.73602	kg	DESCENT HELIUM MASS
PSYS1	690.58469	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	1288.4248	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	164.4531	kg	ASCENT TANK STRUCTURE
TNKS2	548.177	kg	ASCENT PROPELLANT TANKS
HEMASS2	44.079259	kg	ASCENT HELIUM MASS
PTNK2	164.79472	kg	ASCENT PRESSURANT TANK MASS
PSYS2	208.87398	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2323.1125	kg	ASCENT SUPPORT
STRUCT2	507.11246	kg	ASCENT STRUCTURE MASS
STAGE2	12005.924	kg	ASCENT STAGE MASS
GROWTH2	722.30745	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1370.6362	kg	DESCENT RESIDUALS
PROP1	47058.51	kg	DESCENT TOTAL PROP
BOIL1	254.04784	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	551.36471	kg	ASCENT RESIDUALS
PROP2	18930.188	kg	ASCENT TOTAL PROP
BOIL2	.00594995	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #1 NTO/MMH

			---DESCENT TANKS---
FU1	7300.7226	kg	DESCENT FUEL MASS
OX1	40439.665	kg	DESCENT OX MASS
FUVOL1	103.11755	m^3	DESCENT FUEL VOLUME
OXVOL1	35.442301	m^3	DESCENT OX VOLUME
OXTNK1	363.62953	kg	DESCENT OX TANK MASS
FUTNK1	227.24224	kg	DESCENT FUEL TANK MASS
FUTNKV1	18.045571	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	18.607208	M^3	DESCENT OX TANK VOLUME
LENFU1	4.509547	m	DESCENT FUEL TANK LENGTH
ATOTFU1	35.417899	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.6239626	m	DESCENT OX TANK LENGTH
ATOTOX1	36.316518	m^2	DESCENT OX TANK AREA/TANK
MLI1	198.58875	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	6505.2228	kg	ASCENT FUEL MASS
OX2	12424.972	kg	ASCENT OX MASS
FUVOL2	7.3922987	m^3	ASCENT FUEL VOLUME
OXVOL2	8.5867115	m^3	ASCENT OX VOLUME
OXTNK2	145.80846	kg	ASCENT OX TANK MASS
FUTNK2	128.28004	kg	ASCENT FUEL TANK MASS
LENFU2	2.6961723	m	ASCENT FUEL TANK LENGTH
ATOTFU2	12.705414	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.7754403	m	ASCENT OX TANK LENGTH
ATOTOX2	13.950886	m^2	ASCENT OX TANK AREA/TANK
MLI2	0	kg	ASCENT MLI MASS
FUTNKV2	3.8809568	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	4.5080235	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #2 LOX/N2H4

LOX/N2H4 2-STAGE PRESS TRADE #2
(O-WRAP LOX, TI N2H4 ASCENT TANKS)

				---VARIABLS REQUIRING INITIAL GUESSES
	MBURN1	45002.286	kg	DESCENT USED PROPELLANT MASS
	MBURN2	16711.449	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	133.05216	kg	DESCENT FUEL BOILOFF
	BOILOX1	76.295498	kg	DESCENT OX BOILOFF
	BOILFU2	.00419835	kg	ASCENT FUEL BOILOFF
	BOILOX2	104.03918	kg	ASCENT OX BOILOFF
	LGEAR	1493.1296	kg	LANDING GEAR MASS
	APRSFU1	420.47995	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	64299.019	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	94982.619	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
1	NOXTNK1			DESCENT NUMBER OF OX TANKS
2	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
258	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #2 LOX/N2H4

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
348	ISP2	sec	ASCENT ISP
.77	MR2		ASCENT MIXTURE RATIO
1031	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
250	PPRES2	PSI	ASCENT PROP TANK PRESSURE
3.863	DIA2	m	--ASCENT STAGE DIA
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
.75	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.8	OXRAD2	m	ASCENT OX TANK RAD
1.13E9	METSIG2		ASCENT TANK METAL SIGMA
4456	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.000635	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

---DESCENT STAGE BREAKDOWN (1)

PRPSYS1	4568.0933	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	644.3621	kg	DESCENT TANK STRUCTURE
TNKS1	2147.8737	kg	DESCENT PROPELLANT TANKS
SPPT1	5306.3278	kg	DESCENT SUPPORT MASS
STRUCT1	3129.1982	kg	DESCENT STRUCTURE MASS
STAGE1	13242.636	kg	DESCENT STAGE MASS
GROWTH1	1974.8842	kg	DESCENT GROWTH BUDGET
PTNK1	535.85756	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	143.33108	kg	DESCENT HELIUM MASS
PSYS1	679.18864	kg	DESCENT PRESSURIZATION SYSTEM MASS

---ASCENT STAGE BREAKDOWN (2)

PRPSYS2	1503.3281	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	177.42272	kg	ASCENT TANK STRUCTURE
TNKS2	591.40908	kg	ASCENT PROPELLANT TANKS
HEMASS2	86.528734	kg	ASCENT HELIUM MASS
PTNK2	323.49632	kg	ASCENT PRESSURANT TANK MASS
PSYS2	410.02506	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2435.3683	kg	ASCENT SUPPORT
STRUCT2	619.36829	kg	ASCENT STRUCTURE MASS
STAGE2	12440.964	kg	ASCENT STAGE MASS
GROWTH2	787.73928	kg	ASCENT GROWTH BUDGET

---DESCENT PROPELLANT STUFF

RESID1	1350.0686	kg	DESCENT RESIDUALS
PROP1	46352.355	kg	DESCENT TOTAL PROP
BOIL1	209.34766	kg	DESCENT PROP BOILOFF

---ASCENT PROPELLANT STUFF

RESID2	501.34348	kg	ASCENT RESIDUALS
PROP2	17212.793	kg	ASCENT TOTAL PROP
BOIL2	104.04338	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #2 LOX/N2H4

			---DESCENT TANKS---
FU1	7175.2971	kg	DESCENT FUEL MASS
OX1	39806.885	kg	DESCENT OX MASS
FUVOL1	101.346	m^3	DESCENT FUEL VOLUME
OXVOL1	34.887717	m^3	DESCENT OX VOLUME
OXTNK1	601.4124	kg	DESCENT OX TANK MASS
FUTNK1	343.99779	kg	DESCENT FUEL TANK MASS
FUTNKV1	26.603326	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	36.632103	M^3	DESCENT OX TANK VOLUME
LENFU1	5.5464207	m	DESCENT FUEL TANK LENGTH
ATOTFU1	47.046405	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.2484235	m	DESCENT OX TANK LENGTH
ATOTOX1	53.387264	m^2	DESCENT OX TANK AREA/TANK
MLI1	170.47011	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	9724.7459	kg	ASCENT FUEL MASS
OX2	7592.0903	kg	ASCENT OX MASS
FUVOL2	9.4323433	m^3	ASCENT FUEL VOLUME
OXVOL2	6.6538916	m^3	ASCENT OX VOLUME
OXTNK2	115.37826	kg	ASCENT OX TANK MASS
FUTNK2	150.22741	kg	ASCENT FUEL TANK MASS
LENFU2	3.3022476	m	ASCENT FUEL TANK LENGTH
ATOTFU2	15.561473	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.2707548	m	ASCENT OX TANK LENGTH
ATOTOX2	11.414058	m^2	ASCENT OX TANK AREA/TANK
MLI2	60.197744	kg	ASCENT MLI MASS
FUTNKV2	4.9519802	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	3.4932931	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #3 ClF5/N2H4

ClF5/N2H4 PRESS TRADE #3

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	41305.216	kg	DESCENT USED PROPELLANT MASS
	MBURN2	14894.951	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	123.92497	kg	DESCENT FUEL BOILOFF
	BOILOX1	71.997319	kg	DESCENT OX BOILOFF
	BOILFU2	.00223418	kg	ASCENT FUEL BOILOFF
	BOILOX2	.00190672	kg	ASCENT OX BOILOFF
	LGEAR	1370.4646	kg	LANDING GEAR MASS
	APRSFU1	386.04855	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	58468.147	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	87183.291	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
1	NOXTNK1			DESCENT NUMBER OF OX TANKS
2	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
150	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #3 ClF5/N2H4

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
353	ISP2	sec	ASCENT ISP
2.5	MR2		ASCENT MIXTURE R ATIO
1031	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1793	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
350	PPRES2	PSI	ASCENT PROP TANK PRESSURE
4.2	DIA2	m	--ASCENT STAGE DIA--
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
.77	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.87	OXRAD2	m	ASCENT OX TANK RAD
3.1E8	METSIG2		ASCENT TANK METAL SIGMA
2710	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
300	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4245.1627	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	579.97784	kg	DESCENT TANK STRUCTURE
TNKS1	1933.2595	kg	DESCENT PROPELLANT TANKS
SPPT1	4937.9781	kg	DESCENT SUPPORT MASS
STRUCT1	2883.5135	kg	DESCENT STRUCTURE MASS
STAGE1	12401.349	kg	DESCENT STAGE MASS
GROWTH1	1836.6282	kg	DESCENT GROWTH BUDGET
PTNK1	491.92537	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	131.5801	kg	DESCENT HELIUM MASS
PSYS1	623.50548	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	854.68615	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	92.782671	kg	ASCENT TANK STRUCTURE
TNKS2	309.27557	kg	ASCENT PROPELLANT TANKS
HEMASS2	40.022444	kg	ASCENT HELIUM MASS
PTNK2	149.62791	kg	ASCENT PRESSURANT TANK MASS
PSYS2	189.65035	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2183.4575	kg	ASCENT SUPPORT
STRUCT2	367.45753	kg	ASCENT STRUCTURE MASS
STAGE2	11313.795	kg	ASCENT STAGE MASS
GROWTH2	607.62874	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1239.1565	kg	DESCENT RESIDUALS
PROP1	42544.373	kg	DESCENT TOTAL PROP
BOIL1	195.92229	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	446.84853	kg	ASCENT RESIDUALS
PROP2	15341.8	kg	ASCENT TOTAL PROP
BOIL2	.0041409	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #3 ClF5/N2H4

			---DESCENT TANKS---
FU1	6587.741	kg	DESCENT FUEL MASS
OX1	36538.602	kg	DESCENT OX MASS
FUVOL1	93.04719	m^3	DESCENT FUEL VOLUME
OXVOL1	32.023315	m^3	DESCENT OX VOLUME
OXTNK1	526.60886	kg	DESCENT OX TANK MASS
FUTNK1	311.88794	kg	DESCENT FUEL TANK MASS
FUTNKV1	24.424887	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	33.624481	M^3	DESCENT OX TANK VOLUME
LENFU1	5.1659441	m	DESCENT FUEL TANK LENGTH
ATOTFU1	43.819088	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.0090845	m	DESCENT OX TANK LENGTH
ATOTOX1	50.379641	m^2	DESCENT OX TANK AREA/TANK
MLI1	159.09885	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	4383.3736	kg	ASCENT FUEL MASS
OX2	10958.43	kg	ASCENT OX MASS
FUVOL2	4.2515748	m^3	ASCENT FUEL VOLUME
OXVOL2	6.1117849	m^3	ASCENT OX VOLUME
OXTNK2	89.855694	kg	ASCENT OX TANK MASS
FUTNK2	64.782091	kg	ASCENT FUEL TANK MASS
LENFU2	1.7116671	m	ASCENT FUEL TANK LENGTH
ATOTFU2	8.2811346	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	1.9293946	m	ASCENT OX TANK LENGTH
ATOTOX2	10.546786	m^2	ASCENT OX TANK AREA/TANK
MLI2	0	kg	ASCENT MLI MASS
FUTNKV2	2.2320767	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	3.208687	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #4 NTO/MMH HI-EFF

M20/NTO 2 STAGE PRESS TRADE #4
(O-WRAP ASCENT TANKS)

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	44632.53	kg	DESCENT USED PROPELLANT MASS
	MBURN2	17134.78	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	132.13932	kg	DESCENT FUEL BOILOFF
	BOILOX1	75.865624	kg	DESCENT OX BOILOFF
	BOILFU2	.00163958	kg	ASCENT FUEL BOILOFF
	BOILOX2	.00213666	kg	ASCENT OX BOILOFF
	LGEAR	1480.8615	kg	LANDING GEAR MASS
	APRSFU1	417.03636	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	64245.375	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	94202.584	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
1	NOXTNK1			DESCENT NUMBER OF OX TANKS
2	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
130	FESYS2		kg	ASCENT FEED SYSTEM MASS
150	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #4 NTO/MMH HI-EFF

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
331	ISP2	sec	ASCENT ISP
1.33	MR2		ASCENT MIXTURE RATIO
976	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1447	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
350	PPRES2	PSI	ASCENT PROP TANK PRESSURE
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
3.863	DIA2	m	--ASCENT STAGE DIA--
.8	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.8	OXRAD2	m	ASCENT OX TANK RAD
1.13E9	METSIG2		ASCENT TANK METAL SIGMA
4456	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.000635	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
300	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
10002	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4535.6028	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	637.87821	kg	DESCENT TANK STRUCTURE
TNKS1	2126.2607	kg	DESCENT PROPELLANT TANKS
SPPT1	5269.3706	kg	DESCENT SUPPORT MASS
STRUCT1	3104.5092	kg	DESCENT STRUCTURE MASS
STAGE1	13158.124	kg	DESCENT STAGE MASS
GROWTH1	1960.9947	kg	DESCENT GROWTH BUDGET
PTNK1	531.4639	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	142.15586	kg	DESCENT HELIUM MASS
PSYS1	673.61976	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	1150.4719	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	151.82265	kg	ASCENT TANK STRUCTURE
TNKS2	506.07551	kg	ASCENT PROPELLANT TANKS
HEMASS2	56.859184	kg	ASCENT HELIUM MASS
PTNK2	212.57374	kg	ASCENT PRESSURANT TANK MASS
PSYS2	269.43293	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2278.0496	kg	ASCENT SUPPORT
STRUCT2	462.04956	kg	ASCENT STRUCTURE MASS
STAGE2	11799.085	kg	ASCENT STAGE MASS
GROWTH2	685.70429	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1338.9759	kg	DESCENT RESIDUALS
PROP1	45971.506	kg	DESCENT TOTAL PROP
BOIL1	208.00495	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	514.0434	kg	ASCENT RESIDUALS
PROP2	17648.823	kg	ASCENT TOTAL PROP
BOIL2	.00377623	kg	ASCENT PROP BOILOFF

			---DESCENT TANKS---
FU1	7116.5337	kg	DESCENT FUEL MASS
OX1	39480.014	kg	DESCENT OX MASS
FUVOL1	100.51601	m^3	DESCENT FUEL VOLUME
OXVOL1	34.601239	m^3	DESCENT OX VOLUME
OXTNK1	593.81542	kg	DESCENT OX TANK MASS
FUTNK1	340.77812	kg	DESCENT FUEL TANK MASS
FUTNKV1	26.385453	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	36.331301	M^3	DESCENT OX TANK VOLUME
LENFU1	5.508368	m	DESCENT FUEL TANK LENGTH
ATOTFU1	46.723631	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.2244864	m	DESCENT OX TANK LENGTH
ATOTOX1	53.086462	m^2	DESCENT OX TANK AREA/TANK
MLI1	169.33283	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	7574.6039	kg	ASCENT FUEL MASS
OX2	10074.223	kg	ASCENT OX MASS
FUVOL2	7.7608647	m^3	ASCENT FUEL VOLUME
OXVOL2	6.9621446	m^3	ASCENT OX VOLUME
OXTNK2	120.23138	kg	ASCENT OX TANK MASS
FUTNK2	132.80638	kg	ASCENT FUEL TANK MASS
LENFU2	2.5598005	m	ASCENT FUEL TANK LENGTH
ATOTFU2	12.86696	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.3512438	m	ASCENT OX TANK LENGTH
ATOTOX2	11.81864	m^2	ASCENT OX TANK AREA/TANK
MLI2	0	kg	ASCENT MLI MASS
FUTNKV2	4.074454	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	3.6551259	M^3	ASCENT OX TANK VOLUME

LOX/CH4 PRESS TRADE #5

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	47783.879	kg	DESCENT USED PROPELLANT MASS
	MBURN2	17812.893	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	139.91926	kg	DESCENT FUEL BOILOFF
	BOILOX1	104.21532	kg	DESCENT OX BOILOFF
	BOILFU2	86.075487	kg	ASCENT FUEL BOILOFF
	BOILOX2	150.1401	kg	ASCENT OX BOILOFF
	LGEAR	1585.42	kg	LANDING GEAR MASS
	APRSFU1	446.38537	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	68491.411	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	100875.35	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
258	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #5 LOX/CH4 PRESS

238	ECLSS		kg	ECLSS MASS
202	FLUIDS2		kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2		m/sec	ASCENT DELTA V
350	ISP2		sec	ASCENT ISP
2.77	MR2			ASCENT MIXTURE R ATIO
422	FURHO2		kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2		kg/m^3	ASCENT OXIDIZER DENSITY
250	PPRES2		PSI	ASCENT PROP TANK PRESSURE
5.31	DIA2		m	--ASCENT STAGE DIA--
2	NFUTNK2			ASCENT NUMBER FUEL TANKS
1.1	FURAD2		m	ASCENT FUEL TANK RAD
2	NOXTNK2			ASCENT NUMBER OX TANKS
1.1	OXRAD2		m	ASCENT OX TANK RAD
3.1E8	METSIG2			ASCENT TANK METAL SIGMA
2710	METRHO2		kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2		M	ASCENT TANK MINIMUM THICKNESS
510000	FUVAP2		J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2		J/kg	ASCENT OX LATENT HEAT OF VAP
111	TEMPFU2		DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2		DEG K	ASCENT OX TEMPERATURE
49	STIME		Day	STAYTIME
21176.7	HTRATEF			
14190.5	HTRATEO			
				---DESCENT STAGE BREAKDOWN (1)
	PRPSYS1	4906.1442	kg	DESCENT PROPULSION SYSTEM MASS
	TNKST1	714.71237	kg	DESCENT TANK STRUCTURE
	TNKS1	2382.3746	kg	DESCENT PROPELLANT TANKS
	SPPT1	5585.157	kg	DESCENT SUPPORT MASS
	STRUCT1	3315.737	kg	DESCENT STRUCTURE MASS
	STAGE1	13991.773	kg	DESCENT STAGE MASS
	GROWTH1	2098.2602	kg	DESCENT GROWTH BUDGET
	PTNK1	569.05724	kg	DESCENT PRESSURANT TANK MASS
	HEMASS1	152.21132	kg	DESCENT HELIUM MASS
	PSYS1	721.26857	kg	DESCENT PRESSURIZATION SYSTEM MASS
				--ASCENT STAGE BREAKDOWN (2)
	PRPSYS2	2210.327	kg	ASCENT PROPULTION SYSTEM MASS
	TNKST2	246.01329	kg	ASCENT TANK STRUCTURE
	TNKS2	820.04429	kg	ASCENT PROPELLANT TANKS
	HEMASS2	196.13476	kg	ASCENT HELIUM MASS
	PTNK2	733.26942	kg	ASCENT PRESSURANT TANK MASS
	PSYS2	929.40419	kg	ASCENT PRESSURIZATION SYSTEM MASS
	SPPT2	2429.6963	kg	ASCENT SUPPORT
	STRUCT2	613.69631	kg	ASCENT STRUCTURE MASS
	STAGE2	13392.163	kg	ASCENT STAGE MASS
	GROWTH2	928.00466	kg	ASCENT GROWTH BUDGET
				---DESCENT PROPELLANT STUFF
	RESID1	1433.5164	kg	DESCENT RESIDUALS
	PROP1	49217.396	kg	DESCENT TOTAL PROP
	BOIL1	244.13458	kg	DESCENT PROP BOILOFF
				---ASCENT PROPELLANT STUFF
	RESID2	534.38678	kg	ASCENT RESIDUALS
	PROP2	18347.279	kg	ASCENT TOTAL PROP
	BOIL2	236.21558	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #5 LOX/CH4 PRESS

			---DESCENT TANKS---
FU1	7617.3611	kg	DESCENT FUEL MASS
OX1	42290.554	kg	DESCENT OX MASS
FUVOL1	107.58985	m^3	DESCENT FUEL VOLUME
OXVOL1	37.064465	m^3	DESCENT OX VOLUME
OXTNK1	360.86141	kg	DESCENT OX TANK MASS
FUTNK1	368.27754	kg	DESCENT FUEL TANK MASS
FUTNKV1	28.242335	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	19.458844	M^3	DESCENT OX TANK VOLUME
LENFU1	5.8326828	m	DESCENT FUEL TANK LENGTH
ATOTFU1	49.474566	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.2985967	m	DESCENT OX TANK LENGTH
ATOTOX1	36.461987	m^2	DESCENT OX TANK AREA/TANK
MLI1	187.54159	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	4952.7278	kg	ASCENT FUEL MASS
OX2	13630.767	kg	ASCENT OX MASS
FUVOL2	11.736322	m^3	ASCENT FUEL VOLUME
OXVOL2	11.946334	m^3	ASCENT OX VOLUME
OXTNK2	165.6532	kg	ASCENT OX TANK MASS
FUTNK2	162.95574	kg	ASCENT FUEL TANK MASS
LENFU2	2.3542328	m	ASCENT FUEL TANK LENGTH
ATOTFU2	16.271289	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.3832375	m	ASCENT OX TANK LENGTH
ATOTOX2	16.471755	m^2	ASCENT OX TANK AREA/TANK
MLI2	162.82641	kg	ASCENT MLI MASS
FUTNKV2	6.161569	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	6.2718254	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #6 NTO/MMH, PUMP

MMH/NTO PUMP TRADE #6

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	43806.688	kg	DESCENT USED PROPELLANT MASS
	MBURN2	16269.779	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	130.10051	kg	DESCENT FUEL BOILOFF
	BOILOX1	97.360836	kg	DESCENT OX BOILOFF
	BOILFU2	.00380066	kg	ASCENT FUEL BOILOFF
	BOILOX2	.00185311	kg	ASCENT OX BOILOFF
	LGEAR	1453.4609	kg	LANDING GEAR MASS
	APRSFU1	409.34515	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	62515.574	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	92482.845	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
816	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #6 NTO/MMH, PUMP

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
344	ISP2	sec	ASCENT ISP
1.02	MR2		ASCENT MIXTURE R ATIO
880	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1447	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
50	PPRES2	PSI	ASCENT PROP TANK PRESSURE
4.828	DIA2	m	--ASCENT STAGE DIA--
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
1	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.85	OXRAD2	m	ASCENT OX TANK RAD
1.13E9	METSIG2		ASCENT TANK METAL SIGMA
4456	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.000635	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
300	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4551.6228	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	643.80881	kg	DESCENT TANK STRUCTURE
TNKS1	2146.0294	kg	DESCENT PROPELLANT TANKS
SPPT1	5186.9204	kg	DESCENT SUPPORT MASS
STRUCT1	3049.4595	kg	DESCENT STRUCTURE MASS
STAGE1	13075.819	kg	DESCENT STAGE MASS
GROWTH1	1947.7086	kg	DESCENT GROWTH BUDGET
PTNK1	521.78457	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	139.56684	kg	DESCENT HELIUM MASS
PSYS1	661.35141	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	1217.1173	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	49.984997	kg	ASCENT TANK STRUCTURE
TNKS2	166.61666	kg	ASCENT PROPELLANT TANKS
HEMASS2	8.4298034	kg	ASCENT HELIUM MASS
PTNK2	31.515663	kg	ASCENT PRESSURANT TANK MASS
PSYS2	39.945466	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2328.7348	kg	ASCENT SUPPORT
STRUCT2	512.73478	kg	ASCENT STRUCTURE MASS
STAGE2	11891.452	kg	ASCENT STAGE MASS
GROWTH2	709.17042	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1314.2006	kg	DESCENT RESIDUALS
PROP1	45120.889	kg	DESCENT TOTAL PROP
BOIL1	227.46135	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	488.09338	kg	ASCENT RESIDUALS
PROP2	16757.873	kg	ASCENT TOTAL PROP
BOIL2	.00565377	kg	ASCENT PROP BOILOFF

Trade #6 NTO/MMH, PUMP

			---DESCENT TANKS---
FU1	6985.2869	kg	DESCENT FUEL MASS
OX1	38772.408	kg	DESCENT OX MASS
FUVOL1	98.662245	m^3	DESCENT FUEL VOLUME
OXVOL1	33.981077	m^3	DESCENT OX VOLUME
OXTNK1	318.55771	kg	DESCENT OX TANK MASS
FUTNK1	333.59368	kg	DESCENT FUEL TANK MASS
FUTNKV1	25.898839	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	17.840065	M^3	DESCENT OX TANK VOLUME
LENFU1	5.4233781	m	DESCENT FUEL TANK LENGTH
ATOTFU1	46.002721	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.0158678	m	DESCENT OX TANK LENGTH
ATOTOX1	34.063796	m^2	DESCENT OX TANK AREA/TANK
MLI1	174.53924	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	8295.9804	kg	ASCENT FUEL MASS
OX2	8461.898	kg	ASCENT OX MASS
FUVOL2	9.4272505	m^3	ASCENT FUEL VOLUME
OXVOL2	5.8478908	m^3	ASCENT OX VOLUME
OXTNK2	34.879876	kg	ASCENT OX TANK MASS
FUTNK2	48.428452	kg	ASCENT FUEL TANK MASS
LENFU2	2.2420799	m	ASCENT FUEL TANK LENGTH
ATOTFU2	14.087403	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	1.9192712	m	ASCENT OX TANK LENGTH
ATOTOX2	10.250266	m^2	ASCENT OX TANK AREA/TANK
MLI2	0	kg	ASCENT MLI MASS
FUTNKV2	4.9493065	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	3.0701427	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #7 LOX/CH4, PUMP

LOX/CH4 2 STAGE PUMP TRADE #7

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	43755.936	kg	DESCENT USED PROPELLANT MASS
	MBURN2	15714.032	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	129.97522	kg	DESCENT FUEL BOILOFF
	BOILOX1	97.273366	kg	DESCENT OX BOILOFF
	BOILFU2	70.288148	kg	ASCENT FUEL BOILOFF
	BOILOX2	143.28634	kg	ASCENT OX BOILOFF
	LGEAR	1451.7769	kg	LANDING GEAR MASS
	APRSFU1	408.87249	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	62103.762	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	92375.749	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
581	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B

Trade #7 LOX/CH4, PUMP

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
358	ISP2	sec	ASCENT ISP
3.5	MR2		ASCENT MIXTURE RATIO
422	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
50	PPRES2	PSI	ASCENT PROP TANK PRESSURE
5.311	DIA2	m	--ASCENT STAGE DIA--
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
1	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
1.1	OXRAD2	m	ASCENT OX TANK RAD
3.1E8	METSIG2		ASCENT TANK METAL SIGMA
2710	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
511000	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
111	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4547.1333	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	642.912	kg	DESCENT TANK STRUCTURE
TNKS1	2143.04	kg	DESCENT PROPELLANT TANKS
SPPT1	5181.8576	kg	DESCENT SUPPORT MASS
STRUCT1	3046.0806	kg	DESCENT STRUCTURE MASS
STAGE1	13064.195	kg	DESCENT STAGE MASS
GROWTH1	1945.7982	kg	DESCENT GROWTH BUDGET
PTNK1	521.18133	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	139.40548	kg	DESCENT HELIUM MASS
PSYS1	660.58682	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	1391.0803	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	122.94341	kg	ASCENT TANK STRUCTURE
TNKS2	409.81138	kg	ASCENT PROPELLANT TANKS
HEMASS2	33.254566	kg	ASCENT HELIUM MASS
PTNK2	124.32552	kg	ASCENT PRESSURANT TANK MASS
PSYS2	157.58009	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2397.7009	kg	ASCENT SUPPORT
STRUCT2	581.70093	kg	ASCENT STRUCTURE MASS
STAGE2	12207.792	kg	ASCENT STAGE MASS
GROWTH2	757.75625	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1312.6781	kg	DESCENT RESIDUALS
PROP1	45068.614	kg	DESCENT TOTAL PROP
BOIL1	227.24858	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	471.42096	kg	ASCENT RESIDUALS
PROP2	16185.453	kg	ASCENT TOTAL PROP
BOIL2	213.57449	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #7 LOX/CH4, PUMP

			---DESCENT TANKS---
FU1	6977.2211	kg	DESCENT FUEL MASS
OX1	38727.514	kg	DESCENT OX MASS
FUVOL1	98.548321	m^3	DESCENT FUEL VOLUME
OXVOL1	33.94173	m^3	DESCENT OX VOLUME
OXTNK1	318.02844	kg	DESCENT OX TANK MASS
FUTNK1	333.15245	kg	DESCENT FUEL TANK MASS
FUTNKV1	25.868934	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	17.819408	M^3	DESCENT OX TANK VOLUME
LENFU1	5.418155	m	DESCENT FUEL TANK LENGTH
ATOTFU1	45.958417	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.01226	m	DESCENT OX TANK LENGTH
ATOTOX1	34.033193	m^2	DESCENT OX TANK AREA/TANK
MLI1	174.37332	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	3667.0555	kg	ASCENT FUEL MASS
OX2	12731.972	kg	ASCENT OX MASS
FUVOL2	8.6897049	m^3	ASCENT FUEL VOLUME
OXVOL2	11.158608	m^3	ASCENT OX VOLUME
OXTNK2	79.299291	kg	ASCENT OX TANK MASS
FUTNK2	53.080699	kg	ASCENT FUEL TANK MASS
LENFU2	2.1188266	m	ASCENT FUEL TANK LENGTH
ATOTFU2	13.31298	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.2744449	m	ASCENT OX TANK LENGTH
ATOTOX2	15.719835	m^2	ASCENT OX TANK AREA/TANK
MLI2	145.0514	kg	ASCENT MLI MASS
FUTNKV2	4.5620951	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	5.8582693	M^3	ASCENT OX TANK VOLUME

LOX/LH2 2 STAGE PUMP FED TRADE #8

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	44270.297	kg	DESCENT USED PROPELLANT MASS
	MBURN2	13672.666	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	131.24506	kg	DESCENT FUEL BOILOFF
	BOILOX1	98.159843	kg	DESCENT OX BOILOFF
	BOILFU2	301.64549	kg	ASCENT FUEL BOILOFF
	BOILOX2	110.48031	kg	ASCENT OX BOILOFF
	LGEAR	1468.8429	kg	LANDING GEAR MASS
	APRSFU1	413.66282	kg	AUTOGENOUS FU PRESSURE MASS
	APRSFU2	144.01163	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	60880.457	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	93461.133	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
294	FESYS2		kg	ASCENT FEED SYSTEM MASS
873	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS

APPENDIX B
Trade #8 LOX/LH2, PUMP

131	AV2		kg	ASCENT AVIONICS MASS
238	ECLSS		kg	ECLSS MASS
202	FLUIDS2		kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2		m/sec	ASCENT DELTA V
444	ISP2		sec	ASCENT ISP
6	MR2			ASCENT MIXTURE RATIO
70.8	FURHO2		kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2		kg/m^3	ASCENT OXIDIZER DENSITY
50	PPRES2		PSI	ASCENT PROP TANK PRESSURE
6.7	DIA2		m	--ASCENT STAGE DIA--
4	NFUTNK2			ASCENT NUMBER FUEL TANKS
1	FURAD2		m	ASCENT FUEL TANK RAD
1	NOXTNK2			ASCENT NUMBER OX TANKS
1.35	OXRAD2		m	ASCENT OX TANK RAD
3.1E8	METSIG2			ASCENT TANK METAL SIGMA
2710	METRHO2		kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2		M	ASCENT TANK MINIMUM THICKNESS
400900	FUVAP2		J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2		J/kg	ASCENT OX LATENT HEAT OF VAP
21	TEMPFU2		DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2		DEG K	ASCENT OX TEMPERATURE
49	STIME		Day	STAYTIME
21176.7	HTRATEF			
14190.5	HTRATEO			
				---DESCENT STAGE BREAKDOWN (1)
	PRPSYS1	4592.6727	kg	DESCENT PROPULSION SYSTEM MASS
	TNKST1	652.01023	kg	DESCENT TANK STRUCTURE
	TNKS1	2173.3674	kg	DESCENT PROPELLANT TANKS
	SPPT1	5233.1902	kg	DESCENT SUPPORT MASS
	STRUCT1	3080.3473	kg	DESCENT STRUCTURE MASS
	STAGE1	13182.076	kg	DESCENT STAGE MASS
	GROWTH1	1965.1726	kg	DESCENT GROWTH BUDGET
	PTNK1	527.29501	kg	DESCENT PRESSURANT TANK MASS
	HEMASS1	141.04077	kg	DESCENT HELIUM MASS
	PSYS1	668.33577	kg	DESCENT PRESSURIZATION SYSTEM MASS
				---ASCENT STAGE BREAKDOWN (2)
	PRPSYS2	2511.7952	kg	ASCENT PROPULTION SYSTEM MASS
	TNKST2	269.98196	kg	ASCENT TANK STRUCTURE
	TNKS2	899.93986	kg	ASCENT PROPELLANT TANKS
	HEMASS2	46.775107	kg	ASCENT HELIUM MASS
	PTNK2	174.87342	kg	ASCENT PRESSURANT TANK MASS
	PSYS2	221.64852	kg	ASCENT PRESSURIZATION SYSTEM MASS
	SPPT2	3091.392	kg	ASCENT SUPPORT
	STRUCT2	1275.392	kg	ASCENT STRUCTURE MASS
	STAGE2	14398.6	kg	ASCENT STAGE MASS
	GROWTH2	1120.6374	kg	ASCENT GROWTH BUDGET
				---DESCENT PROPELLANT STUFF
	RESID1	1328.1089	kg	DESCENT RESIDUALS
	PROP1	45598.406	kg	DESCENT TOTAL PROP
	BOIL1	229.4049	kg	DESCENT PROP BOILOFF
				---ASCENT PROPELLANT STUFF
	RESID2	410.17997	kg	ASCENT RESIDUALS
	PROP2	14082.846	kg	ASCENT TOTAL PROP
	BOIL2	412.1258	kg	ASCENT PROP BOILOFF

			---DESCENT TANKS---
FU1	7058.9659	kg	DESCENT FUEL MASS
OX1	39182.508	kg	DESCENT OX MASS
FUVOL1	99.702908	m^3	DESCENT FUEL VOLUME
OXVOL1	34.340498	m^3	DESCENT OX VOLUME
OXTNK1	323.40481	kg	DESCENT OX TANK MASS
FUTNK1	337.62573	kg	DESCENT FUEL TANK MASS
FUTNKV1	26.172013	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	18.028761	M^3	DESCENT OX TANK VOLUME
LENFU1	5.4710895	m	DESCENT FUEL TANK LENGTH
ATOTFU1	46.407423	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.0488247	m	DESCENT OX TANK LENGTH
ATOTOX1	34.343346	m^2	DESCENT OX TANK AREA/TANK
MLI1	176.05488	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	2457.4922	kg	ASCENT FUEL MASS
OX2	12181.491	kg	ASCENT OX MASS
FUVOL2	34.710342	m^3	ASCENT FUEL VOLUME
OXVOL2	10.676153	m^3	ASCENT OX VOLUME
OXTNK2	162.34107	kg	ASCENT OX TANK MASS
FUTNK2	116.10959	kg	ASCENT FUEL TANK MASS
LENFU2	3.566936	m	ASCENT FUEL TANK LENGTH
ATOTFU2	22.41172	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	2.8578828	m	ASCENT OX TANK LENGTH
ATOTOX2	24.24142	m^2	ASCENT OX TANK AREA/TANK
MLI2	273.16044	kg	ASCENT MLI MASS
FUTNKV2	9.1114648	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	11.209961	M^3	ASCENT OX TANK VOLUME

SINGLE STAGE PERFORMANCE MODEL-TRADE #9
(with 4 RL-10A-4 Engines)

- NON-STACKED DESCENT TANKS
- STACKED ASCENT TANKS
- SEPERATE ASCENT/DESCENT TANKS

				----VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	47141.272	kg	PROPELLANT MASS FOR 1ST BURN (GUESS)
	MBURN2	20864.882	kg	PROPELLANT MASS FOR 2ND BURN (GUESS)
	BOIL1	260.28107	kg	MASS OF DESCENT PROP BOILED OFF (GUESS
	BOIL2	370.92332	kg	MASS OF ASCENT PROP BOILED OFF (GUESS)
	VOLPOX1	1.7460658	m^3	DESCENT VOLUME OF OX He PRES (GUESS)
	VOLPFU1	.50576301	m^3	DESCENT VOLUME OF FU He PRES (GUESS)
	VOLPOX2	.77984653	m^3	ASCENT VOLUME OF OX He PRES (GUESS)
	VOLPFU2	.50576301	m^3	ASCENT VOLUME OF FU He PRES (GUESS)
	LGEAR	1607.5227	kg	MASS OF LANDING GEAR
	H2AUTO1	443.92618		MASS OF DESCENT AUTOGENOUS H2
	H2AUTO2	201.75431		MASS OF ASCENT AUTOGENOUS H2
				----TOTAL VEHICLE CALC----
	VEHCL	101429.57	kg	TOTAL VEHICLE MASS
	PROPVOL	221.57094	m^3	TOTAL VEHICLE PROP & HE VOLUME
	THROTTL	5.3229283		THROTTLING RANGE REQUIRED TO HOVER
	MFRAC	.76408346		VEHICLE MASS FRACTION
370107	THRUST		N	TOTAL STAGE ENGINE THRUST
	TWDESCE	.69829556		DESCENT FINAL VEH THRUST TO WEIGHT
	TWASCEN	.85469218		ASCENT THRUST TO WEIGHT RATIO
	TWDMOON	2.2554217		DESCENT LUNAR THRUST TO WEIGHT RATIO
	TWAMOON	5.1692542		ASCENT LUNAR THRUST TO WEIGHT RATIO
				----TOTAL STAGE MASS BREAKDOWN----
	PROPSYS	6461.4756	kg	DRY MASS OF PROPULSION SYSTEM
	TOTTNKS	3267.1632	kg	TOTAL PROP TANK MASS
	TNKSTRU	980.14895	kg	TANK SUPPORT STRUCTURAL MASS
	OXTANKS	730.14445	kg	DRY MASS OF ALL OX TANKS
	FUELTAN	2089.8704	kg	DRY MASS OF ALL FUEL TANKS
	PRESSYS	587.98834	kg	DRY MASS OF HE PRESSURANT SYSTEM
	HELIUM	189.17516	kg	MASS OF HE PRESSURANT
	TOTPROP	71323.223	kg	TOTAL PROPELLANT MASS
	SUPPORT	7397.1445	kg	DRY MASS OF STAGE SUPPORT
	STAGE	24056.344	kg	DRY MASS OF STAGE W/ CREW MODULE
	STAGE1	25106.344	kg	MASS OF STAGE W/ FLUID1
	LANDMAS	53584.088	kg	MASS OF VEHICLE AFTER LANDING
	STAGE2	22650.821	kg	MASS OF STAGE W/ FLUID 2
	GROWTH	2771.724	kg	GROWTH BUDGET MASS
				----STAGE STRUCTURE CALCULATIONS----
4.7	DIASTAG		m	DESCENT STAGE MAX DIAMETER
	LENCYL1	4.7125112	m	LENGTH OF DESCENT CYLIND
	ASURF1	139.16503	m^2	SURFACE AREA OF DESCENT STAGE
	ASURF2	51.254858	m^2	SURFACE AREA OF ASCENT TANKS
	ASURFTO	190.41989	m^2	TOTAL VEHICLE SIDEWALL SURFACE
'MAN	DESIGN1			INPUT 'UNMAN or'MAN FOR DESCNT STRUCT
'MAN	DESIGN2			INPUT 'UNMAN or'MAN FOR ASCNT STRUCT
	STRUCT1	2594.2758	kg	STRUCTURAL MASS FOR DESCENT STAGE
	STRUCT2	822.0373	kg	STRUCTURAL MASS FOR ASCENT STAGE
	TOTSTRU	3416.3131	kg	DESCENT + ASCENT STRUCTURAL MASS

				----TOTAL STAGE MASS INPUTS----
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
200	RETCARG		kg	ASCENT PAYLOAD MASS
294	FEEDSYS		kg	DRY MASS OF PROPULSION FEED SYSTEM
873	ENGS		kg	DRY MASS OF ALL ENGINES + ACTUATORS
270	RCSSYS		kg	WET MASS OF DESCENT RCS (N2H4)
1432	POWER		kg	DRY POWER MASS
236	AVIONIC		kg	MASS OF STAGE AVIONICS
238	ECLSS		kg	MASS OF ECLSS
7426	CREWMOD		kg	TOTAL MASS OF CREW MODULE
1050	FLUIDS1		kg	NON-PROP FLUID MASS AT DESCENT
202	FLUIDS2		kg	NON-PROP FLUID MASS AT ASCENT
.2	GROWTH%			PERCENT GROWTH BUDGET/100
				----ROCKET EQUATION CALC----
	RESID1	1414.2381	kg	MASS OF RESIDUAL PROP FOR 1ST BURN
	RESID2	625.94646	kg	MASS OF RESIDUAL PROP FOR 2ND BURN
	NONUSE1	23477.744	kg	MASS OF PROP NOT USED IN 1ST BURN
	NONUSE2	625.94646	kg	MASS OF PROP NOT USED IN 2ND BURN
.03	RESERVE			RESERVE & RESIDUAL PERCENTAGE/100
2780	DELV1		m/s	DELTA V FOR 1ST BURN
2801	DELV2		m/s	DELTA V FOR 2ND BURN
449	ISP		sec	ENGINE ISP
6	MIXRATI			ENGINE MIXTURE RATIO
9.81	G		m/s^2	EARTH GRAVITY ACCELERATION
1.622	GMOON		m/s^2	LUNAR GRAVITY ACCELERATION
				----PROP INPUTS----
198340	OXVAP		J/kg	HEAT OF VAPORIZATION FOR OX
400900	FUVAP		J/kg	HEAT OF VAPORIZATION FOR FUEL
1141	OXRHO		kg/m^3	DENSITY OF OX
70.8	FUELRHO		kg/m^3	DENSITY OF FUEL
21	FUTEMP		K	FUEL PROPELLANT SAT. TEMP (15 psi)
91	OXTEMP		K	OX PROPELLANT SAT. TEMP (15 psi)
				----BOILOFF CALC----
49	STAYTIM		day	NO. OF MISSION DAYS
4	TRIPTIM		day	NO. OF TRIP DAYS TO MOON
54508.9	OXRATE		J/day*m^2	HEAT XFER FOR LO2
54508.9	FURATE		J/day*m^2	HEAT XFER FOR LH2
21176.7	QMOONFU		J/day*m^2	LUNAR HEAT XFER RATE THRU FUEL TNK
14190.5	QMOONOX		J/day*m^2	LUNAR HEAT XFER RATE THRU OX TANK
32705.34	HEATRAT		J/day*m^2	HEAT XFER RATE THRU 2" OF MLI
'NO	VCSOX1			VCS FOR DESCENT OX TNKS? ('YES or 'NO)
'NO	VCSFU1			VCS FOR DESCENT FU TNKS? ('YES or 'NO)
'NO	VCSOX2			VCS FOR ASCENT OX TNKS? ('YES or 'NO)
'NO	VCSFU2			VCS FOR ASCENT FU TNKS? ('YES or 'NO)
	BOILOX1	105.7871	kg	MASS OF DESCENT OX BOILOFF
	BOILFU1	154.49396	kg	MASS OF DESCENT FUEL BOILOFF
	BOILOX2	218.3462	kg	MASS OF ASCENT OX BOILOFF
	BOILFU2	152.57712	kg	MASS OF ASCENT FUEL BOILOFF
				----PROTECTION CALC----
2	METMASS		kg/m^2	METEORIOD SHIELD BLANKET MASS/m^2
.273	FOAMMAS		kg/m^2	FOAM INSULATION MASS/m^2
.493	MLI20L		kg/m^2	MLI BLANKET MASS FOR 20 LAYERS
2.344	MLI88L		kg/m^2	MLI BLANKET MASS FOR 88 LAYERS
2.637	MLI113L		kg/m^2	MLI BLANKET MASS FOR 113 LAYERS

APPENDIX B

Trade #9 SINGLE STAGE

2.93	MLIMASS		kg/m^2	MLI BLANKET MASS FOR 2" (100 LAYERS)
	FOAM	59.653984	kg	TOTAL DESCENT FOAM MASS
	MLI1	144.2206	kg	TOTAL DESCENT MLI MASS
	MLI2OX	84.65807	kg	TOTAL ASCENT OX MLI MASS
	MLI2FU	158.61561	kg	TOTAL ASCENT FU MLI MASS
	MLI2	243.27368	kg	TOTAL ASCENT MLI MASS
	PROT1	380.17548	kg	PROT MASS FOR DESCENT TANKS & HE
	PROT2	87.133259	kg	PROTECTION MASS FOR ASCENT TANKS
	PROTECT	467.30874	kg	TOTAL PROTECTION MASS
	MVCSOX1	0		MASS OF DESCENT OX VCS
	MVCSFU1	0		MASS OF DESCENT FU VCS
	MVCSOX2	0		MASS OF ASCENT OX VCS
	MVCSFU2	0		MASS OF ASCENT FU VCS
	MVCSTOT	0		TOTAL MASS OF VEHICLE VCS USED
				----PROP MASS & VOL CALC----
	MFUEL1	7534.9215	kg	MASS OF FUEL IN DESCENT TANKS
	MOX1	41280.869	kg	MASS OF OX IN DESCENT TANKS
	OXVOL1	38.083739	m^3	VOLUME OF DESCENT OX TANKS
	FUVOL1	112.02678	m^3	VOLUME OF DESCENT FUEL TANKS
	VPROP1	150.11052	m^3	TOTAL VOLUME OF DESCENT PROP
	MFUEL2	3424.4498	kg	MASS OF FUEL IN ASCENT TANKS
	MOX2	18437.302	kg	MASS OF OX IN ASCENT TANKS
	OXVOL2	17.009366	m^3	VOLUME OF ASCENT OX TANK
	FUVOL2	50.913616	m^3	VOLUME OF ASCENT FUEL TANK
	VPROP2	67.922982	m^3	TOTAL VOLUME OF ASCENT PROP
				----PROP TANK INPUTS----
1	ERATIO			ELLIPSE RATIO FOR TANK DOME (HEIGHT/RA
2	NTNKOX1			No. OF DESCENT OX TANKS
6	NTNKFU1			No. OF DESCENT FUEL TANKS
1	NTNKOX2			No. OF ASCENT OX TANKS
1	NTNKFU2			No. OF ASCENT FUEL TANKS
1.25	OXRAD1		m	DESCENT OX TANK RADIUS
1.25	FURAD1		m	DESCENT FUEL TANK RADIUS
1.5	OXRAD2		m	ASCENT OX TANK RADIUS
2	FURAD2		m	ASCENT FUEL TANK RADIUS
344732	TNKPRES		Pa	PROP TANK PRESSURE
.6	GLOAD1			G LOADS ON PRESSURIZED DESCENT TANKS
.75	GLOAD2			G LOADS ON ASCENT TANKS - PRESSURIZED
				----DESCENT PROP TANK CALC----
	DOMEOX1	8.1812309	m^3	DESCENT OX TANK DOME VOLUME (EACH)
	DOMEFU1	8.1812309	m^3	DESCENT FUEL TANK DOME VOLUME (EACH)
	LENOX1	2.2125112	m	LENGTH OF DESCENT OX TANKS
	LENFU1	2.1369849	m	LENGTH OF DESCENT FUEL TANKS
	SRADOX1		m	SPHERE RADIUS OF OX TANK (IF LENOX1<0)
	SRADFU1		m	SPHERE RADIUS OF FU TANK (IF LENFU1<0)
	TWOX1	.00288356	m	DESCENT OX TANK WALL THICKNESS
	TWFU1	.0026559	m	DESCENT FUEL TANK WALL THICKNESS
	ASUROX1	37.011976	m^2	SURFACE AREA OF DESCENT OX TANK (EA)
	ASURFU1	36.418794	m^2	SURFACE AREA OF DESCENT FUEL TNK (EA)
	OXTNK1	259.91912	kg	MASS OF DESCENT OX TANKS (EACH)
	FUTNK1	241.93035	kg	MASS OF DESCENT FUEL TANKS (EACH)
				----ASCENT PROP TANK CALC----
	DOMEOX2	14.137167	m^3	ASCENT OX TANK DOME VOLUME (EACH)
	DOMEFU2	33.510322	m^3	ASCENT FUEL TANK DOME VOLUME (EACH)

APPENDIX B
Trade #9 SINGLE STAGE

	LENOX2	.40633303	m	LENGTH OF ASCENT OX TANK
	LENFU2	1.3849101	m	LENGTH OF ASCENT FUEL TANK
	SRADOX2		m	SPHERE RADIUS OF OX TANK (IF LENOX2<0)
	SRADFU2		m	SPHERE RADIUS OF FU TANK (IF LENFU2<0)
	TWOX2	.00343221	m	ASCENT OX TANK WALL THICKNESS
	TWFU2	.00426013	m	ASCENT FUEL TANK WALL THICKNESS
	ASUROX2	32.103932	m^2	SURFACE AREA OF ASCENT OX TANK (EACH)
	ASURFU2	67.668777	m^2	SURFACE AREA OF ASCENT FUEL TANK (EA)
	OXTNK2	210.30621	kg	MASS OF ASCENT OX TANK (EACH)
	FUTNK2	638.28833	kg	MASS OF ASCENT FUEL TANK (EACH)
				----PRESS SYSTEM INPUTS----
1.66	GAM			RATIO OF SPECIFIC HEATS FOR HE
2077	R			IDEAL GAS CONSTANT FOR HE
	ENDTEMP	121.27715	K	FINAL HE PRESSURANT TEMP
298	INITTEM		K	INITIAL HE PRESSURANT TEMP
3450000	ENDPRES		Pa	FINAL HE PRESSURANT PRESSURE
33100000	INITPRE		Pa	INITIAL HE PRESSURANT PRESSURE
344732.5	PROPPRE		Pa	PROPELLANT TANK PRESSURE
2	MW			MOLECULAR WEIGHT OF H2
				----DESCENT PRESS SYSTEM CALC----
	VPRES1	2.2518288	Pa	VOLUME OF DESCENT HE PRESSURANT
	HeMASS1	120.42332	kg	MASS OF DESCENT HE PRESSURANT
	MHeOX1	93.376123	kg	MASS OF HE PRESS FOR DESCENT OX
	MHeFU1	27.047199	kg	MASS OF HE PRESS FOR DESCENT FUEL
	PCONOX1	69.461463		DESCENT OX PROP TANK CONDITION
	PCONFU1	44.270896		DESCENT FUEL PROP TANK CONDITION
	PTNK1	374.29602	kg	MASS OF DESCENT PRESSURANT TANK
				----ASCENT PRESS SYSTEM CALC----
	VPRES2	1.2856095	m^3	VOLUME OF ASCENT HE PRESSURANT
	HeMASS2	68.751839	kg	MASS OF ASCENT HE PRESSURANT
	MHeOX2	41.70464	kg	MASS OF HE PRESS FOR ASCENT OX
	MHeFU2	27.047199	kg	MASS OF HE PRESS FOR ASCENT FUEL
	PCONOX2	31.023619		ASCENT OX PROP TANK CONDITION
	PCONFU2	20.120111		DESCENT FUEL PROP TANK CONDITION
	PTNK2	213.69232	kg	MASS OF ASCENT PRESSURANT TANK

1.5 STAGE CRYO TRADE #10

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	41395.858	kg	DESCENT USED PROPELLANT MASS
	MBURN2	13636.392	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	141.28485	kg	DESCENT FUEL BOILOFF
	BOILOX1	93.205892	kg	DESCENT OX BOILOFF
	BOILFU2	172.46337	kg	ASCENT FUEL BOILOFF
	BOILOX2	121.08961	kg	ASCENT OX BOILOFF
	LGEAR	1373.472	kg	LANDING GEAR MASS
	APRSFU1	387.95941	kg	AUTOGENOUS FU PRESSURE MASS
	APRSFU2	135.63793	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICHLE STUFF
	TOTPROP	57734.858	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	87412.748	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
100	FESYS1		kg	DESCENT FEED SYSTEM MASS
0	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
6	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.2	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
294	FESYS2		kg	ASCENT FEED SYSTEM MASS
873	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

Trade #10 1.5 STAGE

238	ECLSS		kg	ECLSS MASS
202	FLUIDS2		kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2		m/sec	ASCENT DELTA V
444	ISP2		sec	ASCENT ISP
6	MR2			ASCENT MIXTURE RATIO
70.8	FURHO2		kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2		kg/m^3	ASCENT OXIDIZER DENSITY
50	PPRES2		PSI	ASCENT PROP TANK PRESSURE
1	NFUTNK2			ASCENT NUMBER FUEL TANKS
1.9	FURAD2		m	ASCENT FUEL TANK RAD
1	NOXTNK2			ASCENT NUMBER OX TANKS
1	OXRAD2		m	ASCENT OX TANK RAD
3.1E8	METSIG2			ASCENT TANK METAL SIGMA
2710	METRHO2		kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2		M	ASCENT TANK MINIMUM THICKNESS
400900	FUVAP2		J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2		J/kg	ASCENT OX LATENT HEAT OF VAP
21	TEMPFU2		DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2		DEG K	ASCENT OX TEMPERATURE
49	STIME		Day	STAYTIME
21176.7	HTRATEF			
14190.5	HTRATEO			
				---DESCENT STAGE BREAKDOWN (1)
	PRPSYS1	3282.4697	kg	DESCENT PROPULSION SYSTEM MASS
	TNKST1	603.59597	kg	DESCENT TANK STRUCTURE
	TNKS1	2011.9866	kg	DESCENT PROPELLANT TANKS
	SPPT1	4157.472	kg	DESCENT SUPPORT MASS
2100	STRUCT1		kg	DESCENT STRUCTURE MASS
	STAGE1	10310.035	kg	DESCENT STAGE MASS
	GROWTH1	1487.9883	kg	DESCENT GROWTH BUDGET
	PTNK1	493.88713	kg	DESCENT PRESSURANT TANK MASS
	HEMASS1	132.10483	kg	DESCENT HELIUM MASS
	PSYS1	625.99197	kg	DESCENT PRESSURIZATION SYSTEM MASS
				---ASCENT STAGE BREAKDOWN (2)
	PRPSYS2	2362.9209	kg	ASCENT PROPULTION SYSTEM MASS
	TNKST2	237.02815	kg	ASCENT TANK STRUCTURE
	TNKS2	790.09382	kg	ASCENT PROPELLANT TANKS
	HEMASS2	45.150313	kg	ASCENT HELIUM MASS
	PTNK2	168.79896	kg	ASCENT PRESSURANT TANK MASS
	PSYS2	213.94927	kg	ASCENT PRESSURIZATION SYSTEM MASS
	SPPT2	3216	kg	ASCENT SUPPORT
1400	STRUCT2		kg	ASCENT STRUCTURE MASS
	STAGE2	14367.855	kg	ASCENT STAGE MASS
	GROWTH2	1115.7842	kg	ASCENT GROWTH BUDGET
				---DESCENT PROPELLANT STUFF
	RESID1	1241.8757	kg	DESCENT RESIDUALS
	PROP1	42637.734	kg	DESCENT TOTAL PROP
	BOIL1	234.49074	kg	DESCENT PROP BOILOFF
				---ASCENT PROPELLANT STUFF
	RESID2	409.09175	kg	ASCENT RESIDUALS
	PROP2	14045.483	kg	ASCENT TOTAL PROP
	BOIL2	293.55298	kg	ASCENT PROP BOILOFF

APPENDIX B
Trade #10 1.5 STAGE

			---DESCENT TANKS---
FU1	6620.3491	kg	DESCENT FUEL MASS
OX1	36639.835	kg	DESCENT OX MASS
FUVOL1	93.507755	m^3	DESCENT FUEL VOLUME
OXVOL1	32.112038	m^3	DESCENT OX VOLUME
OXTNK1	293.71003	kg	DESCENT OX TANK MASS
FUTNK1	206.55723	kg	DESCENT FUEL TANK MASS
FUTNKV1	16.363857	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	16.85882	M^3	DESCENT OX TANK VOLUME
LENFU1	4.4172066	m	DESCENT FUEL TANK LENGTH
ATOTFU1	33.304953	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	3.8444878	m	DESCENT OX TANK LENGTH
ATOTOX1	32.610099	m^2	DESCENT OX TANK AREA/TANK
MLI1	185.22312	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	2314.5989	kg	ASCENT FUEL MASS
OX2	12160.075	kg	ASCENT OX MASS
FUVOL2	32.692075	m^3	ASCENT FUEL VOLUME
OXVOL2	10.657384	m^3	ASCENT OX VOLUME
OXTNK2	215.54205	kg	ASCENT OX TANK MASS
FUTNK2	384.85965	kg	ASCENT FUEL TANK MASS
LENFU2	4.2934038	m	ASCENT FUEL TANK LENGTH
ATOTFU2	51.254879	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	4.2286349	m	ASCENT OX TANK LENGTH
ATOTOX2	26.569297	m^2	ASCENT OX TANK AREA/TANK
MLI2	189.69212	kg	ASCENT MLI MASS
FUTNKV2	34.326679	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	11.190253	M^3	ASCENT OX TANK VOLUME

APPENDIX B
Trade #11 ALL ClF5/N2H4

ALL ClF5/N2H4 PRESS TRADE #11

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	50329.319	kg	DESCENT USED PROPELLANT MASS
	MBURN2	14893.083	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	.0012113	kg	DESCENT FUEL BOILOFF
	BOILOX1	.00158544	kg	DESCENT OX BOILOFF
	BOILFU2	.00222856	kg	ASCENT FUEL BOILOFF
	BOILOX2	.00190232	kg	ASCENT OX BOILOFF
	LGEAR	1225.7951	kg	LANDING GEAR MASS
				---VEHICHLE STUFF
	TOTPROP	67179.081	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	91189.159	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
300	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
353	ISP1		sec	DESCENT ISP
2.5	MR1			DESCENT MIXTURE RATIO
1031	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1793	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
350	PPRES1		PSI	DESCENT PROP TANK PRESSURE
6	DIA1		m	--DESCENT STAGE DIA--
3	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1	FURAD1		m	DESCENT FUEL TANK RAD
3	NOXTNK1			DESCENT NUMBER OF OX TANKS
1	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
1E10	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
300	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
300	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
153	FESYS2		kg	ASCENT FEED SYSTEM MASS
150	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS
238	ECLSS		kg	ECLSS MASS

APPENDIX B
Trade #11 ALL ClF5/N2H4

202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2	m/sec	ASCENT DELTA V
353	ISP2	sec	ASCENT ISP
2.5	MR2		ASCENT MIXTURE R ATIO
1031	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1793	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
350	PPRES2	PSI	ASCENT PROP TANK PRESSURE
4.346	DIA2	m	--ASCENT STAGE DIA--
2	NFUTNK2		ASCENT NUMBER FUEL TANKS
.8	FURAD2	m	ASCENT FUEL TANK RAD
2	NOXTNK2		ASCENT NUMBER OX TANKS
.9	OXRAD2	m	ASCENT OX TANK RAD
3.1E8	METSIG2		ASCENT TANK METAL SIGMA
2710	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
1E10	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
1E10	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
300	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
300	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	2441.6462	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	292.8602	kg	DESCENT TANK STRUCTURE
TNKS1	976.20066	kg	DESCENT PROPELLANT TANKS
SPPT1	2818.7649	kg	DESCENT SUPPORT MASS
STRUCT1	908.9698	kg	DESCENT STRUCTURE MASS
STAGE1	7697.7272	kg	DESCENT STAGE MASS
GROWTH1	1052.0822	kg	DESCENT GROWTH BUDGET
PTNK1	505.58533	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	135.23387	kg	DESCENT HELIUM MASS
PSYS1	640.8192	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	854.34884	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	92.709161	kg	ASCENT TANK STRUCTURE
TNKS2	309.03054	kg	ASCENT PROPELLANT TANKS
HEMASS2	40.017423	kg	ASCENT HELIUM MASS
PTNK2	149.60914	kg	ASCENT PRESSURANT TANK MASS
PSYS2	189.62656	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	2182.5955	kg	ASCENT SUPPORT
STRUCT2	366.59551	kg	ASCENT STRUCTURE MASS
STAGE2	11312.351	kg	ASCENT STAGE MASS
GROWTH2	607.38887	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1509.8796	kg	DESCENT RESIDUALS
PROP1	51839.199	kg	DESCENT TOTAL PROP
BOIL1	.00279674	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	446.79248	kg	ASCENT RESIDUALS
PROP2	15339.875	kg	ASCENT TOTAL PROP
BOIL2	.00413088	kg	ASCENT PROP BOILOFF

Trade #11 ALL ClF5/N2H4

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                                  ---DESCENT TANKS---
FU1        14811.201    kg        DESCENT FUEL MASS
OX1        37028.001    kg        DESCENT OX MASS
FUVOL1     14.365859    m^3       DESCENT FUEL VOLUME
OXVOL1     20.651423    m^3       DESCENT OX VOLUME
OXTNK1     190.09317    kg        DESCENT OX TANK MASS
FUTNK1     135.30705    kg        DESCENT FUEL TANK MASS
FUTNKV1    5.0280507    M^3       DESCENT FUEL TANK VOLUME
OXTNKV1    7.2279979    M^3       DESCENT OX TANK VOLUME
LENFU1     2.2671449    m         DESCENT FUEL TANK LENGTH
ATOTFU1    14.24489     m^2       DESCENT FUEL TANK AREA/TANK
LENOX1     2.9674099    m         DESCENT OX TANK LENGTH
ATOTOX1    18.644785    m^2       DESCENT OX TANK AREA/TANK
MLI1       0            kg        DESCENT MLI MASS

                                  ---ASCENT TANKS---
FU2        4382.8237    kg        ASCENT FUEL MASS
OX2        10957.056    kg        ASCENT OX MASS
FUVOL2     4.2510415    m^3       ASCENT FUEL VOLUME
OXVOL2     6.1110182    m^3       ASCENT OX VOLUME
OXTNK2     89.788956    kg        ASCENT OX TANK MASS
FUTNK2     64.726313    kg        ASCENT FUEL TANK MASS
LENFU2     1.643338     m         ASCENT FUEL TANK LENGTH
ATOTFU2    8.260317     m^2       ASCENT FUEL TANK AREA/TANK
LENOX2     1.8607762    m         ASCENT OX TANK LENGTH
ATOTOX2    10.52244     m^2       ASCENT OX TANK AREA/TANK
MLI2       0            kg        ASCENT MLI MASS
FUTNKV2    2.2317968    M^3       ASCENT FUEL TANK VOLUME
OXTNKV2    3.2082846    M^3       ASCENT OX TANK VOLUME
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LOX/LH2 2 STAGE PUMP TRADE #12

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	31514.965	kg	DESCENT USED PROPELLANT MASS
	MBURN2	10843.647	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	97.357378	kg	DESCENT FUEL BOILOFF
	BOILOX1	76.544764	kg	DESCENT OX BOILOFF
	BOILFU2	187.14654	kg	ASCENT FUEL BOILOFF
	BOILOX2	130.74176	kg	ASCENT OX BOILOFF
	LGEAR	1174.936	kg	LANDING GEAR MASS
	APRSFU1	142.91249	kg	AUTOGENOUS FU PRESSURE MASS
	APRSFU2	53.811084	kg	AUTOGENOUS FU PRESSURE MASS
	APRSOX2	65.584758		
	APRSOX1	188.55871		
				---VEHICHLE STUFF
	TOTPROP	44572.028	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	70853.402	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
150	FESYS1		kg	DESCENT FEED SYSTEM MASS
600	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2780	DELV1		m/s	DESCENT DELTA V
480	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
25	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
100	FESYS2		kg	ASCENT FEED SYSTEM MASS
481	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL

169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS
238	ECLSS		kg	ECLSS MASS
202	FLUIDS2		kg	ASCENT NON-PROPULSION FLUIDS MASS
2801	DELV2		m/sec	ASCENT DELTA V
480	ISP2		sec	ASCENT ISP
6	MR2			ASCENT MIXTURE R ATIO
70.8	FURHO2		kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2		kg/m^3	ASCENT OXIDIZER DENSITY
25	PPRES2		PSI	ASCENT PROP TANK PRESSURE
6.518	DIA2		m	--ASCENT STAGE DIA--
2	NFUTNK2			ASCENT NUMBER FUEL TANKS
1.35	FURAD2		m	ASCENT FUEL TANK RAD
2	NOXTNK2			ASCENT NUMBER OX TANKS
.75	OXRAD2		m	ASCENT OX TANK RAD
3.1E8	METSIG2			ASCENT TANK METAL SIGMA
2710	METRHO2		kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2		M	ASCENT TANK MINIMUM THICKNESS
400900	FUVAP2		J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2		J/kg	ASCENT OX LATENT HEAT OF VAP
21	TEMPFU2		DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2		DEG K	ASCENT OX TEMPERATURE
49	STIME		Day	STAYTIME
21176.7	HTRATEF			
14190.5	HTRATEO			
				---DESCENT STAGE BREAKDOWN (1)
	PRPSYS1	2068.3365	kg	DESCENT PROPULSION SYSTEM MASS
	TNKST1	287.38534	kg	DESCENT TANK STRUCTURE
	TNKS1	957.95113	kg	DESCENT PROPELLANT TANKS
	SPPT1	4043.429	kg	DESCENT SUPPORT MASS
	STRUCT1	2184.493	kg	DESCENT STRUCTURE MASS
	STAGE1	8584.1186	kg	DESCENT STAGE MASS
	GROWTH1	1222.3531	kg	DESCENT GROWTH BUDGET
0	PTNK1		kg	DESCENT PRESSURANT TANK MASS
0	HEMASS1		kg	DESCENT HELIUM MASS
	PSYS1	0	kg	DESCENT PRESSURIZATION SYSTEM MASS
				---ASCENT STAGE BREAKDOWN (2)
	PRPSYS2	1287.0107	kg	ASCENT PROPULTION SYSTEM MASS
	TNKST2	162.92556	kg	ASCENT TANK STRUCTURE
	TNKS2	543.08519	kg	ASCENT PROPELLANT TANKS
0	HEMASS2		kg	ASCENT HELIUM MASS
0	PTNK2		kg	ASCENT PRESSURANT TANK MASS
	PSYS2	0	kg	ASCENT PRESSURIZATION SYSTEM MASS
	SPPT2	2937.3686	kg	ASCENT SUPPORT
	STRUCT2	1121.3686	kg	ASCENT STRUCTURE MASS
	STAGE2	12697.255	kg	ASCENT STAGE MASS
	GROWTH2	844.87587	kg	ASCENT GROWTH BUDGET
				---DESCENT PROPELLANT STUFF
	RESID1	945.44895	kg	DESCENT RESIDUALS
	PROP1	32460.414	kg	DESCENT TOTAL PROP
	BOIL1	173.90214	kg	DESCENT PROP BOILOFF
				---ASCENT PROPELLANT STUFF
	RESID2	325.30941	kg	ASCENT RESIDUALS

APPENDIX B
Trade #12 LOX/LH2 IME

PROP2	11168.956	kg	ASCENT TOTAL PROP
BOIL2	317.8883	kg	ASCENT PROP BOILOFF
			---DESCENT TANKS---
FU1	4877.4719	kg	DESCENT FUEL MASS
OX1	28088.316	kg	DESCENT OX MASS
FUVOL1	68.890846	m^3	DESCENT FUEL VOLUME
OXVOL1	24.617279	m^3	DESCENT OX VOLUME
OXTNK1	129.20539	kg	DESCENT OX TANK MASS
FUTNK1	141.91409	kg	DESCENT FUEL TANK MASS
FUTNKV1	18.083847	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	12.924072	M^3	DESCENT OX TANK VOLUME
LENFU1	4.0584457	m	DESCENT FUEL TANK LENGTH
ATOTFU1	34.424955	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	3.1572619	m	DESCENT OX TANK LENGTH
ATOTOX1	26.780843	m^2	DESCENT OX TANK AREA/TANK
MLI1	131.88397	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	1836.5228	kg	ASCENT FUEL MASS
OX2	9769.7177	kg	ASCENT OX MASS
FUVOL2	25.939588	m^3	ASCENT FUEL VOLUME
OXVOL2	8.5624169	m^3	ASCENT OX VOLUME
OXTNK2	59.786548	kg	ASCENT OX TANK MASS
FUTNK2	109.02511	kg	ASCENT FUEL TANK MASS
LENFU2	3.2785099	m	ASCENT FUEL TANK LENGTH
ATOTFU2	27.809305	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	3.0438018	m	ASCENT OX TANK LENGTH
ATOTOX2	14.343578	m^2	ASCENT OX TANK AREA/TANK
MLI2	205.46187	kg	ASCENT MLI MASS
FUTNKV2	13.618284	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	4.4952689	M^3	ASCENT OX TANK VOLUME

TRADE #13: LOX/LH2 TWO STAGE PRESS

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	44824.379	kg	DESCENT USED PROPELLANT MASS
	MBURN2	14282.153	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	132.61295	kg	DESCENT FUEL BOILOFF
	BOILOX1	76.088665	kg	DESCENT OX BOILOFF
	BOILFU2	250.81274	kg	ASCENT FUEL BOILOFF
	BOILOX2	164.41602	kg	ASCENT OX BOILOFF
	LGEAR	1509.2409	kg	LANDING GEAR MASS
	APRSFU1	418.82307	kg	AUTOGENOUS FU PRESSURE MASS
				---VEHICLE STUFF
	TOTPROP	61922.482	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	95341.111	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
294	FESYS1		kg	DESCENT FEED SYSTEM MASS
873	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2750	DELV1		m/s	DESCENT DELTA V
440	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
50	PPRES1		PSI	DESCENT PROP TANK PRESSURE
9.4	DIA1		m	--DESCENT STAGE DIA--
4	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.35	FURAD1		m	DESCENT FUEL TANK RAD
1	NOXTNK1			DESCENT NUMBER OF OX TANKS
2	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
294	FESYS2		kg	ASCENT FEED SYSTEM MASS
250	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS
1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS

APPENDIX B
Trade #13 LOX/LH2, PRESS

238	ECLSS	kg	ECLSS MASS
202	FLUIDS2	kg	ASCENT NON-PROPULSION FLUIDS MASS
2777	DELV2	m/sec	ASCENT DELTA V
440	ISP2	sec	ASCENT ISP
6	MR2		ASCENT MIXTURE RATIO
70.8	FURHO2	kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2	kg/m^3	ASCENT OXIDIZER DENSITY
250	PPRES2	PSI	ASCENT PROP TANK PRESSURE
8.7	DIA2	m	--ASCENT STAGE DIA--
3	NFUTNK2		ASCENT NUMBER FUEL TANKS
1.45	FURAD2	m	ASCENT FUEL TANK RAD
3	NOXTNK2		ASCENT NUMBER OX TANKS
1	OXRAD2	m	ASCENT OX TANK RAD
3.1E8	METSIG2		ASCENT TANK METAL SIGMA
2710	METRHO2	kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2	M	ASCENT TANK MINIMUM THICKNESS
400900	FUVAP2	J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2	J/kg	ASCENT OX LATENT HEAT OF VAP
70	TEMPFU2	DEG K	ASCENT FUEL TEMPERATURE
170	TEMPOX2	DEG K	ASCENT OX TEMPERATURE
49	STIME	Day	STAYTIME
21176.7	HTRATEF		
14190.5	HTRATEO		

			---DESCENT STAGE BREAKDOWN (1)
PRPSYS1	4552.4552	kg	DESCENT PROPULSION SYSTEM MASS
TNKST1	641.24116	kg	DESCENT TANK STRUCTURE
TNKS1	2137.4705	kg	DESCENT PROPELLANT TANKS
SPPT1	5310.5569	kg	DESCENT SUPPORT MASS
STRUCT1	3117.316	kg	DESCENT STRUCTURE MASS
STAGE1	13228.38	kg	DESCENT STAGE MASS
GROWTH1	1972.6024	kg	DESCENT GROWTH BUDGET
PTNK1	533.74356	kg	DESCENT PRESSURANT TANK MASS
HEMASS1	142.76562	kg	DESCENT HELIUM MASS
PSYS1	676.50919	kg	DESCENT PRESSURIZATION SYSTEM MASS
			---ASCENT STAGE BREAKDOWN (2)
PRPSYS2	2848.2858	kg	ASCENT PROPULTION SYSTEM MASS
TNKST2	441.71606	kg	ASCENT TANK STRUCTURE
TNKS2	1472.3869	kg	ASCENT PROPELLANT TANKS
HEMASS2	447.28301	kg	ASCENT HELIUM MASS
PTNK2	390.18286	kg	ASCENT PRESSURANT TANK MASS
PSYS2	837.46586	kg	ASCENT PRESSURIZATION SYSTEM MASS
SPPT2	3080.8527	kg	ASCENT SUPPORT
STRUCT2	1264.8527	kg	ASCENT STRUCTURE MASS
STAGE2	15190.249	kg	ASCENT STAGE MASS
GROWTH2	1185.8277	kg	ASCENT GROWTH BUDGET
			---DESCENT PROPELLANT STUFF
RESID1	1344.7314	kg	DESCENT RESIDUALS
PROP1	46169.111	kg	DESCENT TOTAL PROP
BOIL1	208.70162	kg	DESCENT PROP BOILOFF
			---ASCENT PROPELLANT STUFF
RESID2	428.46459	kg	ASCENT RESIDUALS
PROP2	14710.618	kg	ASCENT TOTAL PROP
BOIL2	415.22876	kg	ASCENT PROP BOILOFF

Trade #13 LOX/LH2, PRESS

			---DESCENT TANKS---
FU1	7147.0233	kg	DESCENT FUEL MASS
OX1	39649.612	kg	DESCENT OX MASS
FUVOL1	100.94666	m^3	DESCENT FUEL VOLUME
OXVOL1	34.749879	m^3	DESCENT OX VOLUME
OXTNK1	597.75393	kg	DESCENT OX TANK MASS
FUTNK1	342.44842	kg	DESCENT FUEL TANK MASS
FUTNKV1	26.498497	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	36.487373	M^3	DESCENT OX TANK VOLUME
LENFU1	5.5281117	m	DESCENT FUEL TANK LENGTH
ATOTFU1	46.891103	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	4.2369062	m	DESCENT OX TANK LENGTH
ATOTOX1	53.242534	m^2	DESCENT OX TANK AREA/TANK
MLI1	169.92291	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	2352.3295	kg	ASCENT FUEL MASS
OX2	12773.517	kg	ASCENT OX MASS
FUVOL2	33.224994	m^3	ASCENT FUEL VOLUME
OXVOL2	11.195019	m^3	ASCENT OX VOLUME
OXTNK2	107.66943	kg	ASCENT OX TANK MASS
FUTNK2	293.42354	kg	ASCENT FUEL TANK MASS
LENFU2	2.7272114	m	ASCENT FUEL TANK LENGTH
ATOTFU2	24.846583	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	1.9138865	m	ASCENT OX TANK LENGTH
ATOTOX2	12.025304	m^2	ASCENT OX TANK AREA/TANK
MLI2	269.10795	kg	ASCENT MLI MASS
FUTNKV2	11.628748	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	3.9182567	M^3	ASCENT OX TANK VOLUME

1.5 STAGE IME CRYO TRADE #14

				---VARIABLES REQUIRING INITIAL GUESSES
	MBURN1	31080.344	kg	DESCENT USED PROPELLANT MASS
	MBURN2	10919.893	kg	ASCENT USED PROPELLANT MASS
	BOILFU1	109.90093	kg	DESCENT FUEL BOILOFF
	BOILOX1	75.427626	kg	DESCENT OX BOILOFF
	BOILFU2	145.77281	kg	ASCENT FUEL BOILOFF
	BOILOX2	100.80257	kg	ASCENT OX BOILOFF
	LGEAR	1175.475	kg	LANDING GEAR MASS
	APRSFU1	141.36075	kg	AUTOGENOUS FU PRESSURE MASS
	APRSFU2	52.900866	kg	AUTOGENOUS FU PRESSURE MASS
	APRSOX1	184.70955		
	APRSOX2	65.395385		
				---VEHICHLE STUFF
	TOTPROP	43886.41	kg	VEHICLE TOTAL PROPELLANT
	VEHCL	70448.173	kg	TLI MASS
				---GLOBAL INPUTS
.2	GROWTH%			GROWTH FRACTION
5000	PAYLOAD		kg	DESCENT PAYLOAD MASS
7426	CREWMOD		kg	CREW MODULE MASS
9.81	G		m/s^2	GRAVITY
200	RETCARG		kg	ASCENT CARGO
.03	RESERVE			PROPELLANT RESERVE FRACTION
				---DESCENT INPUTS (1)
150	FESYS1		kg	DESCENT FEED SYSTEM MASS
600	ENGS1		kg	DESCENT ENGINE(S) MASS TOTAL
270	RCSSYS1		kg	DESCENT RCS SYSTEM WET MASS
425	PROT1		kg	DESCENT PROTECTION MASS
154	POWER1		kg	DESCENT POWER MASS
105	AV1		kg	DESCENT AVIONICS MASS
1050	FLUIDS1		kg	NON-PROPULSION FLUIDS MASS
2750	DELV1		m/s	DESCENT DELTA V
480	ISP1		sec	DESCENT ISP
6	MR1			DESCENT MIXTURE RATIO
70.8	FURHO1		kg/m^3	DESCENT FUEL DENSITY
1141	OXRHO1		kg/m^3	DESCENT OXIDIZER DENSITY
25	PPRES1		PSI	DESCENT PROP TANK PRESSURE
6	NFUTNK1			DESCENT NUMBER OF FUEL TANKS
1.2	FURAD1		m	DESCENT FUEL TANK RAD
2	NOXTNK1			DESCENT NUMBER OF OX TANKS
1.35	OXRAD1		m	DESCENT OX TANK RAD
3.1E8	METSIG1			DESCENT TANK METAL SIGMA
2710	METRHO1		kg/m^3	DESCENT TANK METAL RHO
.001143	TMIN1		M	DESCENT TANK MINIMUM THICKNESS
400900	FUVAP1		J/kg	DESCENT FUEL LATENT HEAT OF VAP
198340	OXVAP1		J/kg	DESCENT OX LATENT HEAT OF VAP
21	TEMPFU1		DEG K	DESCENT FUEL TEMPERATURE
91	TEMPOX1		DEG K	DESCENT OX TEMPERATURE
				---ASCENT INPUTS (2)
100	FESYS2		kg	ASCENT FEED SYSTEM MASS
600	ENGS2		kg	ASCENT ENGINE(S) MASS TOTAL
169	PROT2		kg	ASCENT PROTECTION MASS

APPENDIX B
Trade #14 STAGE 1/2 IME

1278	POWER2		kg	ASCENT POWER MASS
131	AV2		kg	ASCENT AVIONICS MASS
238	ECLSS		kg	ECLSS MASS
202	FLUIDS2		kg	ASCENT NON-PROPULSION FLUIDS MASS
2777	DELV2		m/sec	ASCENT DELTA V
480	ISP2		sec	ASCENT ISP
6	MR2			ASCENT MIXTURE R ATIO
70.8	FURHO2		kg/m^3	ASCENT FUEL DENSITY
1141	OXRHO2		kg/m^3	ASCENT OXIDIZER DENSITY
25	PPRES2		PSI	ASCENT PROP TANK PRESSURE
1	NFUTNK2			ASCENT NUMBER FUEL TANKS
1.8	FURAD2		m	ASCENT FUEL TANK RAD
1	NOXTNK2			ASCENT NUMBER OX TANKS
1	OXRAD2		m	ASCENT OX TANK RAD
3.1E8	METSIG2			ASCENT TANK METAL SIGMA
2710	METRHO2		kg/m^3	ASCENT TANK METAL RHO
.001143	TMIN2		M	ASCENT TANK MINIMUM THICKNESS
400900	FUVAP2		J/kg	ASCENT FUEL LATENT HEAT OF VAP
198340	OXVAP2		J/kg	ASCENT OX LATENT HEAT OF VAP
21	TEMPFU2		DEG K	ASCENT FUEL TEMPERATURE
91	TEMPOX2		DEG K	ASCENT OX TEMPERATURE
49	STIME		Day	STAYTIME
21176.7	HTRATEF			
14190.5	HTRATEO			
				---DESCENT STAGE BREAKDOWN (1)
	PRPSYS1	2125.8498	kg	DESCENT PROPULSION SYSTEM MASS
	TNKST1	300.65765	kg	DESCENT TANK STRUCTURE
	TNKS1	1002.1922	kg	DESCENT PROPELLANT TANKS
	SPPT1	3959.475	kg	DESCENT SUPPORT MASS
2100	STRUCT1		kg	DESCENT STRUCTURE MASS
	STAGE1	8552.3897	kg	DESCENT STAGE MASS
	GROWTH1	1217.065	kg	DESCENT GROWTH BUDGET
0	PTNK1		kg	DESCENT PRESSURANT TANK MASS
0	HEMASS1		kg	DESCENT HELIUM MASS
	PSYS1	0	kg	DESCENT PRESSURIZATION SYSTEM MASS
				---ASCENT STAGE BREAKDOWN (2)
	PRPSYS2	1268.4775	kg	ASCENT PROPULTION SYSTEM MASS
	TNKST2	131.18712	kg	ASCENT TANK STRUCTURE
	TNKS2	437.29039	kg	ASCENT PROPELLANT TANKS
0	HEMASS2		kg	ASCENT HELIUM MASS
0	PTNK2		kg	ASCENT PRESSURANT TANK MASS
	PSYS2	0	kg	ASCENT PRESSURIZATION SYSTEM MASS
	SPPT2	3216	kg	ASCENT SUPPORT
1400	STRUCT2		kg	ASCENT STRUCTURE MASS
	STAGE2	13009.373	kg	ASCENT STAGE MASS
	GROWTH2	896.8955	kg	ASCENT GROWTH BUDGET
				---DESCENT PROPELLANT STUFF
	RESID1	932.41033	kg	DESCENT RESIDUALS
	PROP1	32012.755	kg	DESCENT TOTAL PROP
	BOIL1	185.32855	kg	DESCENT PROP BOILOFF
				---ASCENT PROPELLANT STUFF
	RESID2	327.59679	kg	ASCENT RESIDUALS
	PROP2	11247.49	kg	ASCENT TOTAL PROP
	BOIL2	246.57538	kg	ASCENT PROP BOILOFF

			---DESCENT TANKS---
FU1	4824.5123	kg	DESCENT FUEL MASS
OX1	27514.932	kg	DESCENT OX MASS
FUVOL1	68.142829	m^3	DESCENT FUEL VOLUME
OXVOL1	24.114752	m^3	DESCENT OX VOLUME
OXTNK1	125.08181	kg	DESCENT OX TANK MASS
FUTNK1	101.15669	kg	DESCENT FUEL TANK MASS
FUTNKV1	11.924995	M^3	DESCENT FUEL TANK VOLUME
OXTNKV1	12.660245	M^3	DESCENT OX TANK VOLUME
LENFU1	3.4360027	m	DESCENT FUEL TANK LENGTH
ATOTFU1	25.90685	m^2	DESCENT FUEL TANK AREA/TANK
LENOX1	3.111183	m	DESCENT OX TANK LENGTH
ATOTOX1	26.389988	m^2	DESCENT OX TANK AREA/TANK
MLI1	145.08841	kg	DESCENT MLI MASS
			---ASCENT TANKS---
FU2	1805.4579	kg	ASCENT FUEL MASS
OX2	9741.508	kg	ASCENT OX MASS
FUVOL2	25.500818	m^3	ASCENT FUEL VOLUME
OXVOL2	8.5376933	m^3	ASCENT OX VOLUME
OXTNK2	109.43616	kg	ASCENT OX TANK MASS
FUTNK2	168.41418	kg	ASCENT FUEL TANK MASS
LENFU2	3.8305619	m	ASCENT FUEL TANK LENGTH
ATOTFU2	43.322635	m^2	ASCENT FUEL TANK AREA/TANK
LENOX2	3.5201804	m	ASCENT OX TANK LENGTH
ATOTOX2	22.117946	m^2	ASCENT OX TANK AREA/TANK
MLI2	159.44005	kg	ASCENT MLI MASS
FUTNKV2	26.775859	M^3	ASCENT FUEL TANK VOLUME
OXTNKV2	8.9645779	M^3	ASCENT OX TANK VOLUME

APPENDIX C

Launch Operability Index

Application of the Launch Operability Index (LOI) to the FLO Propulsion System Study

Rob Moreland
NASA/JSC/EP4
July 27, 1992

BASED ON CHARTS:

Launch Operability Index
Operationally Efficient Propulsion System Study

Rockwell International
Space Systems Division

JIM ZIESE
ROCKWELL
INTERNATIONAL
JULY 15-16, 1992

LOI is Determined Using Computer Program

WHAT LOI IS

- A NUMERICAL RATING OF A PROPULSION SYSTEMS OPERABILITY
    - LOI = 0: WORST POSSIBLE SYSTEM - PROBABLY COULD NEVER BE LAUNCHED
    - LOI = 1.0: PERFECT SYSTEM - LAUNCHES ITSELF
- BASED ON OEPSS CONCERN LIST
- OEPSS CONCERNS TRANSFORMED INTO "DESIGN FEATURES" FOR EVALUATION
- EACH FEATURE OF THE SYSTEM BEING ASSESSED IS COMPARED TO A LIST OF OPTIONS FOR THAT FEATURE WITH EACH OPTION ASSIGNED A NUMERICAL RATING
    - A DEFAULT RANKING IS PROVIDED FOR FOR IMMATURE SYSTEMS IN WHICH ONE OR MORE FEATURE IS UNDEFINED
    - PERMITS EVALUATION OF A PROPULSION SYSTEM AT ANY STAGE OF DEVELOPMENT
- WEIGHTING FACTORS ARE ASSIGNED FOR EACH DESIGN FEATURES BASED ON OPERATIONS COMPLEXITY AND POTENTIAL FOR LAUNCH DELAY
- PRODUCTS OF FEATURE RATINGS AND WEIGHTING FACTORS ARE COMBINED TO OBTAIN THE LOI NUMBER
- THE VERSION OF LOI USED FOR THE FLO TRADE STUDY IS CONSIDERED BETA, AND REPRESENTS A TEST CASE FOR THE CONCEPT

Example LOI Calculation

DESIGN FEATURE	1	2	3	4	5	. . . .	16	17
WEIGHTING FACTOR	8	9	9	7	8		2	8
OPERABILITY RATING	5	6	3	7	9		6	6
WF X OR	40	54	27	49	72		63	42
Σ(WF X OR) = 581								

$$\text{LOI} = \frac{\text{CALCULATED } \Sigma(\text{WF X OR})}{\Sigma(\text{WF X MAXIMUM OR})} = \frac{581}{1340} = 0.433$$

Design Features

1. COMPARTMENT CONFIGURATION (8)
2. DEGREE OF CHECKOUT AUTOMATION (9)
3. NUMBER/TYPE OF PROPELLANTS (9)
4. RECOVERY METHOD (7)
5. AUXILIARY PROPULSION TYPE (8)
6. ORDNANCE SYSTEMS (7)
7. ACTUATOR SYSTEM TYPE (6)
8. HEAT SHIELD TYPE (6)
9. PURGE SYSTEM TYPE (5)
10. TVC SYSTEM TYPE (5)
11. FLUID GROUND INTERFACE TYPE (5)
12. TANK PRESSURIZATION SYSTEMS (4)
13. PRECONDITIONING REQTS (4)
14. ACCESSIBILITY (9)
15. POTENTIAL FOR LEAKAGE (8)
16. DEGREE OF HARDWARE INTEGRATION(7)
17. GROUND SUPPORT REQTS (7)
18. ENGINE TYPE (9)

(X) = Weighting Factor

Design Feature #1 - Compartment Configuration

OPERABILITY RATING	FEATURE OPTION
10	COMPLETELY OPEN - NO COMPARTMENTS OR TRAPS
9	COMPLETELY OPEN BEFORE FLIGHT - SINGLE SIMPLE COVER ADDED FOR LAUNCH
8	COMPLETELY OPEN BEFORE FLIGHT - MULTIPLE SIMPLE COVERS ADDED FOR LAUNCH
7	OPEN BUT SMALL TRAP AREA
6	OPEN BUT MULTIPLE OR LARGE TRAP AREAS
5	OPEN EXCEPT FEW SMALL CLOSED COMPARTMENTS
4	OPEN EXCEPT MANY OR LARGE CLOSED COMPARTMENTS
3*	COMPLETELY CLOSED COMPARTMENT - ACCESS THROUGH LARGE EASILY UTILIZED DOORS
2	COMPLETELY CLOSED COMPARTMENT - ACCESS THROUGH MULTIPLE SMALL HATCHES
1	COMPLETELY CLOSED COMPARTMENT - ACCESS THROUGH SINGLE SMALL HATCH

* DEFAULT FOR THIS FEATURE = 3

Design Feature #2 - Checkout Automation

OPERABILITY RATING	FEATURE OPTION
10	NO USING SITE CHECKOUT REQUIRED
9	TOTALLY AUTOMATED - SINGLE COMMAND REQUIRED FOR COMPLETE CHECKOUT
6.5	TOTALLY AUTOMATED EXCEPT MULTIPLE MANUAL COMMANDS REQUIRED FOR COMPLETE CHECKOUT
5	FUNCTIONAL CHECKS OF ALL ACTIVE COMPONENTS AUTOMATED - MOST LEAK CHECKS AUTOMATED
4	FUNCTIONAL CHECKS OF ALL ACTIVE COMPONENTS AUTOMATED - SOME LEAK CHECKS AUTOMATED
2	FUNCTIONAL CHECKS OF ALL ACTIVE COMPONENTS AUTOMATED - LEAK CHECKS PERFORMED MANUALLY
1.5*	FUNCTIONAL CHECKS OF SOME ACTIVE COMPONENTS AUTOMATED - LEAK CHECKS PERFORMED MANUALLY
1	NO AUTOMATION - ALL CHECKOUT PERFORMED MANUALLY

* DEFAULT FOR THIS FEATURE = 1.5

Design Feature #3 - Number/Type of Propellants

OPERABILITY RATING	FEATURE OPTION
10	SINGLE, AMBIENT TEMPERATURE, NON-TOXIC PROPELLANT
9	MULTIPLE, AMBIENT TEMPERATURE, NON-TOXIC PROPELLANTS
9	PREPACKAGED, SEALED PROPELLANTS
7	LO2 WITH HYDROCARBON FUEL
5	LH2
4	LH2, LO2
3.5	LO2 WITH HYDROCARBON FUEL, AND HYPERGOLIC BI-PROPELLANTS
3	LO2, LH2, AND HYDRAZINE MONO-PROPELLANTS
3	LO2, LH2, AND BIPROPELLANTS **
2.5*	LO2, LH2, AND HYPERGOLIC BI-PROPELLANTS
2	LO2, LH2, HYPERGOLIC BI-PROPELLANTS, AND HYDROCARBONS
1	EXTREMELY HAZARDOUS/TOXIC PROPELLANTS (E.G.: FLUORINE, FLOX, PYROPHORICS, ETC.)

* DEFAULT FOR THIS FEATURE = 2.5

**This rating added to original LOI

Design Feature #4 - Recovery Method

OPERABILITY RATING	FEATURE OPTION
10	EXPENDABLE - NO RECOVERY
4	HORIZONTAL LAND (SOFT LANDING)
3.5	VERTICAL LAND (SOFT LANDING)
3	OCEAN RECOVERY WITH COMPLETE EXPOSURE PROTECTION
1	OCEAN RECOVERY WITH NO EXPOSURE PROTECTION

* DEFAULT FOR THIS FEATURE = 10

Design Feature #5 - Auxiliary Propulsion

OPERABILITY RATING	FEATURE OPTION
10	NO AUXILIARY PROPULSION
9	AUXILIARY PROPULSION PREPACKAGED & SEALED
8.5	SINGLE AUXILIARY PROPULSION SYSTEM USING MAIN ENGINE PROPELLANTS FROM SAME TANKS
8	MULTIPLE AUXILIARY PROPULSION SYSTEMS USING MAIN ENGINE PROPELLANTS FROM SAME TANKS
7	SINGLE AUXILIARY PROPULSION SYSTEM USING MAIN ENGINE TYPE PROPELLANTS LOADED OR CHARGED SEPARATELY FROM ME PROPELLANTS
6.5	MULTIPLE AUXILIARY PROPULSION SYSTEM USING MAIN ENGINE TYPE PROPELLANTS LOADED OR CHARGED SEPARATELY FROM ME PROPELLANTS
4	SINGLE AUXILIARY PROPULSION SYSTEM USING A TOXIC OR HAZARDOUS PROPELLANT
3.5	MULTIPLE AUXILIARY PROPULSION SYSTEMS USING A COMMON TOXIC OR HAZARDOUS PROPELLANT
2	MULTIPLE AUXILIARY PROPULSION SYSTEMS, EACH WITH DIFFERENT TYPE TOXIC PROPELLANTS

* DEFAULT FOR THIS FEATURE = 3.5

Design Feature #6 - Ordnance Systems

OPERABILITY RATING	FEATURE OPTION
10	NO ORDNANCE
9	PREINSTALLED BENIGN IGNITION (E.G.: LASER)
8	PREINSTALLED ELECTRICAL IGNITION
7.5	LAUNCH SITE INSTALLATION - CLEARING OF PERSONNEL NOT REQD
6	SINGLE LAUNCH SITE INSTALLATION OPERATION - CLEARING OF PERSONNEL REQD
4	MULTIPLE LAUNCH SITE INSTALLATION OPERATIONS - CLEARING OF PERSONNEL REQD

* DEFAULT FOR THIS FEATURE = 4

Design Feature #7 - Valve Actuator System Type

OPERABILITY RATING	FEATURE OPTION
10	NO ACTUATORS
8	ALL EMA
7.5	ALL EHA
5	PNEUMATIC
4.5	EMA WITH PNEUMATIC BACK-UP
4.0	EMA WITH ACTIVE PNEUMATICS**
3	DISTRIBUTED HYDRAULICS
2*	DISTRIBUTED HYDRAULICS WITH PNEUMATIC BACK-UP

* DEFAULT FOR THIS FEATURE = 2
**This rating added to original LOI

Design Feature #8 - Heatshield Type

OPERABILITY RATING	FEATURE OPTION
10	NO HEATSHIELD
9	SPRAY ON FOAM HEATSHIELD
7	GIMBAL PLANE HEATSHIELD + ENGINE BLANKETS
6	LOCAL SHIELDING OF CRITICAL COMPONENTS
3*	AFT HEATSHIELD WITH DYNAMIC SEAL TO ACCOMMODATE ENGINE GIMBALLING

* DEFAULT FOR THIS FEATURE = 3

Design Feature #9 - Purge System Type

OPERABILITY RATING	FEATURE OPTION
10	NO PNEUMATIC SYSTEM
9	SINGLE GROUND ONLY PURGE. GROUND SUPPLIED & CONTROLLED.
8	MULTIPLE GROUND ONLY PURGES. GROUND SUPPLIED & CONTROLLED.
7	MULTIPLE GROUND ONLY PURGES. VEHICLE PROVIDES ON-OFF CONTROL.
6	MULTIPLE GROUND ONLY PURGES. VEHICLE PROVIDES REGULATION & DISTRIBUTION.
5	SIMPLE STORAGE & DISTRIBUTION PROVIDES FEW FLIGHT PURGES.
4	SIMPLE STORAGE, DISTRIBUTION, & REGULATION PROVIDES FEW FLIGHT PURGES.
3*	STORAGE, DISTRIBUTION, & REGULATION FOR MULTIPLE FLIGHT PURGES <u>OR</u> SIMPLE VALVE PNEUMATIC CONTROL SYSTEM.
2	PNEUMATIC STORAGE, REGULATION & DISTRIBUTION. MULTIPLE GROUND & FLIGHT PURGES. SOME PNEUMATIC VALVE CONTROL
1	COMPLEX PNEUMATIC STORAGE, REGULATION & DISTRIBUTION. MULTIPLE GROUND & FLIGHT PURGES. EXTENSIVE PNEUMATIC VALVE CONTROL SYS.

* DEFAULT FOR THIS FEATURE = 3

Design Feature #10 - TVC System Type

OPERABILITY RATING	FEATURE OPTION
10	DIFFERENTIAL THROTTLING - FIXED MAIN ENGINE NOZZLES
7.5	AUXILIARY THRUSTERS - ALL ENGINE NOZZLES FIXED
6	FLUID INJECTION - FIXED MAIN ENGINE NOZZLES
5.5	MAIN ENGINE NOZZLES FIXED - AUXILIARY THRUSTERS GIMBALLED BY EMA'S
5*	MAIN ENGINES GIMBALLED WITH EMA'S
3.5	MAIN ENGINE NOZZLES FIXED - AUXILIARY THRUSTERS GIMBALLED BY HYDRAULICS - BATTERIES PROVIDE POWER
3	MAIN ENGINE NOZZLES GIMBALLED WITH HYDRAULIC ACTUATORS - BATTERIES PROVIDE POWER
2	MAIN ENGINE NOZZLES GIMBALLED WITH HYDRAULIC ACTUATORS - ENGINES PROVIDE POWER**
1.5	MAIN ENGINE NOZZLES FIXED - AUXILIARY THRUSTERS GIMBALLED BY HYDRAULICS - HYDRAZINE APU PROVIDES POWER
1	MAIN ENGINE NOZZLES GIMBALLED WITH HYDRAULIC ACTUATORS - HYDRAZINE APU PROVIDES POWER

* DEFAULT FOR THIS FEATURE = 5

**This rating added to original LOI

Design Feature #11 - Fluid Ground Interface Type

OPERABILITY RATING	FEATURE OPTION
10	FLUIDS (2) ONLY - EXPENDABLE, RISE OFF CONNECTIONS LOCATED ON BASE OF VEHICLE, ZERO EXTERNAL LEAKAGE DESIGN
10	FLUIDS (2) ONLY - EXPENDABLE, NO LEAKAGE, LOADED OFF-LINE**
9	MULTI-FLUID - EXPENDABLE, RISE OFF CONNECTIONS LOCATED ON BASE OF VEHICLE, ZERO EXTERNAL LEAKAGE DESIGN
6	MULTI-FLUID - EXPENDABLE, RISE OFF CONNECTIONS LOCATED ON BASE OF VEHICLE
4	MILTI-FLUID - PULL AWAY CONNECTIONS LOCATED AT VEHICLE BASE AND OTHER CONVENTIONAL VEHICLE / GROUND INTERFACE POINTS REQUIRING QD PROTECTION
2*	MULTI-FLUID - RETRACT AT COMMIT, CONNECTIONS LOCATED AT CONVENTIONAL VEHICLE / GROUND INTERFACE POINTS, REQUIRING TAIL SERVICE MAST INFRASTRUCTURE, TOWERS AND SWING ARM INFRASTRUCTURE, AND REUSABLE, SOPHISTICATED QD CONFIGURATION REQUIRING EXTENSIVE MAINTENANCE / REFURBISHMENT

* DEFAULT FOR THIS FEATURE = 2

**This rating added to original LOI

Design Feature #12 - Tank Pressurization Systems

OPERABILITY RATING	FEATURE OPTION
10	TANKS SELF PRESSURIZED
8	AUTOGENOUS - FIXED ORIFICE CONTROL
7.5	AMBIENT HELIUM - FIXED ORIFICE CONTROL
7	AUTOGENOUS - OPEN LOOP CONTROL VALVE
6	AMBIENT HELIUM - CLOSED LOOP FLOW CONTROL VALVE
5.5*	AUTOGENOUS - CLOSED LOOP FLOW CONTROL VALVE
5	AUTOGENOUS AND AMBIENT HELIUM, CLOSED LOOP**
5	COLD HELIUM, HEAT EXCHANGER - FIXED ORIFICE CONTROL
4	COLD HELIUM, HEAT EXCHANGER - CLOSED LOOP FLOW CONTROL VALVE

* DEFAULT FOR THIS FEATURE = 5.5

**This rating added to original LOI

Design Feature #13 - Preconditioning Requirements

OPERABILITY RATING	FEATURE OPTION
10	NO PRECONDITIONING REQUIRED
9	PRECONDITIONING THRU NATURAL CONVECTION
8.5	PRECONDITIONING THRU ENGINE EXTERNAL BLEED/LEAKAGE OVERBOARD
7	PRECONDITIONING BY PASSIVE FEED LINE BLEEDS TO TANKS
6	PRECONDITIONING BY PASSIVE FEED LINE BLEEDS TO GROUND
5	GROUND PUMPS REQUIRED FOR PRECONDITIONING
3*	FLIGHT PUMPS REQUIRED FOR PRECONDITIONING

* DEFAULT FOR THIS FEATURE = 3

Design Feature #14 - Accessibility

OPERABILITY RATING	FEATURE OPTION
10	EACH COMPONENT & SUBSYSTEM COMPLETELY ACCESSIBLE WITHOUT REMOVAL OF ANY OTHER PARTS OR USE OF ANY SUPPORT EQUIPMENT (STANDS, PLATFORMS, ETC.)
7	EACH COMPONENT & SUBSYSTEM COMPLETELY ACCESSIBLE WITHOUT REMOVAL OF ANY OTHER . SUPPORT EQUIPMENT REQUIRED FOR ACCESS TO SOME ITEMS.
5	ACCESS TO SOME COMPONENTS OR SUBSYSTEMS REQUIRES REMOVAL OF PANELS. EACH COMPONENT & SUBSYSTEM COMPLETELY ACCESSIBLE WITHOUT REMOVAL OF ANY OTHER . LIMITED SUPPORT EQUIPMENT REQUIRED.
3*	ACCESS TO SOME COMPONENTS OR SUBSYSTEMS REQUIRES REMOVAL OF PANELS. ACCESS TO SOME LRU'S REQUIRES REMOVAL OF OTHER HARDWARE. SUPPORT EQUIPMENT REQUIRED FOR ACCESS TO SOME ITEMS.
2	ACCESS TO MOST COMPONENTS OR SUBSYSTEMS REQUIRES REMOVAL OF PANELS. ACCESS TO SOME LRU'S REQUIRES REMOVAL OF OTHER HARDWARE. SUPPORT EQUIPMENT REQD FOR ACCESS TO SOME ITEMS.
1	ACCESS TO ANY COMPONENT OR SUBSYSTEM REQUIRES REMOVAL OF STRUCTURAL PANELS. ACCESS TO MANY LRU'S REQUIRES REMOVAL OF OTHER HARDWARE. EXTENSIVE SUPPORT EQUIPMENT MUST BE USED.

* DEFAULT FOR THIS FEATURE = 3

Design Feature #15 - Leakage Potential

OPERABILITY RATING	FEATURE OPTION
10	HERMETIC SEALING OF ALL FLUID SYSTEMS
7	FEW STATIC SEALS ONLY USED IN FLUID SYSTEMS.
5	STATIC SEALS ONLY USED IN FLUID SYSTEMS.
3*	EXTENSIVE USE OF STATIC SEALS IN ALL FLUID SYSTEMS. FEW DYNAMIC SEALS USED.
1	EXTENSIVE USE OF STATIC & DYNAMIC SEALS IN ALL FLUID SYSTEMS

* DEFAULT FOR THIS FEATURE = 3

Design Feature #16 - Hardware Integration

OPERABILITY RATING	FEATURE OPTION
10	FULLY INTEGRATED - ESSENTIALLY A SINGLE SUBSYSTEM
7	PHYSICAL INTEGRATION OF MAJOR SUBSYSTEMS - COMMON REQUIREMENTS WHERE POSSIBLE
3*	LITTLE PHYSICAL INTEGRATION - SOME COMMON SUBSYSTEM REQUIREMENTS
1	NO INTEGRATION - EACH SUBSYSTEM HAS DIFFERING REQUIREMENTS

* DEFAULT FOR THIS FEATURE = 3

Design Feature #17 - Ground Support Requirements

OPERABILITY RATING	FEATURE OPTION
10	NO GROUND SUPPORT EQUIPMENT REQUIRED
9	ONLY SIMPLE STANDARD TOOLS AND EQUIPMENT REQUIRED FOR GROUND SUPPORT
7	COMPLEX EQUIPMENT REQUIRED BUT ALL COMMON USAGE WITH LITTLE MAINTENANCE NEEDED
3*	SOME SPECIALLY DEVELOPMENT EQUIPMENT EQUIPMENT NEEDED WITH SIGNIFICANT MAINTENANCE REQUIRED
1	COMPLEX SPECIALLY DEVELOPED EQUIPMENT NEEDED WITH EXTENSIVE MAINTENANCE REQUIREMENTS

* DEFAULT FOR THIS FEATURE = 3

Design Feature #18 - Main Engine Type

OPERABILITY RATING	FEATURE OPTION
10	PRESSURE FED MONOPROP
9.5	PRESSURE FED MONOPROP, THROTTLE
9	PRESSURE FED BI-PROP
8.5	PRESSURE FED BI-PROP, THROTTLE
6	PUMP FED GAS GENERATOR BI-PROP
5	PUMP FED EXPANDER, LH2 AUTOGENOUS
4.5	PUMP FED EXPANDER, LH2 AUTOGENOUS, THROTTLE
4	PUMP FED EXPANDER, LH2&LO2 HEAT EXCHANGER
3.5*	PUMP FED EXPANDER, LH2&LO2 HEAT EXCHANGER, THROTTLE
3	PUMP FED EXPANDER, LH2 AUTOGENOUS, LH2 RECIRC PUMP
1	STAGED COMBUSTION, LH2 & LO2 HEAT EXCHANGER
0.5	STAGED COMBUSTION, LH2 & LO2 HEAT EXCHANGER, THROTTLE

* DEFAULT FOR THIS FEATURE = 3.5

**This rating added to original LOI

LAUNCH OPERABILITY INDEX Summary

Design Feature	Weight Factor	Trade 1		Trade 2		Trade 3		Trade 4		Trade 5		Trade 6		Trade 7		Trade 8		Trade 9		Trade 10		Trade 11		Trade 12		Trade 13		Trade 14	
		LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET	LAN	RET
#1 Comp Config.	8	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	10	3	10	3	3	3	3	3	3	3	10
#2 Checkout Auto	9	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
#3 Propellants	9	3	3	3	3	3	1	3	3	3	7	3	3	3	7	3	4	3	4	3	4	1	1	4	4	3	4	4	4
#4 Recovery	7	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
#5 RCS Type	8	4	10	4	10	4	10	4	10	4	10	4	10	4	10	4	10	4	10	4	10	8.5	10	8.5	10	4	10	10	10
#6 Ordnance	7	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
#7 Valve Actuators	6	4	8	4	8	4	8	4	8	4	8	4	8	4	4	4	4	4	10	4	10	8	8	8	8	4	8	8	8
#8 Heat Shield	6	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	6	10	6	10	10	10	10	10	10	10	10	10
#9 Purge	5	2	10	2	9	2	10	2	10	2	9	2	2	2	2	2	2	2	2	2	2	10	10	10	10	2	10	10	10
#10 TVC System	5	2	5	2	5	2	5	2	5	2	5	2	5	2	2	2	2	2	10	2	10	5	5	10	10	2	5	10	10
#11 Fluid/Gnd. Inter	5	2	10	2	4	2	10	2	10	2	4	2	10	2	2	2	2	2	10	2	10	10	10	2	2	2	2	2	10
#12 Tank Press	4	5	6	5	6	5	6	5	6	5	6	5	6	5	5	5	5	5	5	5	5	6	6	8	8	5	4	5.5	5.5
#13 Precondition	4	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
#14 Accessibility	9	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
#15 Leakage Potent.	8	3	10	3	3	3	10	3	10	3	3	3	10	3	3	3	3	3	3	3	3	7	10	3	3	3	3	3	3
#16 Hdwr Integrat	7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	10	3	3	7	7	3	3	7	10
#17 GSE Reqts	7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	10	3	10	3	3	3	3	3	3	3	10
#18 Engine Type	9	4.5	9	4.5	9	4.5	9	4.5	9	4.5	9	4.5	6	4.5	4.5	4.5	3	4.5	10	4.5	10	9	9	3.5	3.5	4.5	9	4.5	10
LOI Score		538	816	538	725	538	798	538	816	538	761	538	749	538	632	538	592	514	876	500	925	752	798	718	740	538	721	729	955
LOI Possible	1230																												
LOI Number		.44	.66	.44	.59	.44	.65	.44	.66	.44	.62	.44	.61	.44	.51	.44	.48	.42	.71	.41	.75	.61	.65	.58	.60	.44	.59	.59	.78

APPENDIX D

D1 Subcriteria Weights and Pairwise Comparison Matrices

The following section provides the reader with the weighted levels lower in the criteria hierarchy than those presented in Section 7.0. For example, the subcriteria "Supportability" consists of a measure for the Lander (descent) and Return (ascent) stage Launch Operability Index (LOI). Thus, the descent LOI is weighted against the ascent LOI, and for this study the ascent LOI weight equals the descent LOI weight. Similarly, the ratings for each LOI score are weighted against one another and these weights are also presented. The weights for all seven of the subcriteria are presented in this section.

D1.1 Supportability
D1.2 Operability
D1.3 Vehicle Design Issues
D1.4 Complexity
D1.5 Vehicle Metrics
D1.6 Hardware Readiness Level
D1.7 Evolution

D2 Cumulative Weights

The different subcriteria can appear multiple times in the hierarchy, under Cost, Schedule, Performance and Risk. Since a subcriteria can have one weight under Cost and another weight under Schedule, these weights can be added and the cumulative weight of each subcriteria can be calculated. A detailed cumulative weights discussion is presented in Section 7.1.3 and the cumulative weights of the subcriteria are presented in Figure 7.9. This appendix presents the cumulative weights of the hierarchical level just below the subcriteria. The weights at this level add to a score of 1.

APPENDIX Section D1.1

Supportability

Data with respect to:
SUPPORT < GOAL

Node: 10000

	VALUE
DESC LOI	0.50000
ASC LOI	0.50000

GOAL: Select Propulsion System best Meeting Program Resources and Req

ASC LOI --- Launch Operability Index for Return Stage
DESC LOI --- Launch Operability Index for Lander Stage
SUPPORT --- Measure of the Vehicle Launch Supportibility

PRIORITIES

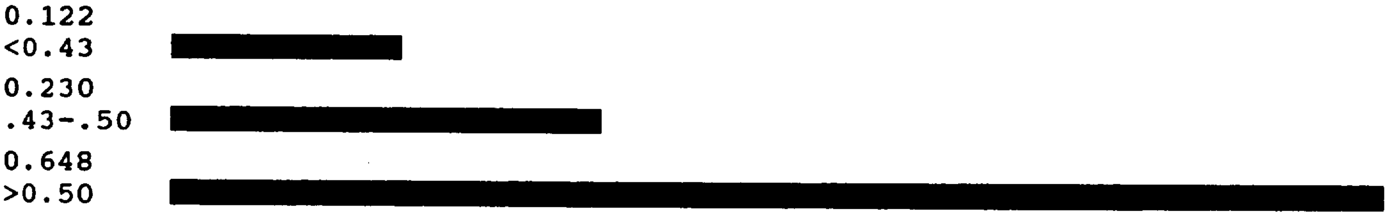
```
                                  JUDGMENTS WITH RESPECT TO
                                  DESC LOI < SUPPORT < GOAL

          <0.43     .43-.50   >0.50
 <0.43               ( 2.0)   ( 5.0)
 .43-.50                      ( 3.0)
 >0.50

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

   GOAL: Select Propulsion System best Meeting Program Resources and Req

.43-.50  --- Value of Descent LOI
<0.43    --- Value of Descent LOI
>0.50    --- Value of Descent LOI
DESC LOI --- Launch Operability Index for Lander Stage
SUPPORT  --- Measure of the Vehicle Launch Supportibility
                                        PRIORITIES
```



```
                        INCONSISTENCY RATIO = 0.004.
```

JUDGMENTS WITH RESPECT TO
ASC LOI < SUPPORT < GOAL

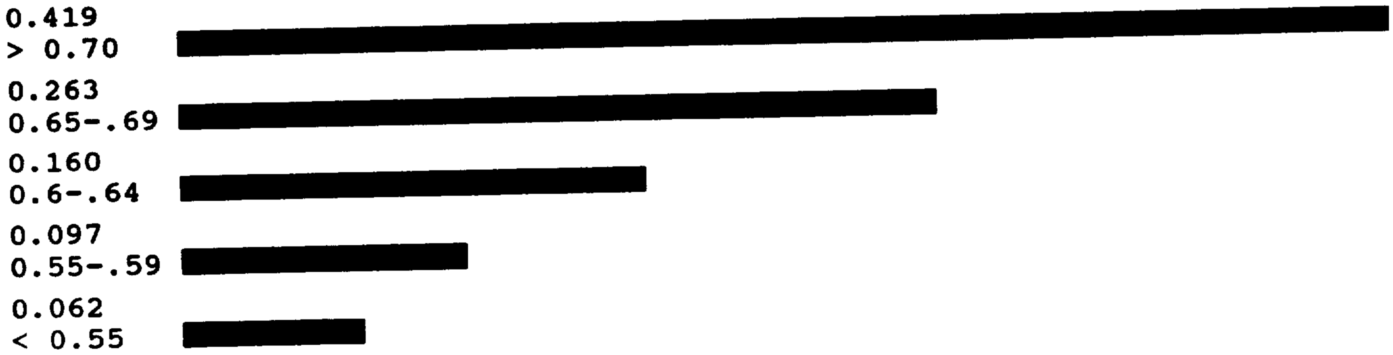
	> 0.70	0.65-.69	0.6-.64	0.55-.59	< 0.55
> 0.70		2.0	3.0	4.0	5.0
0.65-.69			2.0	3.0	4.0
0.6-.64				2.0	3.0
0.55-.59					2.0
< 0.55					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

0.55-.59 --- Value of Return LOI
0.6-.64 --- Value of Return LOI
0.65-.69 --- Value of Return LOI
< 0.55 --- Value of Return LOI
> 0.70 --- Value of Return LOI
ASC LOI --- Launch Operability Index for Return Stage
SUPPORT --- Measure of the Vehicle Launch Supportibility

PRIORITIES



INCONSISTENCY RATIO = 0.015.

APPENDIX Section D1.2

Operability

Verbal judgments of IMPORTANCE with respect to:
OPERABLE < GOAL

Node: 20000

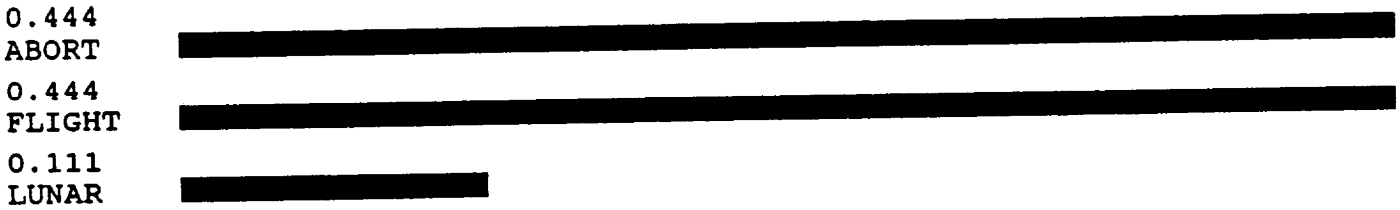
1	ABORT	9 8 7 6 5 4 3 2	█	2 3 4 5 6 7 8 9	FLIGHT
2	ABORT	9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9	LUNAR
3	FLIGHT	9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9	LUNAR

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

ABORT --- Abort Operability Measure
FLIGHT --- Flight Operability Measure
LUNAR --- Lunar Operability Measure
OPERABLE --- Measure of the Complexity of Operations

PRIORITIES



INCONSISTENCY RATIO = 0.000.

Verbal judgments of PREFERENCE with respect to:
ABORT < OPERABLE < GOAL

Node: 21000

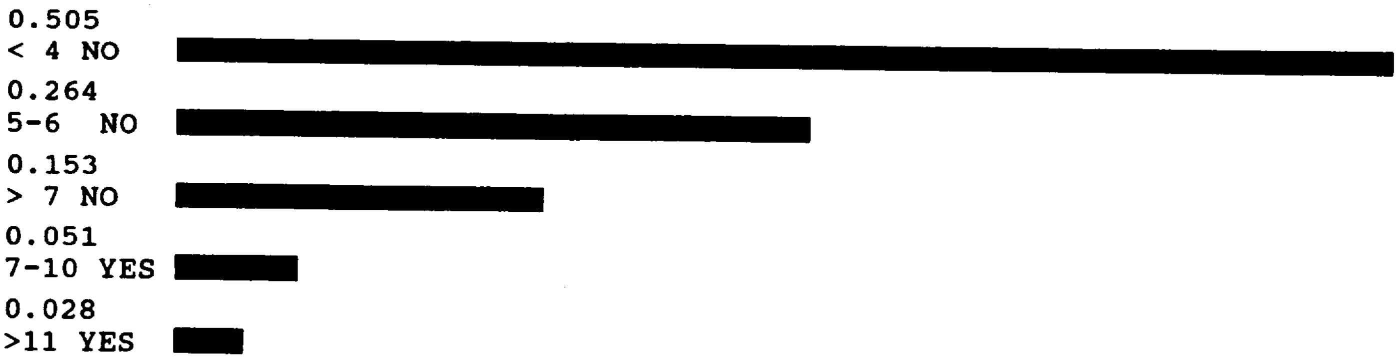
1	< 4 NO	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	5-6 NO
2	< 4 NO	9 8 7 6 █ 4 3 2	1	2 3 4 5 6 7 8 9	> 7 NO
3	< 4 NO	9 █ 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	7-10 YES
4	< 4 NO	█ 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	>11 YES
5	5-6 NO	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	> 7 NO
6	5-6 NO	9 8 7 █ 5 4 3 2	1	2 3 4 5 6 7 8 9	7-10 YES
7	5-6 NO	9 █ 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	>11 YES
8	> 7 NO	9 8 7 6 █ 4 3 2	1	2 3 4 5 6 7 8 9	7-10 YES
9	> 7 NO	9 █ 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	>11 YES
10	7-10 YES	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	>11 YES

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

5-6 NO --- # of Abort Ops without any Prechill
7-10 YES --- Number of Abort Ops with Prechill Required to anticipate aborts
< 4 NO --- # of Abort Ops without any Prechill
> 7 NO --- # of Abort Ops without any Prechill
>11 YES --- Number of Abort Ops with Prechill Required to Anticipate Abort
ABORT --- Abort Operability Measure
OPERABLE --- Measure of the Complexity of Operations

PRIORITIES



INCONSISTENCY RATIO = 0.088.

JUDGMENTS WITH RESPECT TO
FLIGHT < OPERABLE < GOAL

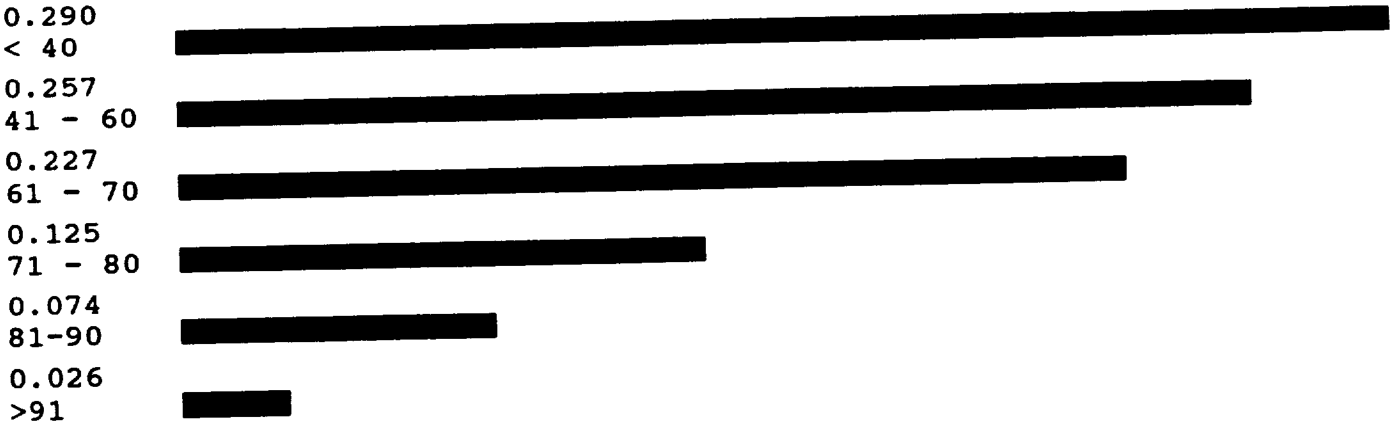
	< 40	41 - 60	61 - 70	71 - 80	81-90	>91
< 40		1.2	1.3	3.0	4.0	9.0
41 - 60			1.2	2.8	3.6	8.0
61 - 70				2.6	3.2	7.0
71 - 80					3.0	6.0
81-90						5.0
>91						

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

41 - 60 --- # of Flight Ops
61 - 70 --- # of Flight Ops
71 - 80 --- # of Flight Ops
81-90 --- # of Flight Ops
< 40 --- # of Flight Ops
>91 --- # of Flight Ops
FLIGHT --- Flight Operability Measure
OPERABLE --- Measure of the Complexity of Operations

PRIORITIES



INCONSISTENCY RATIO = 0.031.

Verbal judgments of PREFERENCE with respect to:
LUNAR < OPERABLE < GOAL
Node: 23000

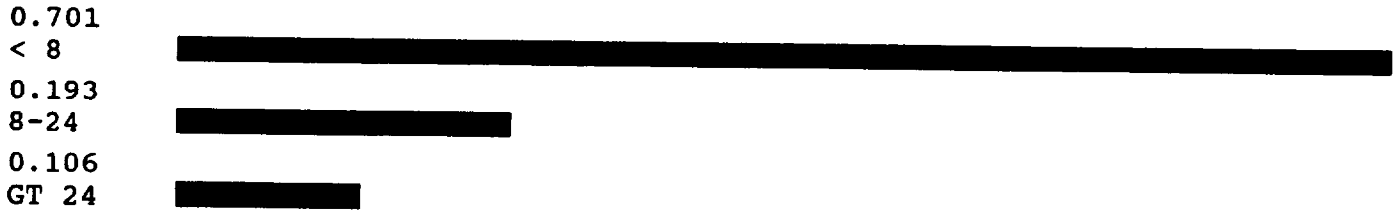
1	< 8 9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9 8-24
2	< 8 9 8 7 █ 5 4 3 2	1	2 3 4 5 6 7 8 9 GT 24
3	8-24 9 8 7 6 5 4 3 █	1	2 3 4 5 6 7 8 9 GT 24

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

8-24 --- Number of Lunar Operations Required
< 8 --- Number of Lunar Operations Required
GT 24 --- Number of Lunar Operations Required
LUNAR --- Lunar Operability Measure
OPERABLE --- Measure of the Complexity of Operations

PRIORITIES



INCONSISTENCY RATIO = 0.009.

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APPENDIX Section D1.3

Vehicle Design Issues

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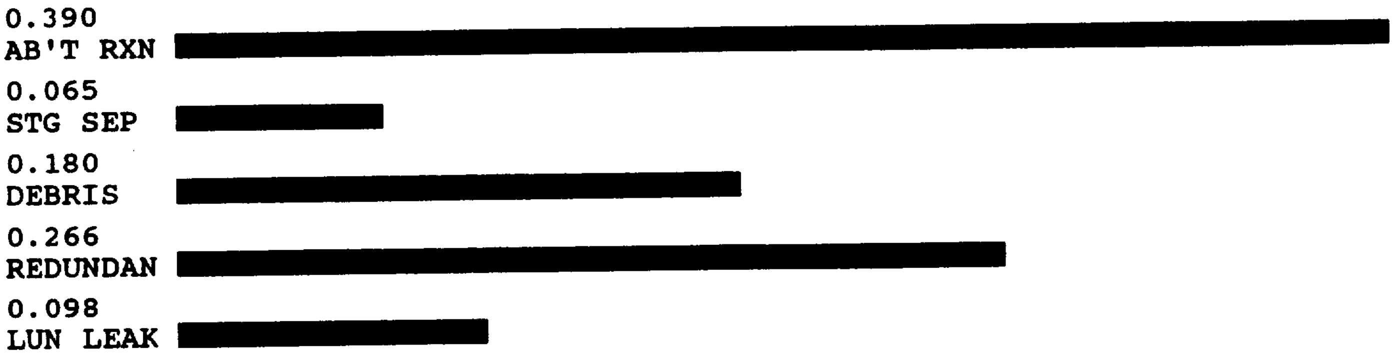
```
                    JUDGMENTS WITH RESPECT TO
                        DSN ISSU < GOAL

           AB'T RXN  STG SEP   DEBRIS    REDUNDAN  LUN LEAK
AB'T RXN               4.0       3.0       2.0       3.0
STG SEP                        ( 3.0)    ( 4.0)    ( 2.0)
DEBRIS                                   ( 2.0)      3.0
REDUNDAN                                             3.0
LUN LEAK

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more IMPORTANT than COLUMN element unless enclosed in parenthesis.


   GOAL: Select Propulsion System best Meeting Program Resources and Req

AB'T RXN --- Abort Reaction Time:90% Thrust for Return Engines During Landing
DEBRIS   --- Exposure Level of Return Stage Engines to Surface Debris
DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
LUN LEAK --- Leakage Potential on the Lunar Surface
REDUNDAN --- Level of Redundancy: # faults during (landing,return,post-abort)
STG SEP  --- Stage Separation Characteristics
                                  PRIORITIES
```



```
                    INCONSISTENCY RATIO = 0.040.
```

Verbal judgments of PREFERENCE with respect to:
AB'T RXN < DSN ISSU < GOAL

Node: 31000

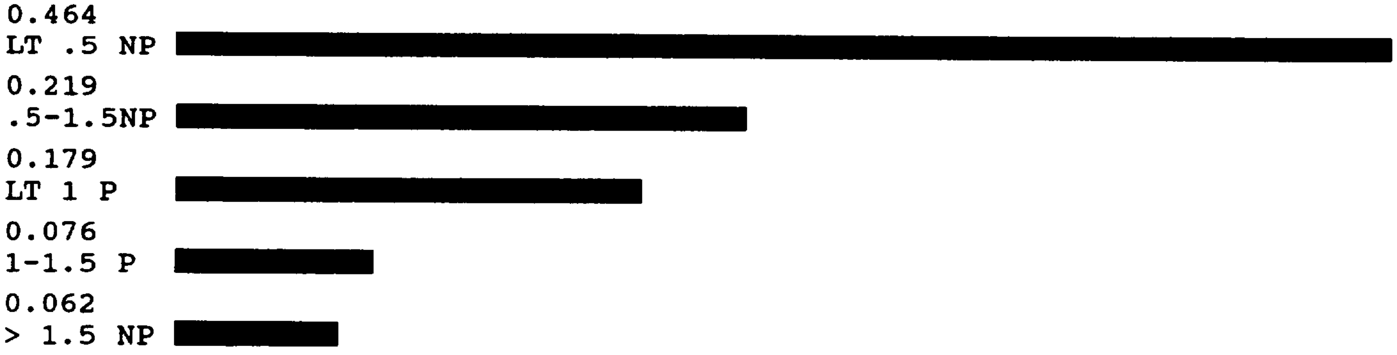
1	LT .5 NP	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	.5-1.5NP
2	LT .5 NP	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	LT 1 P
3	LT .5 NP	9 8 7 █ 5 4 3 2	1	2 3 4 5 6 7 8 9	1-1.5 P
4	LT .5 NP	9 8 7 6 █ 4 3 2	1	2 3 4 5 6 7 8 9	> 1.5 NP
5	.5-1.5NP	9 8 7 6 5 4 3 █	1	2 3 4 5 6 7 8 9	LT 1 P
6	.5-1.5NP	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	1-1.5 P
7	.5-1.5NP	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	> 1.5 NP
8	LT 1 P	9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9	1-1.5 P
9	LT 1 P	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	> 1.5 NP
10	1-1.5 P	9 8 7 6 5 4 3 █	1	2 3 4 5 6 7 8 9	> 1.5 NP

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

.5-1.5NP --- Abort Reaction Time, No pre-chill required
1-1.5 P --- Abort Reaction Time, Prechill Required
> 1.5 NP --- Abort Reaction Time with No Prechill
AB'T RXN --- Abort Reaction Time:90% Thrust for Return Engines During Landing
DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
LT .5 NP --- Abort Reaction Time, No pre-chill required.
LT 1 P --- Abort Reaction Time, Prechill Required

PRIORITIES



INCONSISTENCY RATIO = 0.050.

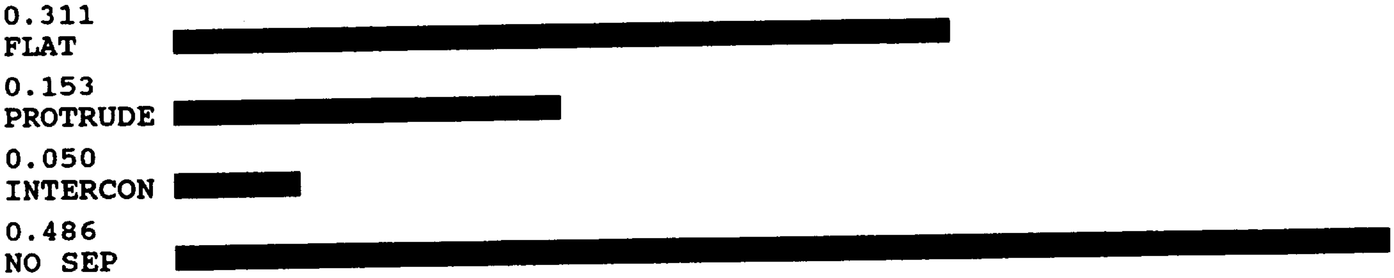
```
                    JUDGMENTS WITH RESPECT TO
                    STG SEP < DSN ISSU < GOAL

           FLAT       PROTRUDE  INTERCON  NO SEP
FLAT                    2.0       8.0     ( 2.0)
PROTRUDE                          3.0     ( 3.0)
INTERCON                                  ( 8.0)
NO SEP

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

   GOAL: Select Propulsion System best Meeting Program Resources and Req

DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
FLAT     --- Flat Interface Between Stages
INTERCON --- Return Stage Completely Surrounded by Lander Stage
NO SEP   --- No Separation Required
PROTRUDE --- Return Engines Protude Into Lander Stage
STG SEP  --- Stage Separation Characteristics
                              PRIORITIES
```



```
                INCONSISTENCY RATIO = 0.016.
```

Data with respect to:
DEBRIS < DSN ISSU < GOAL

Node: 33000

	VALUE
PROTECT	1.00000
EXPOSED	0.00000

GOAL: Select Propulsion System best Meeting Program Resources and Req

DEBRIS --- Exposure Level of Return Stage Engines to Surface Debris
DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
EXPOSED --- Return Stage Engines are Exposed to Debris During Lunar Landing
PROTECT --- Return Stage Engines are Protected From Debris During Landing

PRIORITIES

Verbal judgments of PREFERENCE with respect to:
REDUNDAN < DSN ISSU < GOAL

Node: 34000

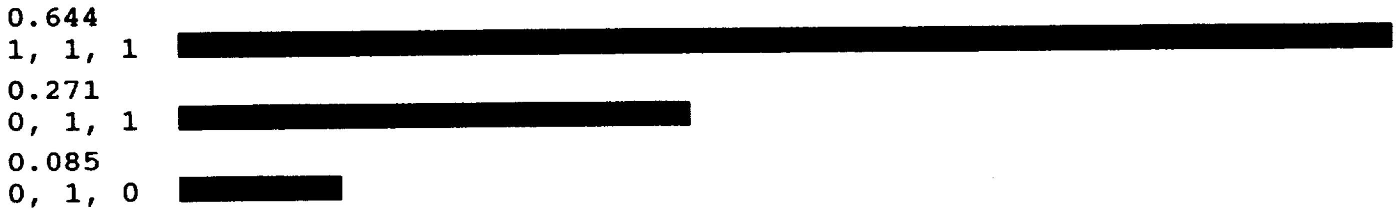
1	1, 1, 1	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	0, 1, 1
2	1, 1, 1	9 8 7 █ 5 4 3 2	1	2 3 4 5 6 7 8 9	0, 1, 0
3	0, 1, 1	9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9	0, 1, 0

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

0, 1, 0 --- Number of Faults for (landing, return, post-abort)
0, 1, 1 --- Number of Faults for (landing,return,post-abort)
1, 1, 1 --- Number of Faults for (landing,return,post-abort)
DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
REDUNDAN --- Level of Redundancy: # faults during (landing,return,post-abort)

PRIORITIES



INCONSISTENCY RATIO = 0.051.

```
                          JUDGMENTS WITH RESPECT TO
                         LUN LEAK < DSN ISSU < GOAL

        LOW       MODERATE  HI
 LOW                2.0       5.0
 MODERATE                     4.0
 HI

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.


    GOAL: Select Propulsion System best Meeting Program Resources and Req

DSN ISSU --- Design Issues Affecting Success Which Will Require Design Effort
HI       --- Hi Leakage Potential
LOW      --- Low Leakage Potential
LUN LEAK --- Leakage Potential on the Lunar Surface
MODERATE --- Moderate Leakage Potential
                                   PRIORITIES
```

```
                      INCONSISTENCY RATIO = 0.023.
```

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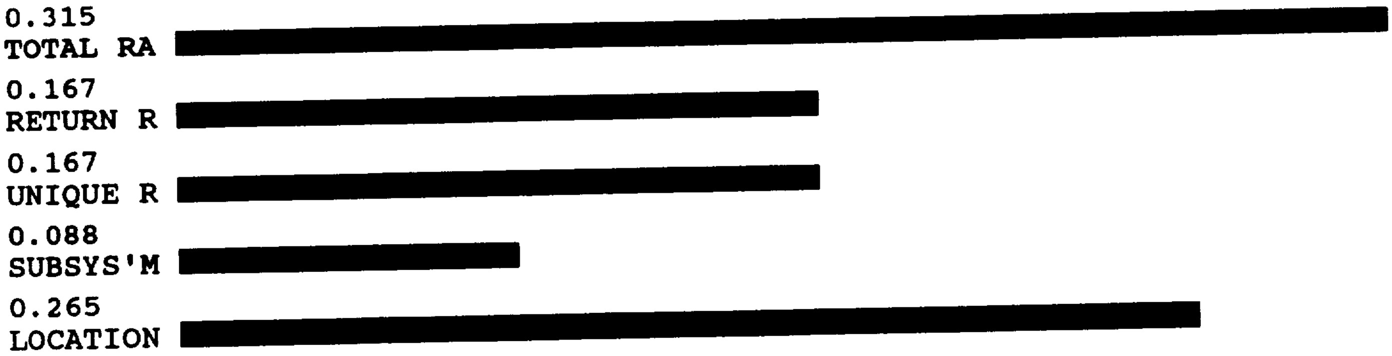
APPENDIX Section D1.4

Complexity

```
                    JUDGMENTS WITH RESPECT TO
                       COMPLEX < GOAL

          TOTAL RA  RETURN R  UNIQUE R  SUBSYS'M  LOCATION
TOTAL RA               1.5       1.5       3.0       2.0
RETURN R                         1.0       2.0     ( 2.0)
UNIQUE R                                   2.0     ( 2.0)
SUBSYS'M                                           ( 3.0)
LOCATION

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more IMPORTANT than COLUMN element unless enclosed in parenthesis.

   GOAL: Select Propulsion System best Meeting Program Resources and Req

COMPLEX  --- Measure of the Complexity
LOCATION --- Number of Instrumentation Locations
RETURN R --- Complexity Rating for Number of Return Components
SUBSYS'M --- Number of Subsystems
TOTAL RA --- Complexity Rating for Total Number of Components
UNIQUE R --- Complexity Rating for Number of Unique Components
                                    PRIORITIES
```



```
                    INCONSISTENCY RATIO = 0.024.
```

JUDGMENTS WITH RESPECT TO
TOTAL RA < COMPLEX < GOAL

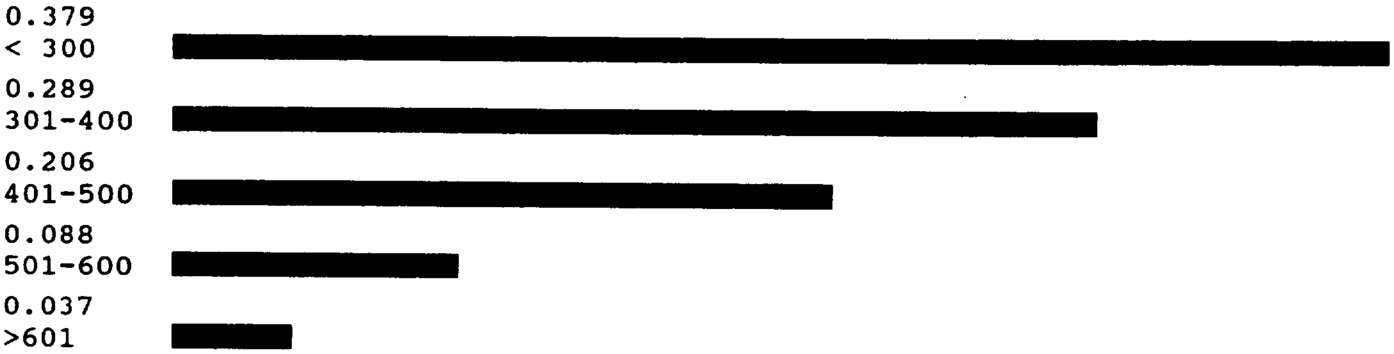
	< 300	301-400	401-500	501-600	>601
< 300		1.5	2.0	4.0	9.0
301-400			1.5	3.5	8.0
401-500				3.0	5.0
501-600					3.0
>601					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

301-400 --- Rating for Total Number of Components
401-500 --- Rating for Total Number of Components
501-600 --- Rating for Total Number of Components
< 300 --- Rating for Total Number of Components
>601 --- Rating for Total Number of Compontents
COMPLEX --- Measure of the Complexity
TOTAL RA --- Complexity Rating for Total Number of Components

PRIORITIES



INCONSISTENCY RATIO = 0.008.

Verbal judgments of PREFERENCE with respect to:
RETURN R < COMPLEX < GOAL

Node: 42000

1	<95	9 8 7 6 5 4 3 ■	1	2 3 4 5 6 7 8 9	95-120
2	<95	9 8 7 6 5 ■ 3 2	1	2 3 4 5 6 7 8 9	120-200
3	<95	9 8 7 ■ 5 4 3 2	1	2 3 4 5 6 7 8 9	200-300
4	<95	9 ■ 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	300-350
5	<95	■ 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	350-400
6	95-120	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	120-200
7	95-120	9 8 7 6 ■ 4 3 2	1	2 3 4 5 6 7 8 9	200-300
8	95-120	9 8 ■ 6 5 4 3 2	1	2 3 4 5 6 7 8 9	300-350
9	95-120	■ 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	350-400
10	120-200	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	200-300
11	120-200	9 8 7 6 ■ 4 3 2	1	2 3 4 5 6 7 8 9	300-350
12	120-200	9 8 ■ 6 5 4 3 2	1	2 3 4 5 6 7 8 9	350-400
13	200-300	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	300-350
14	200-300	9 8 7 ■ 5 4 3 2	1	2 3 4 5 6 7 8 9	350-400
15	300-350	9 8 7 6 5 4 3 ■	1	2 3 4 5 6 7 8 9	350-400

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

120-200 --- Complexity Rating for Number of Return Components
200-300 --- Complexity Rating for Number of Return Components
300-350 --- Complexity Rating for Number of Retrun Components
350-400 --- Complexity Rating for Number of Return Components
95-120 --- Complexity Rating for Number of Return Components
<95 --- Complexity Rating for Number of Return Components
COMPLEX --- Measure of the Complexity
RETURN R --- Complexity Rating for Number of Return Components

PRIORITIES

```
0.025
350-400  ████

                         INCONSISTENCY RATIO = 0.054.
```

Verbal judgments of PREFERENCE with respect to:
UNIQUE R < COMPLEX < GOAL Node: 43000

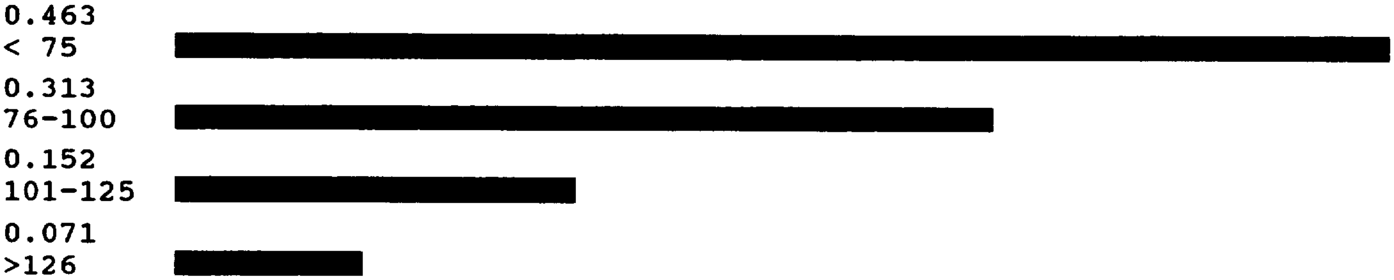
1	< 75	9 8 7 6 5 4 3 █	1	2 3 4 5 6 7 8 9	76-100
2	< 75	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	101-125
3	< 75	9 8 7 6 █ 4 3 2	1	2 3 4 5 6 7 8 9	>126
4	76-100	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	101-125
5	76-100	9 8 7 6 5 █ 3 2	1	2 3 4 5 6 7 8 9	>126
6	101-125	9 8 7 6 5 4 █ 2	1	2 3 4 5 6 7 8 9	>126

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

101-125 --- Rating for Number of Unique Components
76-100 --- Rating for Number of Unique Components
< 75 --- Rating for Number of Unique Components
>126 --- Rating for Number of unique Components
COMPLEX --- Measure of the Complexity
UNIQUE R --- Complexity Rating for Number of Unique Components

PRIORITIES



INCONSISTENCY RATIO = 0.040.

Verbal judgments of PREFERENCE with respect to:
SUBSYS'M < COMPLEX < GOAL Node: 44000

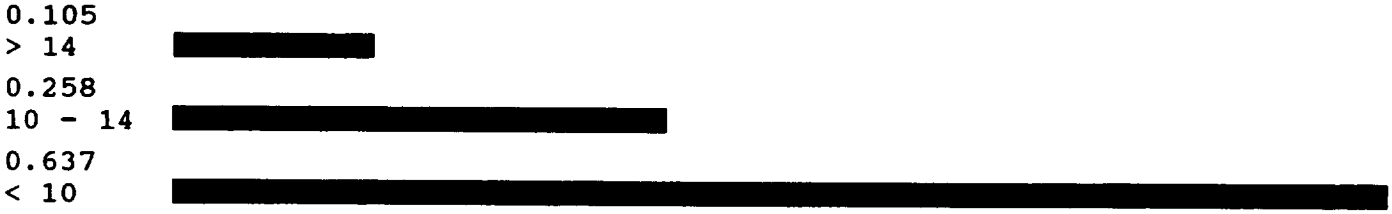
1	> 14	9 8 7 6 5 4 3 2	1	2 █ 4 5 6 7 8 9	10 - 14
2	> 14	9 8 7 6 5 4 3 2	1	2 3 4 █ 6 7 8 9	< 10
3	10 - 14	9 8 7 6 5 4 3 2	1	2 █ 4 5 6 7 8 9	< 10

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

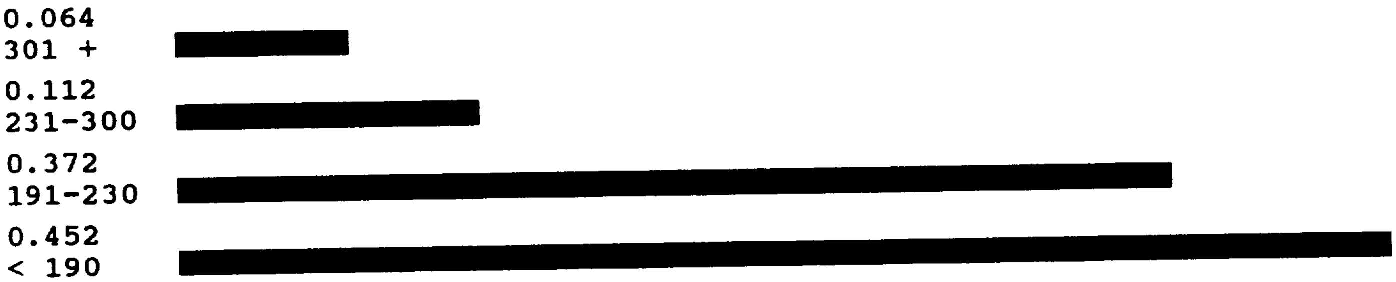
10 - 14 --- Number of Subsystems
< 10 --- Number of Subsystems
> 14 --- Number of Subsystems
COMPLEX --- Measure of the Complexity
SUBSYS'M --- Number of Subsystems

PRIORITIES



INCONSISTENCY RATIO = 0.037.

```
                       JUDGMENTS WITH RESPECT TO
                       LOCATION < COMPLEX < GOAL

          301 +      231-300   191-230   < 190
301 +                ( 3.0)    ( 5.0)    ( 5.0)
231-300                        ( 5.0)    ( 5.0)
191-230                                  ( 1.5)
< 190

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.


   GOAL: Select Propulsion System best Meeting Program Resources and Req

191-230   --- Number of Instrumentation Locations
231-300   --- Number of Instrumentation Locations
301 +     --- Number of Instrumentation Locations
< 190     --- Number of Instrumentation Locations
COMPLEX   --- Measure of the Complexity
LOCATION  --- Number of Instrumentation Locations
                               PRIORITIES
```



```
                    INCONSISTENCY RATIO = 0.066.
```

APPENDIX Section D1.5

Vehicle Metrics

```
                        JUDGMENTS WITH RESPECT TO
                           V-METRIC < GOAL

         POST TLI   HAB-ASC    VOLUME    CG HEIGH
POST TLI               5.0       3.0       5.0
HAB-ASC                        ( 5.0)      1.0
VOLUME                                     5.0
CG HEIGH

Matrix entry indicates that ROW element is ___
  1 EQUALLY   3 MODERATELY   5 STRONGLY   7 VERY STRONGLY   9 EXTREMELY
more IMPORTANT than COLUMN element unless enclosed in parenthesis.


    GOAL: Select Propulsion System best Meeting Program Resources and Req

CG HEIGH --- Center of Gravity Height To Lunar Surface Upon Lunar Landing
HAB-ASC  --- Difference in Mass Between Habitat (Cargo) and Crew Mission
POST TLI --- Post TLI Mass of Lander/Return Vehicle
V-METRIC --- Vehicle Metric Characterstics
VOLUME   --- Volume of the Crew Vehicle Propellant and Pressurant
```

PRIORITIES

INCONSISTENCY RATIO = 0.058.

Verbal judgments of PREFERENCE with respect to:
POST TLI < V-METRIC < GOAL

Node: 51000

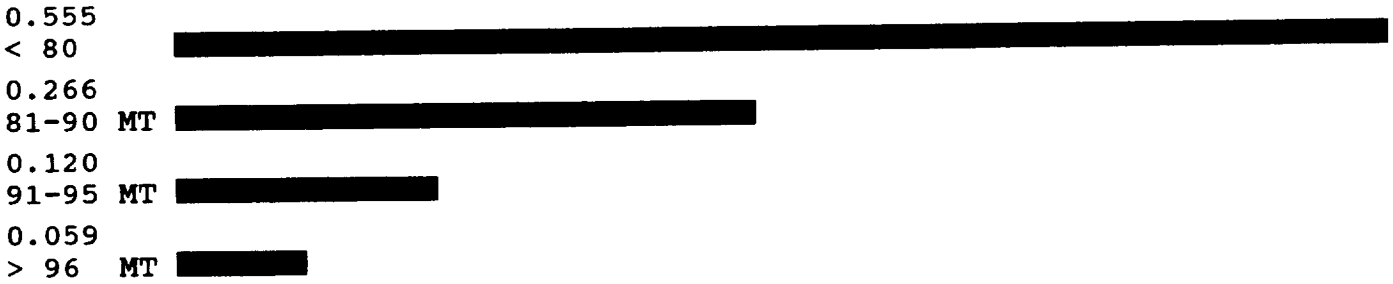
1	< 80	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	81-90 MT
2	< 80	9 8 7 6 ■ 4 3 2	1	2 3 4 5 6 7 8 9	91-95 MT
3	<				> 96 MT
4	81-90 MT	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	91-95 MT
5	81-90 MT	9 8 7 6 ■ 4 3 2	1	2 3 4 5 6 7 8 9	> 96 MT
6	91-95 MT	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	> 96 MT

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

81-90 MT --- Post TLI Mass
91-95 MT --- Post TLI Mass
< 80 --- Post TLI Mass
> 96 MT --- Post TLI Mass
POST TLI --- Post TLI Mass of Lander/Return Vehicle
V-METRIC --- Vehicle Metric Characterstics

PRIORITIES



INCONSISTENCY RATIO = 0.057.

Verbal judgments of PREFERENCE with respect to:
HAB-ASC < V-METRIC < GOAL

Node: 52000

1	NEGATIVE	9 8 7 6 5 4 3 2	1	2 ■ 4 5 6 7 8 9	EQUAL
2	NEGATIVE	9 8 7 6 5 4 3 2	1	■ 3 4 5 6 7 8 9	POSITIVE
3	EQUAL	9 8 7 6 5 4 3 ■	1	2 3 4 5 6 7 8 9	POSITIVE

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

EQUAL --- The Habitat Vehicle Mass is EQUAL to the Crew Vehicle
HAB-ASC --- Difference in Mass Between Habitat (Cargo) and Crew Mission
NEGATIVE --- The Habitat Vehicle Mass is LESS Than the Crew Vehicle
POSITIVE --- The Habitat Vehicle Mass is MORE than the Crew Vehicle
V-METRIC --- Vehicle Metric Characterstics

PRIORITIES

INCONSISTENCY RATIO = 0.009.

JUDGMENTS WITH RESPECT TO
VOLUME < V-METRIC < GOAL

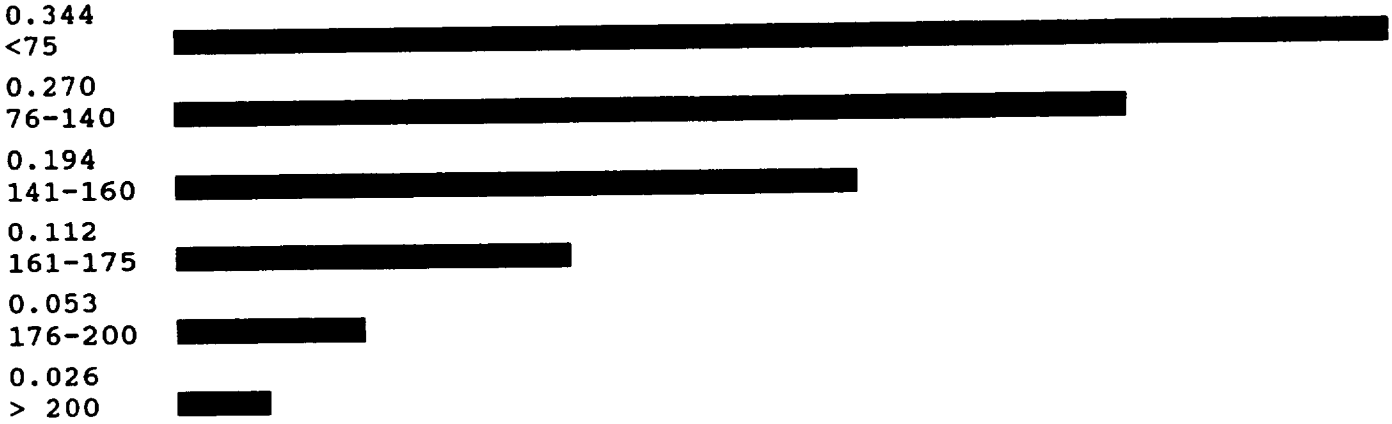
	<75	76-140	141-160	161-175	176-200	> 200
<75		1.5	2.5	3.0	6.0	9.0
76-140			2.0	2.5	5.0	9.0
141-160				3.0	4.0	7.0
161-175					3.0	5.0
176-200						3.0
> 200						

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

141-160 --- Volume of Propellant and Pressurant
161-175 --- Volume of Pressurant
176-200 --- Volume of Propellant and Pressurant
76-140 --- Volume of Propellant and Pressurant
<75 --- Volume of Propellant and Pressurant
> 200 --- Volume of Propellant and Pressurant
V-METRIC --- Vehicle Metric Characterstics
VOLUME --- Volume of the Crew Vehicle Propellant and Pressurant

PRIORITIES



INCONSISTENCY RATIO = 0.029.

JUDGMENTS WITH RESPECT TO
CG HEIGH < V-METRIC < GOAL

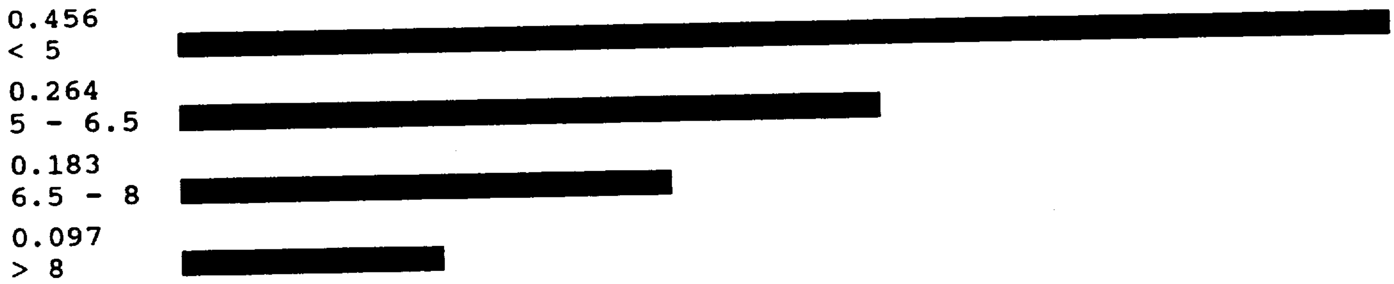
	< 5	5 - 6.5	6.5 - 8	> 8
< 5		2.0	2.5	4.0
5 - 6.5			1.5	3.0
6.5 - 8				2.0
> 8				

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

5 - 6.5 --- CG Height at Lunar Landing
6.5 - 8 --- CG Height at Lunar Landing
< 5 --- Cg Height at Lunar Landing
> 8 --- CG Height at Lunar Landing
CG HEIGH --- Center of Gravity Height To Lunar Surface Upon Lunar Landing
V-METRIC --- Vehicle Metric Characterstics

PRIORITIES



INCONSISTENCY RATIO = 0.006.

APPENDIX Section D1.6

Hardware Readiness Level

JUDGMENTS WITH RESPECT TO
HARDWRE < GOAL

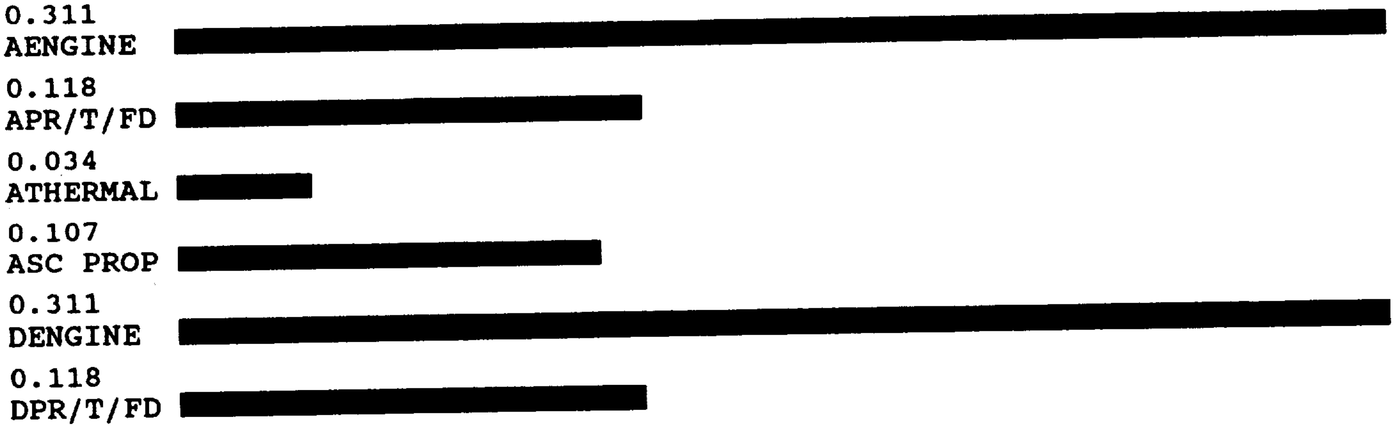
	AENGINE	APR/T/FD	ATHERMAL	ASC PROP	DENGINE	DPR/T/FD
AENGINE		3.0	7.0	3.0	1.0	3.0
APR/T/FD			5.0	1.0	(3.0)	1.0
ATHERMAL				(3.0)	(7.0)	(5.0)
ASC PROP					(3.0)	1.0
DENGINE						3.0
DPR/T/FD						

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

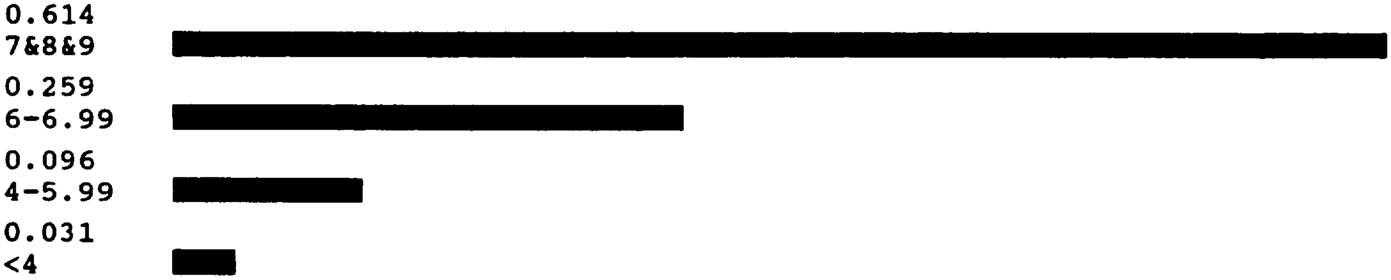
AENGINE --- Readiness of Ascent (return) Engines
APR/T/FD --- Readiness of Ascent (return) Pressurization, Tank and Feed System
ASC PROP --- Readiness of Propellant Manufacturing and Handling for Ascent
ATHERMAL --- Readiness of Ascent (return) Propellant Thermal Controls
DENGINE --- Readiness of Descent Engines
DPR/T/FD --- Hardware Readiness of Descent Pressurization/Tank/Feed Systems
HARDWRE --- Measure of the Hardware Readiness: Function of TRL and Difficulty

PRIORITIES



INCONSISTENCY RATIO = 0.013.

```
                          JUDGMENTS WITH RESPECT TO
                          AENGINE < HARDWRE < GOAL

          7&8&9      6-6.99     4-5.99     <4
 7&8&9                5.0        7.0        9.0
 6-6.99                          6.0        8.0
 4-5.99                                     7.0
 <4

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.


    GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99    --- HR Level
6-6.99    --- HR Level
7&8&9     --- HR Level
<4        --- HR Level
AENGINE   --- Readiness of Ascent (return) Engines
HARDWRE   --- Measure of the Hardware Readiness: Function of TRL and Difficulty
                                    PRIORITIES
```



```
                    INCONSISTENCY RATIO = 0.247.
```

JUDGMENTS WITH RESPECT TO
APR/T/FD < HARDWRE < GOAL

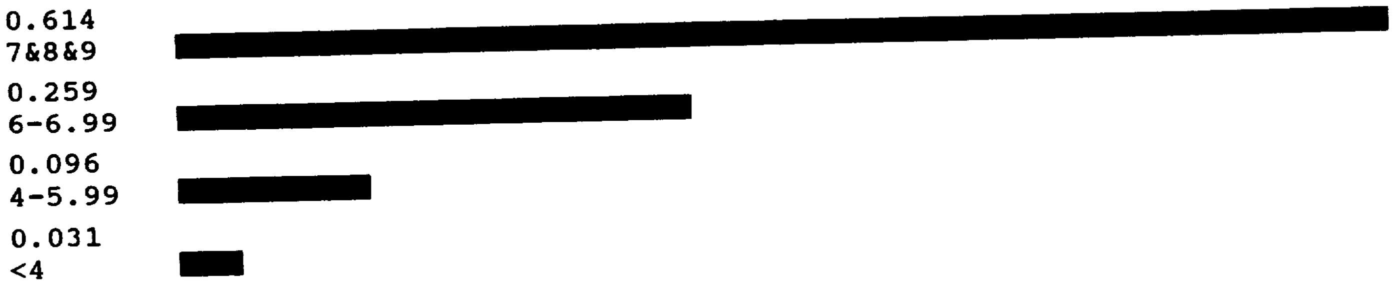
	7&8&9	6-6.99	4-5.99	<4
7&8&9		5.0	7.0	9.0
6-6.99			6.0	8.0
4-5.99				7.0
<4				

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99 --- HR Level
6-6.99 --- HR Level
7&8&9 --- HR Level
<4 --- HR Level
APR/T/FD --- Readiness of Ascent (return) Pressurization, Tank and Feed System
HARDWRE --- Measure of the Hardware Readiness: Function of TRL and Difficulty

PRIORITIES



INCONSISTENCY RATIO = 0.247.

JUDGMENTS WITH RESPECT TO
ATHERMAL < HARDWRE < GOAL

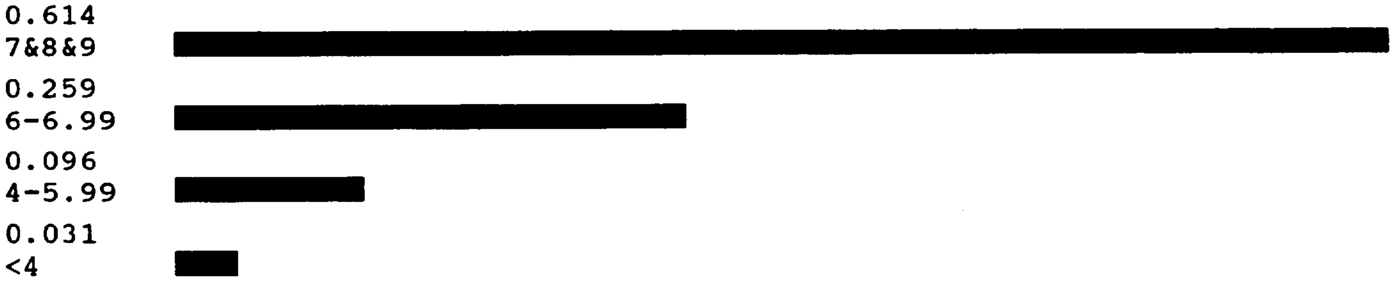
	7&8&9	6-6.99	4-5.99	<4
7&8&9		5.0	7.0	9.0
6-6.99			6.0	8.0
4-5.99				7.0
<4				

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99 --- HR Level
6-6.99 --- HR Level
7&8&9 --- HR Level
<4 --- HR Level
ATHERMAL --- Readiness of Ascent (return) Propellant Thermal Controls
HARDWRE --- Measure of the Hardware Readiness: Function of TRL and Difficulty

PRIORITIES



INCONSISTENCY RATIO = 0.247.

JUDGMENTS WITH RESPECT TO
ASC PROP < HARDWRE < GOAL

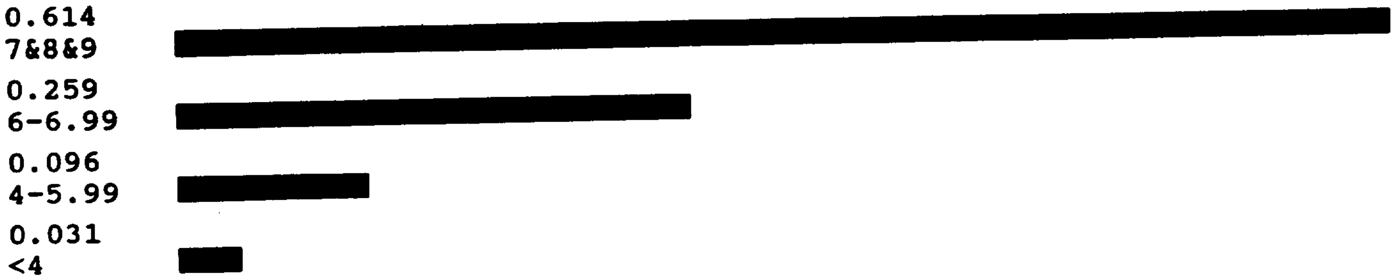
	7&8&9	6-6.99	4-5.99	<4
7&8&9		5.0	7.0	9.0
6-6.99			6.0	8.0
4-5.99				7.0
<4				

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99 --- HR Level
6-6.99 --- HR Level
7&8&9 --- HR Level
<4 --- HR Level
ASC PROP --- Readiness of Propellant Manufacturing and Handling for Ascent
HARDWRE --- Measure of the Hardware Readiness: Function of TRL and Difficulty

PRIORITIES

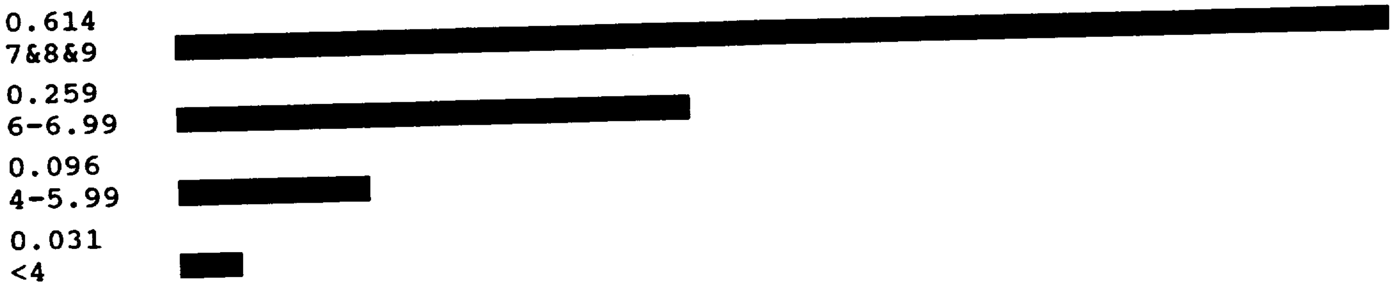


INCONSISTENCY RATIO = 0.247.

```
                        JUDGMENTS WITH RESPECT TO
                        DENGINE < HARDWRE < GOAL

          7&8&9      6-6.99     4-5.99     <4
 7&8&9                5.0        7.0        9.0
 6-6.99                          6.0        8.0
 4-5.99                                     7.0
 <4

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

    GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99   --- HR Level
```

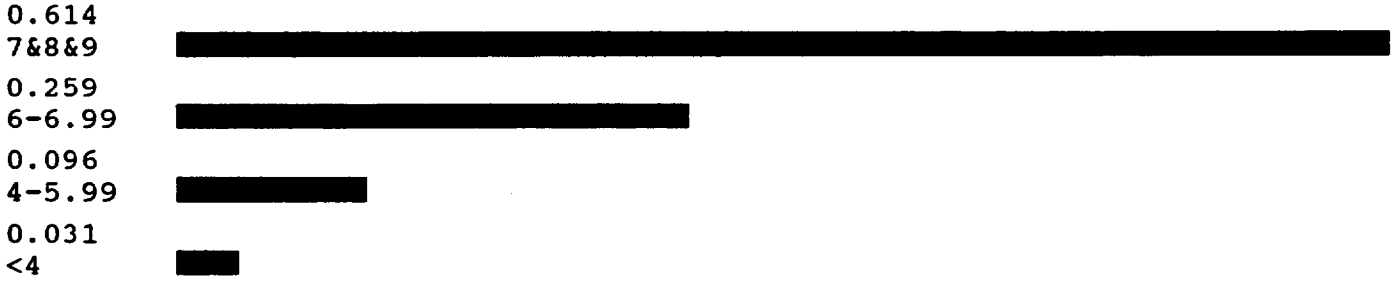
6-6.99 --- HR Level
7&8&9 --- HR Level
<4 --- HR Level
DENGINE --- Readiness of Descent Engines
HARDWRE --- Measure of the Hardware Readiness: Function of TRL and Difficulty

PRIORITIES



INCONSISTENCY RATIO = 0.247.

```
                    JUDGMENTS WITH RESPECT TO
                    DPR/T/FD < HARDWRE < GOAL

          7&8&9     6-6.99    4-5.99    <4
 7&8&9               5.0       7.0       9.0
 6-6.99                        6.0       8.0
 4-5.99                                  7.0
 <4

Matrix entry indicates that ROW element is ___
  1 EQUALLY  3 MODERATELY  5 STRONGLY  7 VERY STRONGLY  9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

    GOAL: Select Propulsion System best Meeting Program Resources and Req

4-5.99   --- HR Level
6-6.99   --- HR Level
7&8&9    --- HR Level
<4       --- HR Level
DPR/T/FD --- Hardware Readiness of Descent Pressurization/Tank/Feed Systems
HARDWRE  --- Measure of the Hardware Readiness: Function of TRL and Difficulty
                                PRIORITIES
```



```
                    INCONSISTENCY RATIO = 0.247.
```

APPENDIX Section D1.7

Evolution

C-4

Verbal judgments of IMPORTANCE with respect to:
EVOLVE < GOAL   Node: 70000

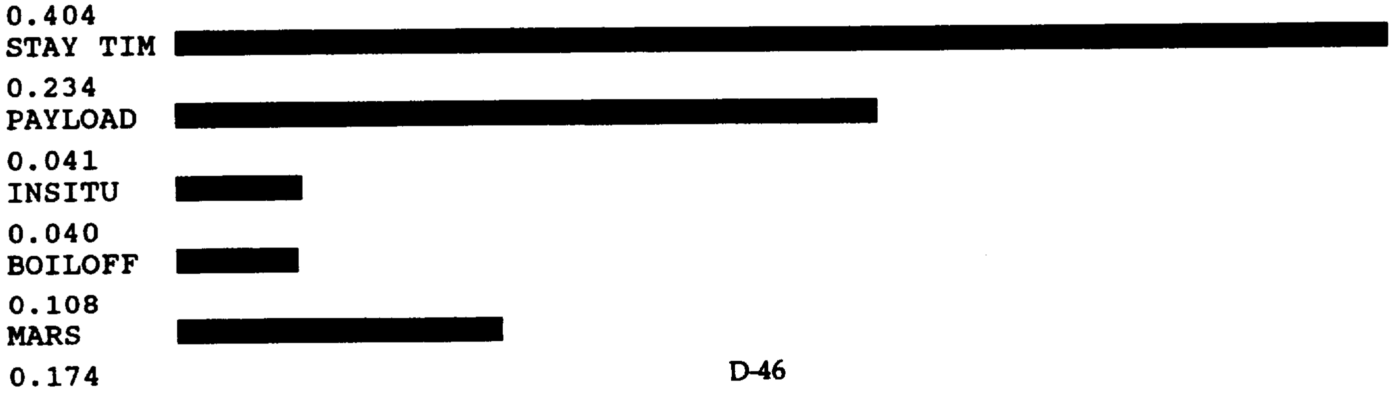
1	STAY TIM	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	PAYLOAD
2	STAY TIM	9 8 ■ 6 5 4 3 2	1	2 3 4 5 6 7 8 9	INSITU
3	STAY TIM	9 8 ■ 6 5 4 3 2	1	2 3 4 5 6 7 8 9	BOILOFF
4	STAY TIM	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	MARS
5	STAY TIM	9 8 7 6 5 4 ■ 2	1	2 3 4 5 6 7 8 9	LOG VOL
6	PAYLOAD	9 8 7 ■ 5 4 3 2	1	2 3 4 5 6 7 8 9	INSITU
7	PAYLOAD	9 8 7 ■ 5 4 3 2	1	2 3 4 5 6 7 8 9	BOILOFF
8	PAYLOAD	9 8 7 6 5 ■ 3 2	1	2 3 4 5 6 7 8 9	MARS
9	PAYLOAD	9 8 7 6 5 4 3 2	■	2 3 4 5 6 7 8 9	LOG VOL
10	INSITU	9 8 7 6 5 4 3 2	■	2 3 4 5 6 7 8 9	BOILOFF
11	INSITU	9 8 7 6 5 4 3 2	1	2 ■ 4 5 6 7 8 9	MARS
12	INSITU	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	LOG VOL
13	BOILOFF	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	MARS
14	BOILOFF	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	LOG VOL
15	MARS	9 8 7 6 5 4 3 2	1	■ 3 4 5 6 7 8 9	LOG VOL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

BOILOFF --- Evolution Towards Using Propellant for RCS, Power, Consumables,..
EVOLVE --- Measure of the SEI Evolvability of each Vehicle
INSITU --- Insitu Resoure Utilization is the Evolution Towards Lunar Prop.
LOG VOL --- Evolution Towards Increased Logistics Volume
MARS --- Mars Evolution for Mars ISRU or Aeroshell Packaging
PAYLOAD --- Evolution Potential for Extra Payload to 96 mt Post-TLI Limit
STAY TIM --- Evolution Potential for Longer Lunar Stay Times

PRIORITIES



LOG VOL [redacted]

INCONSISTENCY RATIO = 0.037.

JUDGMENTS WITH RESPECT TO
STAY TIM < EVOLVE < GOAL

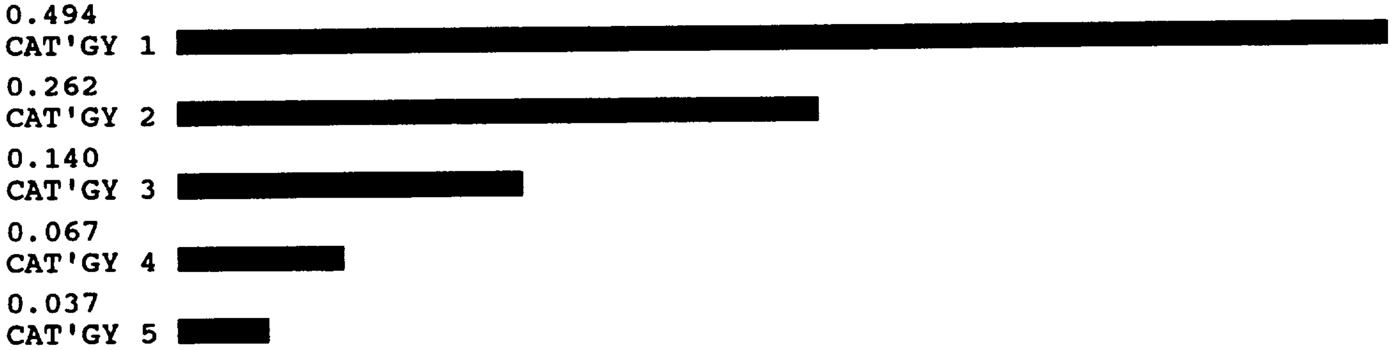
	CAT'GY 1	CAT'GY 2	CAT'GY 3	CAT'GY 4	CAT'GY 5
CAT'GY 1		3.0	5.0	6.0	7.0
CAT'GY 2			3.0	5.0	6.0
CAT'GY 3				3.0	6.0
CAT'GY 4					3.0
CAT'GY 5					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

CAT'GY 1 --- Category 1: See Evolution Definitions
CAT'GY 2 --- Category Two: See Evolution Definitions
CAT'GY 3 --- Category 3: See Evolution Definitions
CAT'GY 4 --- Category 4: See Evolution Definitions
CAT'GY 5 --- Ccategory 5: See Evolution Definitions
EVOLVE --- Measure of the SEI Evolvability of each Vehicle
STAY TIM --- Evolution Potential for Longer Lunar Stay Times

PRIORITIES



INCONSISTENCY RATIO = 0.078.

Verbal judgments of PREFERENCE with respect to:
PAYLOAD < EVOLVE < GOAL

Node: 72000

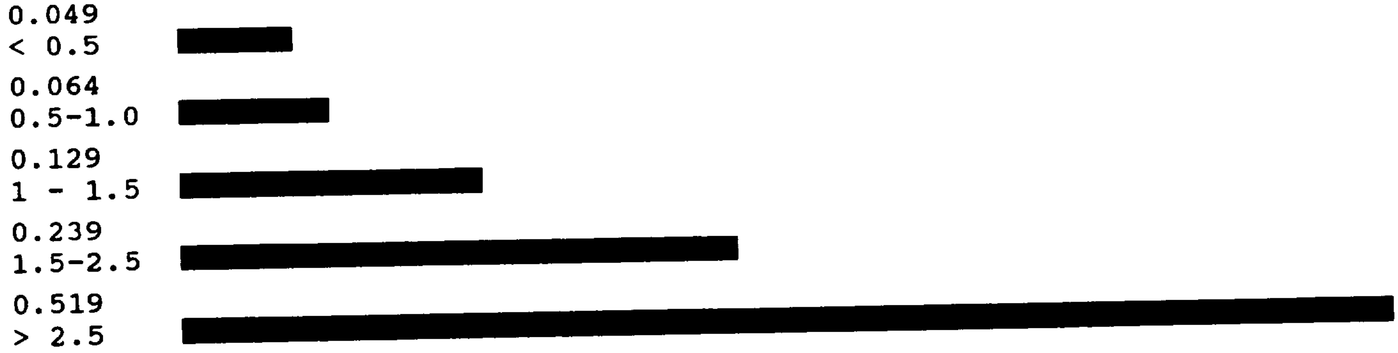
1	< 0.5	9 8 7 6 5 4 3 2	1	■ 3 4 5 6 7 8 9	0.5-1.0
2	< 0.5	9 8 7 6 5 4 3 2	1	2 ■ 4 5 6 7 8 9	1 - 1.5
3	< 0.5	9 8 7 6 5 4 3 2	1	2 3 4 ■ 6 7 8 9	1.5-2.5
4	< 0.5	9 8 7 6 5 4 3 2	1	2 3 4 5 ■ 7 8 9	> 2.5
5	0.5-1.0	9 8 7 6 5 4 3 2	1	2 ■ 4 5 6 7 8 9	1 - 1.5
6	0.5-1.0	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	1.5-2.5
7	0.5-1.0	9 8 7 6 5 4 3 2	1	2 3 4 5 6 ■ 8 9	> 2.5
8	1 - 1.5	9 8 7 6 5 4 3 2	1	2 ■ 4 5 6 7 8 9	1.5-2.5
9	1 - 1.5	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	> 2.5
10	1.5-2.5	9 8 7 6 5 4 3 2	1	2 3 ■ 5 6 7 8 9	> 2.5

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

0.5-1.0 --- Payload Evolution in metric tons
1 - 1.5 --- Payload Evolution in metric tons
1.5-2.5 --- Payload Evolution in metric tons
< 0.5 --- Payload Evolution in metric tons
> 2.5 --- Payload Evolution in metric tons
EVOLVE --- Measure of the SEI Evolvability of each Vehicle
PAYLOAD --- Evolution Potential for Extra Payload to 96 mt Post-TLI Limit

PRIORITIES



INCONSISTENCY RATIO = 0.060.

Data with respect to:
INSITU < EVOLVE < GOAL

Node: 73000

	VALUE
YES	1.00000
NO	0.00000

GOAL: Select Propulsion System best Meeting Program Resources and Req

EVOLVE	--- Measure of the SEI Evolvability of each Vehicle
INSITU	--- Insitu Resoure Utilization is the Evolution Towards Lunar Prop.
NO	--- No, the Propellant Type is Not Compatible With Lunar ISRU
YES	--- Yes, the Propellant Type is Compatible with Lunar ISRU

PRIORITIES

Data with respect to:
BOILOFF < EVOLVE < GOAL

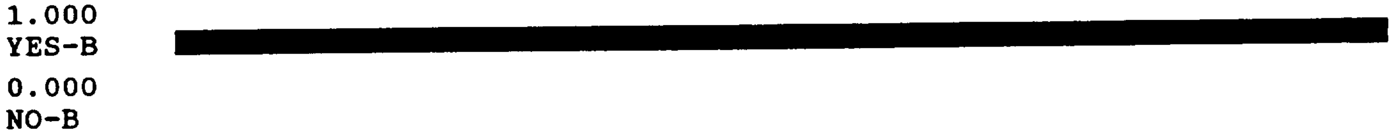
Node: 74000

	VALUE
YES-B	1.00000
NO-B	0.00000

GOAL: Select Propulsion System best Meeting Program Resources and Req

BOILOFF --- Evolution Towards Using Propellant for RCS, Power, Consumables,..
EVOLVE --- Measure of the SEI Evolvability of each Vehicle
NO-B --- No,Propellant Type Will Not Evolve Towards Boiloff Utilization
YES-B --- Yes,the Propellant Type is Can Evolve Twoards Boiloff Utilization

PRIORITIES



JUDGMENTS WITH RESPECT TO
MARS < EVOLVE < GOAL

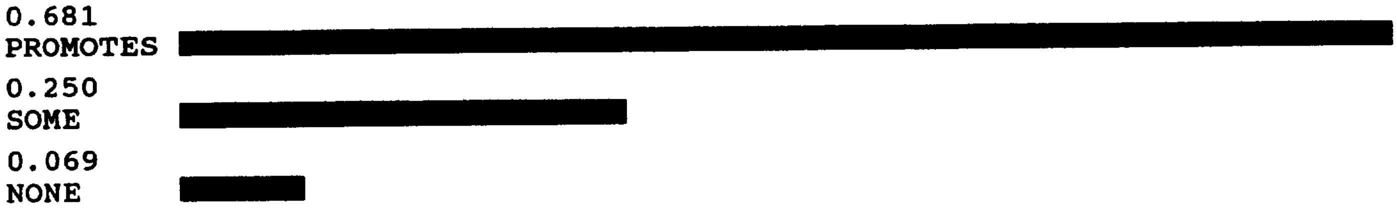
	PROMOTES	SOME	NONE
PROMOTES		3.0	9.0
SOME			4.0
NONE			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: Select Propulsion System best Meeting Program Resources and Req

EVOLVE --- Measure of the SEI Evolvability of each Vehicle
MARS --- Mars Evolution for Mars ISRU or Aeroshell Packaging
NONE --- No Significant Mars Evolution Potential
PROMOTES --- Promotes Mars Evolution
SOME --- Only Some Mars Evolution Applicability

PRIORITIES



INCONSISTENCY RATIO = 0.009.

Verbal judgments of PREFERENCE with respect to:
LOG VOL < EVOLVE < GOAL   Node: 76000

1	<20 M^3	9 8 7 6 5 4 3 2	1	2 3 █ 5 6 7 8 9	20 - 35
2	<20 M^3	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 █ 9	>35 M^3
3	20 - 35	9 8 7 6 5 4 3 2	1	2 3 4 █ 6 7 8 9	>35 M^3

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

GOAL: Select Propulsion System best Meeting Program Resources and Req

20 - 35 --- Logistics Volume Available Within the Shroud
<20 M^3 --- Logistics Volume Available within shroud
>35 M^3 --- Logistics Volume Available Under the Shroud
EVOLVE --- Measure of the SEI Evolvability of each Vehicle
LOG VOL --- Evolution Towards Increased Logistics Volume

PRIORITIES

INCONSISTENCY RATIO = 0.090.

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APPENDIX Section D2

Cumulative Weights

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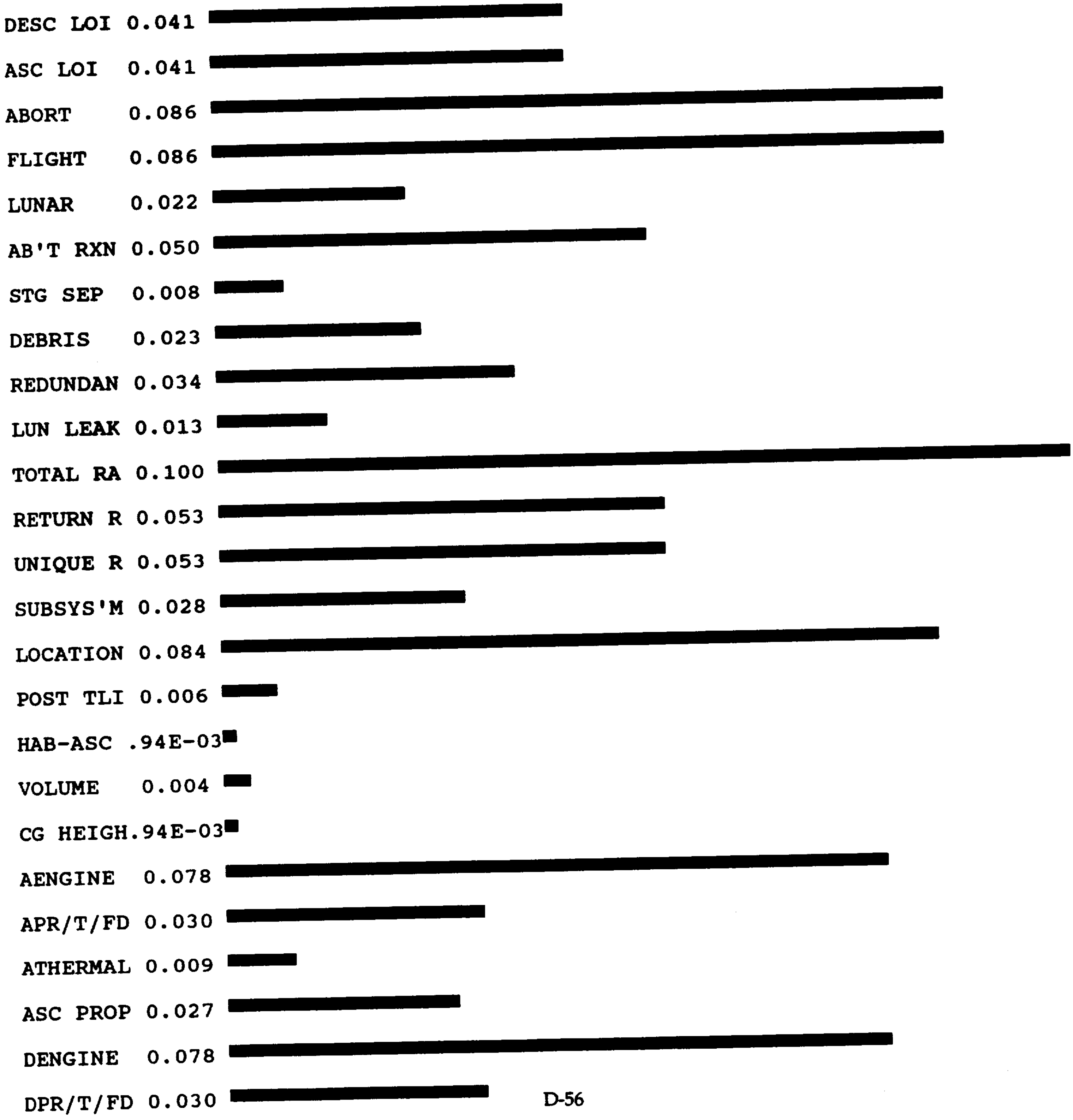
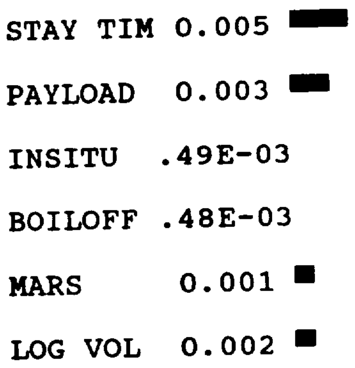
C:\EC8\MODELS\ZRATE 12-07-1992 NASA Johnson Space Center

Select Propulsion System best Meeting Program Resources and Req

Synthesis of Level 2 Nodes with respect to GOAL
DISTRIBUTIVE MODE

OVERALL INCONSISTENCY INDEX = 0.00





AB'T RXN --- Abort Reaction Time:90% Thrust for Return Engines During Landing
ABORT --- Abort Operability Measure
AENGINE --- Readiness of Ascent (return) Engines
APR/T/FD --- Readiness of Ascent (return) Pressurization, Tank and Feed System
ASC LOI --- Launch Operability Index for Return Stage
ASC PROP --- Readiness of Propellant Manufacturing and Handling for Ascent
ATHERMAL --- Readiness of Ascent (return) Propellant Thermal Controls
BOILOFF --- Evolution Towards Using Propellant for RCS, Power, Consumables,..
CG HEIGH --- Center of Gravity Height To Lunar Surface Upon Lunar Landing
DEBRIS --- Exposure Level of Return Stage Engines to Surface Debris
DENGINE --- Readiness of Descent Engines
DESC LOI --- Launch Operability Index for Lander Stage
DPR/T/FD --- Hardware Readiness of Descent Pressurization/Tank/Feed Systems
FLIGHT --- Flight Operability Measure
HAB-ASC --- Difference in Mass Between Habitat (Cargo) and Crew Mission
INSITU --- Insitu Resoure Utilization is the Evolution Towards Lunar Prop.
LOCATION --- Number of Instrumentation Locations
LOG VOL --- Evolution Towards Increased Logistics Volume
LUN LEAK --- Leakage Potential on the Lunar Surface
LUNAR --- Lunar Operability Measure
MARS --- Mars Evolution for Mars ISRU or Aeroshell Packaging
PAYLOAD --- Evolution Potential for Extra Payload to 96 mt Post-TLI Limit
POST TLI --- Post TLI Mass of Lander/Return Vehicle
REDUNDAN --- Level of Redundancy: # faults during (landing,return,post-abort)
RETURN R --- Complexity Rating for Number of Return Components
STAY TIM --- Evolution Potential for Longer Lunar Stay Times
STG SEP --- Stage Separation Characteristics
SUBSYS'M --- Number of Subsystems
TOTAL RA --- Complexity Rating for Total Number of Components
UNIQUE R --- Complexity Rating for Number of Unique Components
VOLUME --- Volume of the Crew Vehicle Propellant and Pressurant

*U.S. GOVERNMENT PRINTING OFFICE: 1993-762-623-No Program

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13. ABSTRACT *(Maximum 200 words)*

This trade study was initiated at NASA/JSC in May 1992 to develop and evaluate main propulsion system alternatives to the reference First Lunar Outpost (FLO) lander and return-stage transportation system concept. Thirteen alternative configurations were developed to explore the impacts of various combinations of return stage propellants, using either pressure or pump-fed propulsion systems and various staging options. Besides two-stage vehicle concepts, the merits of single-stage and stage-and-a-half options were also assessed in combination with high-performance liquid oxygen and liquid hydrogen propellants. Configurations using an integrated modular cryogenic engine were developed to assess potential improvements in packaging efficiency, mass performance, and system reliability compared to non-modular cryogenic designs. The selection process to evaluate the various designs was the Analytic Hierarchy Process. The trade study showed that a pressure-fed MMH/N2O4 return stage and RL10-based lander stage is the best option for a 1999 launch. While results of this study are tailored to FLO needs, the design date, criteria, and selection methodology are applicable to the design of other crewed lunar landing and return vehicles.

14. SUBJECT TERMS
Propulsion Trade Study, Space Exploration Initiatives (SEI), First Lunar Outpost (FLO), interplanetary spacecraft, Apollo, chlorine pentafluoride, Analytic Hierarchy Process (AHP), propellants, Moon

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