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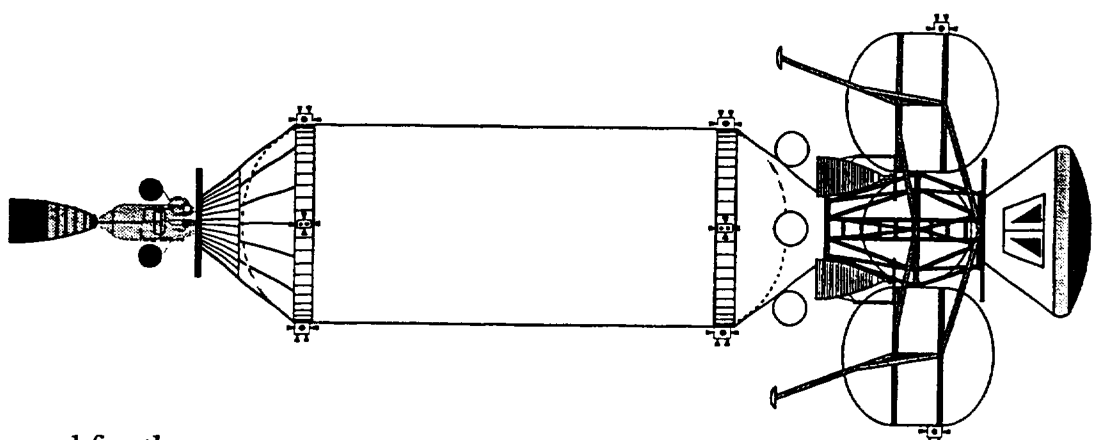

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HIGH LEVERAGE SPACE TRANSPORTATION SYSTEM TECHNOLOGIES FOR HUMAN EXPLORATION MISSIONS TO THE MOON AND BEYOND

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ABSTRACT

The feasibility of returning humans to the Moon by 2004, the 35th anniversary of the Apollo 11 landing, is examined assuming the use of existing launch vehicles (the Space Shuttle and Titan IVB), a near term, advanced technology space transportation system, and extraterrestrial propellant--specifically "lunar-derived" liquid oxygen or LUNOX. The lunar transportation system (LTS) elements consist of an expendable, nuclear thermal rocket (NTR)-powered translunar injection (TLI) stage and a combination lunar lander / Earth return vehicle (LERV) using cryogenic liquid oxygen and hydrogen (LOX/LH_2) chemical propulsion. The "wet" LERV, carrying a crew of 2, is configured to fit within the Shuttle orbiter cargo bay and requires only modest assembly in low Earth orbit. After Earth orbit rendezvous and docking of the LERV with the Titan IVB-launched NTR TLI stage, the initial mass in low Earth orbit (IMLEO) is ~40 t. To maximize mission performance at minimum mass, the LERV carries no return LOX but uses ~7 t of LUNOX to "reoxidize" itself for a "direct return" flight to Earth followed by an "Apollo-style" capsule recovery. Without LUNOX, mission capability is constrained and the total LTS mass approaches the combined Shuttle-Titan IVB IMLEO limit of ~45 t even with enhanced NTR and chemical engine performance. Key technologies are discussed, lunar mission scenarios described, and LTS vehicle designs and characteristics are presented. Mission versatility provided by using a small "all LH_2" NTR engine or a "LOX-augmented" derivative, either individually or in clusters, for outer planet robotic orbiter, small Mars cargo, lunar "commuter", and human Mars exploration class missions is also briefly discussed.

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INTRODUCTION

In January 1996, NASA issued its strategic plan for the Human Exploration and Development of Space (HEDS).[1] The HEDS enterprise envisions an exciting future where humans travel routinely and economically *"to and through space"* to the Moon initially, then on to Mars and other planetary bodies in our Solar System. Preceding a human lunar return, robotic orbiter missions like Lunar Prospector[2] will first map the chemical composition of the lunar surface to help identify sites for possible outposts and settlements that are rich in extraterrestrial resources. Teleoperated surface lander experiments would then demonstrate the ability to extract these resources and process them into propellants and life support gases allowing humans to "live off the land." In addition to "in-situ" resource utilization (ISRU), efficient surface power generation, cryofluid storage and transfer and advanced propulsion technologies will also be required if sustained human presence at dramatically lower costs are to be achieved. These same technologies will also help open the space frontier for commercial and industrial development.

Planning future human missions to the Moon and Mars in today's environment is particularly challenging. Despite an expected decline in its future budgets, NASA and its field centers are examining a variety of mission architectures and "high leverage" technology options that could be developed to send humans "back to the Moon" before 2005 and then on to Mars no later than 2018. Prospects for an early human lunar return mission in 2001 for under $1 billion dollars[3] is presently being examined by engineers at the Johnson Space Center. Designing such a mission appears particularly challenging given that the International Space Station will still be in its final assembly phase in the 2001-2002 timeframe and that the Lunar Prospector Discovery mission is estimated to cost $ 63 million dollars.[2] Futhermore, with decreasing budgets in its future, NASA must invest its scarce resources wisely and cannot afford to waste them on developing *"short shelf life"* technologies to conduct a few *"see we can do it "* missions. The agency would then have to invest in new technologies to do the *"Real Lunar Program,"* as well as, initiating the follow-on *"Mars Program"* in the post-2010 timeframe. The challenge to NASA therefore, is to identify and develop the fewest number of high leverage technologies that can accomplish most of NASA's planned missions (e.g., cargo and piloted, lunar and Mars, as well as, robotic science missions) and do it at an acceptable cost.

This paper examines the feasibility of returning humans to the Moon as early as 2004, the 35th anniversary of Apollo 11, using currently existing U.S. launch vehicles (the Space Shuttle and the Titan IVB), and a near term, advanced technology LTS consisting of a small NTR-powered TLI stage and a cryogenic, integrated lunar lander / Earth return vehicle (LERV) carrying a 2-person crew. The LERV is designed to utilize LUNOX propellant produced earlier using facilities and lunar surface vehicles operated telerobotically from Earth. In the Apollo Program, the heavy lift "Saturn V" launch vehicle was used to place ~140 t into LEO consisting of the S-IVB TLI stage and its payload--the "3 person" Command and Service Module (CSM) and the Lunar Excursion Module (LEM) weighing ~32 t and 16 t, respectively (Figure 1). A single 200 thousand pounds thrust (200 klbf) LOX/LH_2 J2 engine (specific impulse, Isp~425 s) powered the S-IVB stage while storable, pressure-fed, hypergolic propellants were used in both the CSM (Isp~314 s) and the LEM (Isp~305 s). A "lunar orbit rendezvous" (LOR) mission profile was also adopted for Apollo because of its mass efficiency.

The LTS discussed here uses a single 20 t-class LERV with LOX/LH_2 chemical engines and a "lunar direct" mission profile which provides "global access" to the Moon and an "anytime abort" capability for the crew once the LERV is refueled, or more appropriately, "reoxidized" with LUNOX propellant. Because ~7 kilograms of mass is required in LEO for each kilogram of mass delivered to the lunar surface, the utilization of LUNOX from the outset enables a LERV with robust payload / vehicle margin while maintaining size and mass compatible with that of the Space Shuttle orbiter. To deliver the LERV to the required TLI conditions in a mass efficient manner, a small (~15 klbf), "all LH_2" NTR transfer stage, also weighing ~20 t, is utilized. Although the principal focus of this paper is on the LTS elements for the initial human lunar return mission, the technologies and systems described here provide the basis for a LTS that can evolve with time from an expendable architecture to one where reusable lunar landing and transfer vehicles (LLVs and LTVs) benefit from the production and utilization of LUNOX both on the lunar surface and in low lunar orbit (LLO). Once available in LLO, even conventional LH_2 NTR vehicles could benefit from LUNOX usage by outfitting them with an oxygen propellant module, feed system and "LOX-afterburner" nozzle allowing bipropellant operation and revolutionary performance[4] enhancements equivalent to that found in "gas-core" NTR engines.

This paper describes system and mission analysis results performed by Lewis Research Center's Advanced Space Analysis Office over the last nine months in support of NASA's *Human Lunar Return Study* and the *Space Transportation Strategic Plan*. The paper first discusses the key technologies assumed in our study and describes their characteristics. Mission and transportation system ground rules and assumptions are then presented along with a description of a reference lunar mission scenario. The lunar transportation system elements are then described and the benefits of using LUNOX to increase delivered payload while decreasing vehicle size are illustrated through comparison with a system using only Earth-supplied LOX. The paper concludes with a brief discussion of the applicability / evolvability of the small NTR engine and a "LOX-augmented" derivative for other NASA missions.

LUNOX, CRYOGENIC LUNAR LANDER AND NTR PROPULSION TECHNOLOGY DESCRIPTION

LUNOX Production and Utilization

Lunar - derived oxygen (LUNOX) has been identified[5] as the most promising initial resource to be developed on the lunar surface. A local source of LOX could replenish life support systems, and fuel cells used to power electric surface vehicles. Most importantly, the ability to provide the LERV's "oxygen-rich" chemical rocket engines (which typically operate at mixture ratios of ~5 to 6) with a source of return propellant oxidizer reduces the size and mass of the LERV, as well as, the TLI

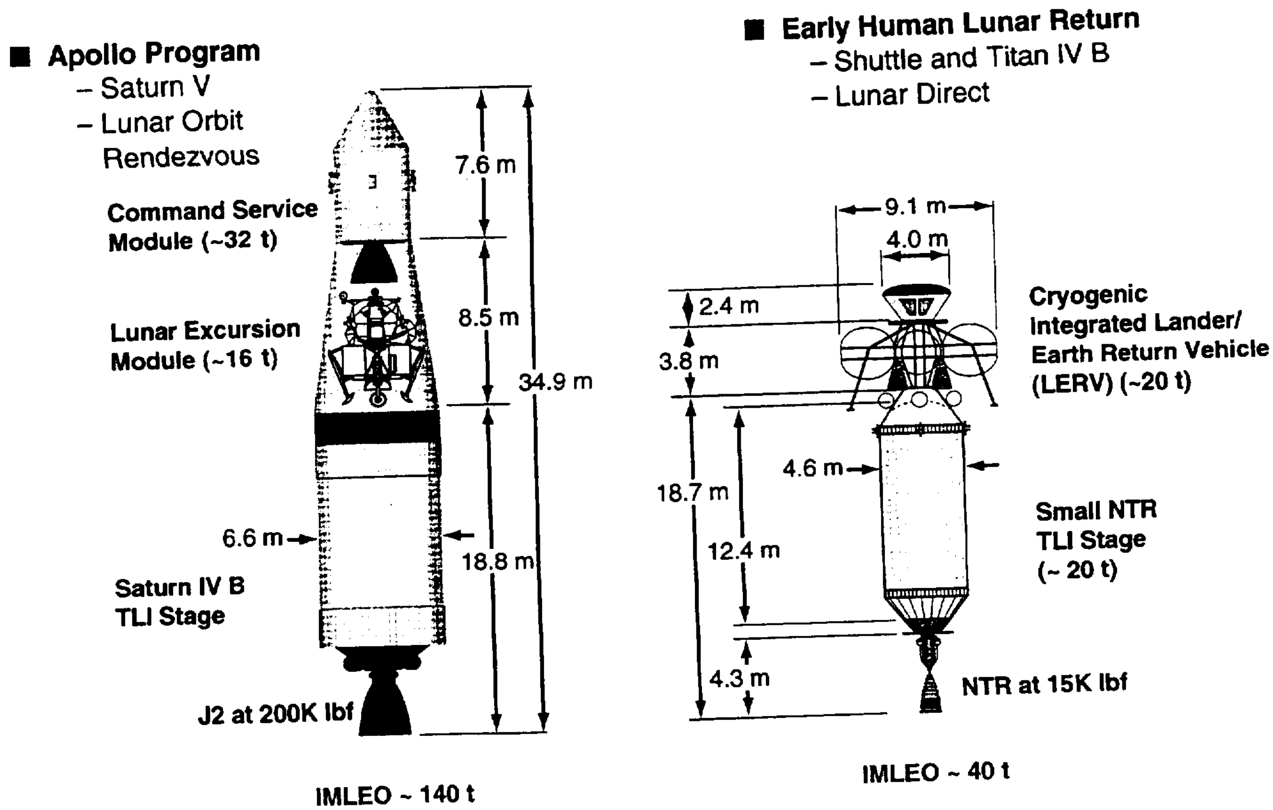


Fig. 1 Lunar Transportation Systems Relative Size and Mass--Then and Now

stage which provides the LERV with its required injection velocity. This "feedback effect" can cut the required mission IMLEO by a factor of 2.

Oxygen is also attractive as a resource because it is abundant in the lunar regolith (~45% by mass)[5] and can be extracted using a variety of techniques.[6] Two of the more promising concepts for oxygen production involve hydrogen reduction of ilmenite ($FeTiO_3$) in high-titanium mare soil and ferrous iron in volcanic glass.[7] Oxygen production via hydrogen reduction is a two step process. First, the iron oxide (FeO) in ilmenite or volcanic glass is reduced and oxygen is liberated to form water:

$$FeTiO_3(s) + H_2(g) \longrightarrow Fe(s) + TiO_2(s) + H_2O(g)$$

or

$$FeO(s) + H_2(g) \longrightarrow Fe(s) + H_2O(g)$$

Next, the water vapor is electrolyzed to regenerate the hydrogen reactant and oxygen resource. The hydrogen is recycled back to react with more lunar feedstock while the oxygen is liquified and stored in "well-insulated" storage tanks.

Reduction experiments[7] on samples of high-titanium mare soil and iron-rich volcanic glass collected during the Apollo 17 mission to the Taurus-Littrow region of the Moon have produced significant amounts of oxygen. Yields of ~3.0 weight percent (wt %) have been measured for ilmenite-rich, titanium soil at a reduction temperature of ~1050 C after 3 hours. Using the iron-rich "orange" volcanic glass, a yield of ~5.1 wt % was achieved at ~1100 C over the same time period. These experimental results suggest that iron- and titanium-rich soils and iron-rich glasses, in particular, would be attractive feed-stocks for lunar oxygen production. In addition to each existing in large quantities on the Moon, both are fined grained and friable and could be used with little or no processing prior to reduction. A 4 to 5% extraction efficiency (~20 to 25 t of lunar feedstock per ton of LUNOX) represents an *order of magnitude improvement* in oxygen yield over earlier estimates.[8] This is very important because reduced mining and beneficiation of bulk regolith can lower the mass and power requirements of a LUNOX production plant and its support vehicles.

Because the lunar mission architecture examined here assumes that LUNOX is available to support the first piloted mission, cargo missions will be required in advance to establish the necessary mining infrastructure on the lunar surface. It is envisioned[9] that initial cargo flights will deliver the LUNOX production plant and nuclear power supply. A reactor sytem is preferred because it allows operation during the lunar night and is less massive than a photovoltaic system with energy storage. The reactor would be mounted on a small teleoperated cart and transported a safe distance away from the LUNOX facility before power generation begins. Subsequent flights would deliver high duty-cycle, electric vehicles for loading and handling regolith and for transporting LUNOX from the production site to the LERV (see Figure 2).

The mass and power requirements for a teleoperated lunar production facility providing ~10.5 t of LUNOX per year (enough for 1 piloted mission per year with a 50% reserve) are estimated to be ~4.8 t and ~35 kW_e (~312 kg LUNOX / kW_e), respectively. Additional system element masses for the above production facility include the nuclear reactor system at ~3.0 t, 2 regolith loaders and haulers at ~3.5 t and ~1.9 t, respectively, and 2 LUNOX tanker vehicles at ~2.9 t.

Because the LUNOX scenario places such heavy reliance on teleoperated facilities and support vehicles for mission success and crew safety, it is important that such systems be rigorously tested first on the ground and then in dress rehearsal on the Moon before committing to the actual piloted mission. NASA Lewis is studying the requirements for a demonstration test of a subscale teleoperated "LUNOX tanker" and its mission functions under lunar vacuum and thermal conditions at its Plum Brook Space Power Facility (SPF), the world's largest space environment test chamber.[10] Using a currently existing "quonsent hut" support structure outfitted with a cold wall and quartz heating lamp arrangement to simulate lunar day / night thermal conditions, the tanker demo would receive oxygen from a LOX donor tank, then store, transport and transfer its LOX cargo to a receiver tank simulating the LERV (illustrated in Figure 3). These functions would be conducted during lunar morning, noon and nighttime thermal conditions to determine insulation effectiveness,

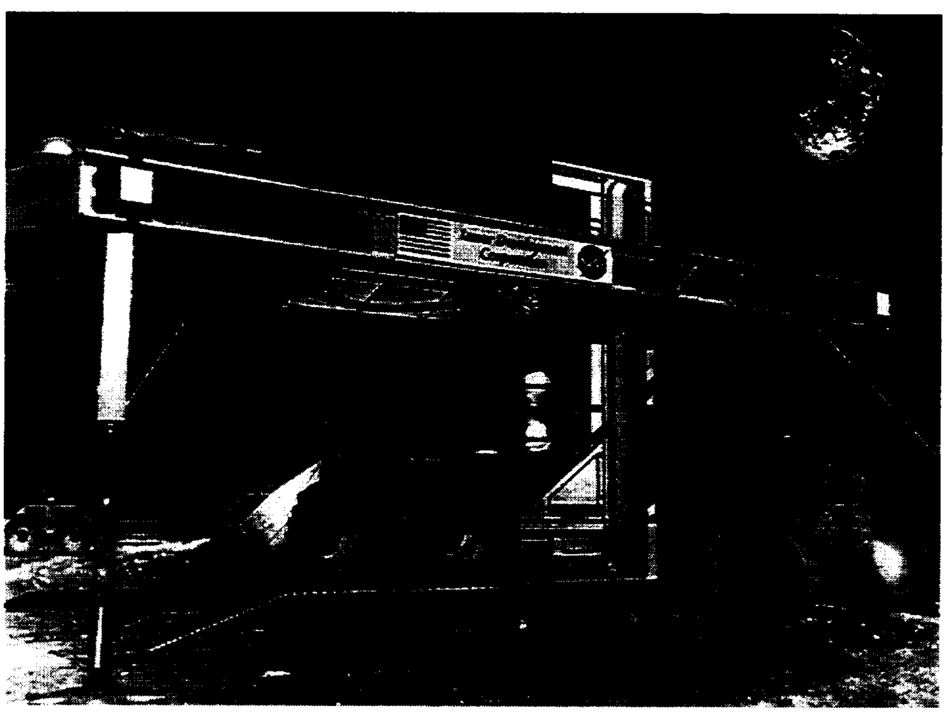


Fig. 2 "LUNOX" Facility and Teleoperated Support Vehicles

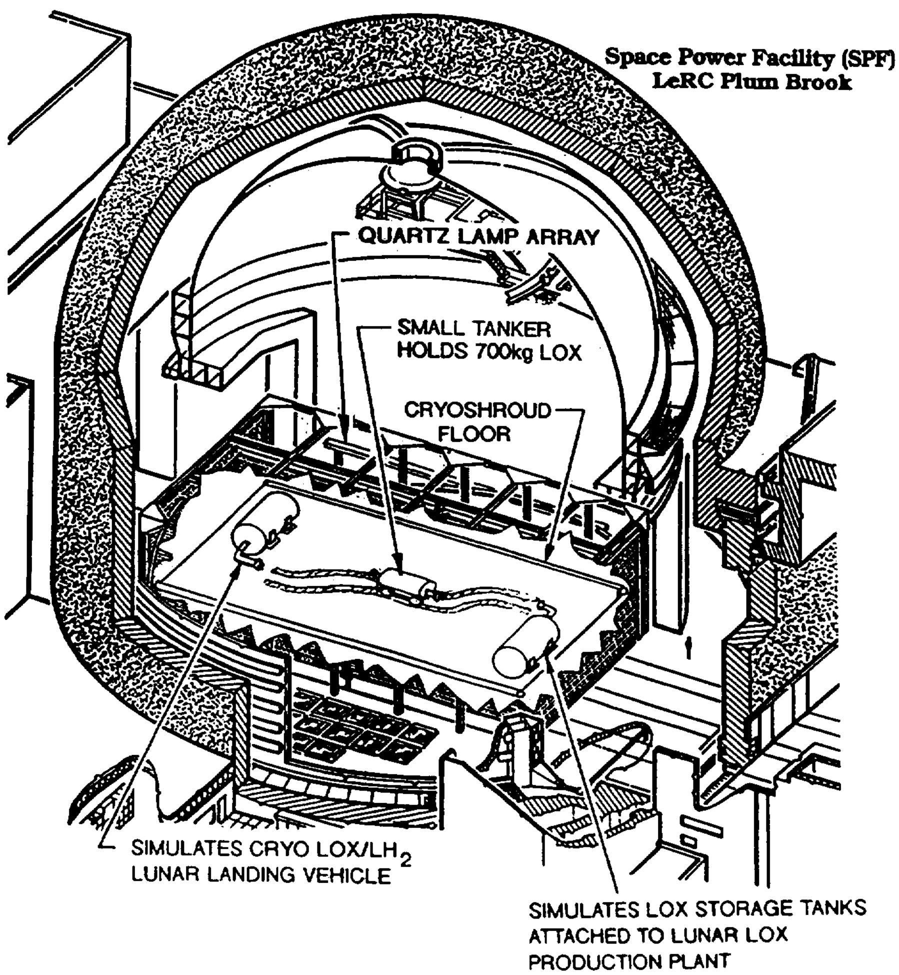


Fig. 3 Illustration of LUNOX Tanker Operation / Mission Functions in Lewis Research Center's Plum Brook Space Power Facility (SPF)

boiloff, quick-connect/disconnect systems, and transfer losses occuring during various phases of the lunar day/night cycle. A teleoperated rover chassis would carry the LOX tanker system and would be operated both locally and from afar possibly over the Internet.

Cryogenic Lander / Earth Return Vehicle (LERV) Technology Description and Development Status

A variety of cryogenic lunar landing vehicles have been proposed and studied by NASA over the last 10 years (Figure 4). In its "90-Day Study Report,"[11] NASA examined in detail a single stage, cryogenic LOX/LH_2 lunar landing vehicle (LLV) capable of supporting a crew of 4 on the lunar surface for ~30 days (see Figure 4c). The LLV used four, throttleable ~15-20 klbf engines with an Isp of ~465 s and an integrated gaseous O_2/H_2 RCS system. The total mass of the LLV in LEO was ~46 t which included a surface payload (14 t), the crew module (3.6 t) and 4 suited crew (0.8 t), propellant (22.3 t), and the lander stage (5.0 t or ~11% of the LLV total mass). The "2 stage" Apollo Lunar Excursion Module (Figure 4d) supported a crew of 2 for ~3.25 days, used storable propellants, and delivered less than 1 t of cargo to the lunar surface. Its total mass was ~16 t.

In the "First Lunar Outpost" Study,[12,13] NASA abandoned the lunar orbit rendezvous (LOR) approach of Apollo, with its separate transfer and landing vehicles, in favor of a "lunar direct" mission profile using an integrated, 2 stage vehicle consisting of a cryogenic capture/ lander stage, and a storable ascent/ Earth return stage (Figure 4a). The storable stage carried a 4 person crew capsule for

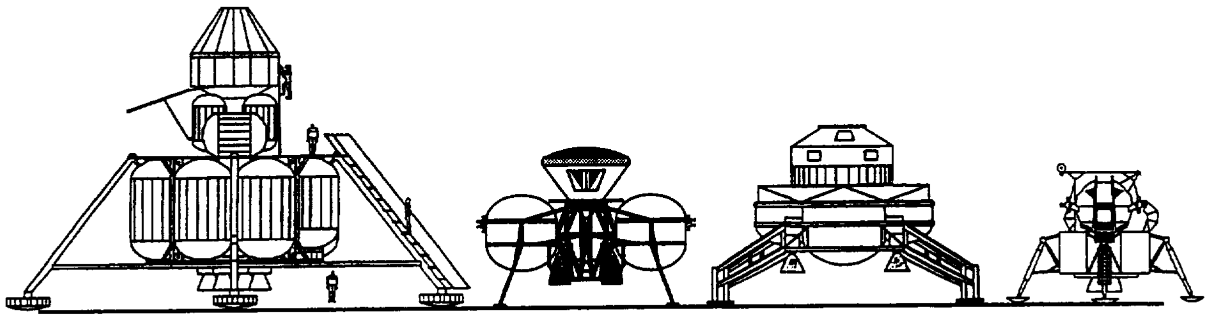


Fig. 4 Relative Size and Mass of Proposed Cryogenic Lunar Lander Vehicles and the Apollo Lunar Module

direct Earth entry at mission end. The FLO study also adopted a "lunar campsite" strategy in which a pre-integrated, reusable habitat module was delivered to the Moon in advance of the crew. The mass of the hab module needed to support the crew for ~45 days on the Moon (a lunar day, night, day cycle) was ~36 t which resulted in the need for a large cryogenic lander stage weighing ~57 t.

In the LERV concept examined here (Figure 4b), features from both the "90-Day" and FLO lunar studies are adopted. A single stage, cryogenic lander is utilized to reduce the system complexity and added mass of a second stage, and to achieve the high performance needed for the "lunar direct" mission profile assumed here. A 2 person crew and short duration (~3 days) stay on the Moon, reduces the requirements on / and mass of the crew capsule subsystems, and allows for cryogenic propellant usage with acceptable boiloff levels. A "common" crew module / Earth return capsule allows direct reentry at mission end and reduces the size and mass of the LTS elements, which would grow if reusability was imposed on the scenario.

The technologies to support a cryogenic LERV are presently under active development in other NASA and ESA programs. In the Delta Clipper-Experimental Advanced (DC-XA) program,[14] technologies are being tested for future single-stage-to-orbit vehicle concepts. The "vertical take-off and landing" DC-XA vehicle has already demonstrated feasibility for many of the systems required for a LERV like a throttleable LOX/LH_2 engine--the RL10A-5 provides the DC-XA with a throttling capability from ~30% to full thrust. Other advanced "weight-saving" technologies include a Russian-built aluminum lithium (Al/Li) LOX tank, a graphite epoxy composite LH_2 tank, composite intertank structure, and an integrated liquid-to-gas O_2/H_2 RCS system to control the DC-XA through its various airborne maneuvers in a propellant efficient way. It is possible that the DC-XA vehicle could serve as technology testbed for a LERV program in the near future. Lastly, ESA is currently developing a Crew Transfer Vehicle (CTV) and a smaller, unmanned Atmospheric Reentry Demonstrator (ARD), to be flight tested in 1997, which is derived from an "Apollo-style" command module.[15] The ARD will test lightweight construction materials, heat shield tiles and coatings and demonstrate a parachute / recovery system for the 2.8 t ARD capsule. Many of these technologies and possibly a "CTV/ARD-derivative" vehicle could form the basis for the LERV capsule.

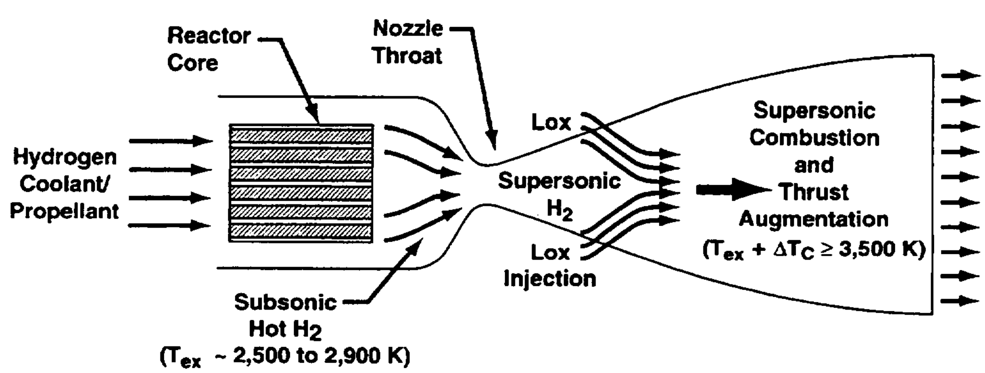
Conventional and "LOX-Augmented" Nuclear Thermal Rocket (NTR) Propulsion Technology

NTR propulsion is the key to providing *"low cost access through space"* for human exploration missions of the future. Unfortunately, NASA's investment in this technology has been fleeting at best--a Nuclear Propulsion Office existed briefly at Lewis Research Center from 1991 through 1993--despite the NTR's proven performance. During the Rover/ NERVA (Nuclear Engine for Rocket Vehicle Application) nuclear rocket programs (1955-1973),[16] a total of twenty rocket reactors were designed, built and tested "open air" at the Nuclear Rocket Development Station at the Nevada Test

Site. These integrated reactor /engine tests,using LH_2 as both reactor coolant and propellant, demonstrated a wide range of engine sizes (~50 to 250 klbf), high temperature graphite fuel providing substantial hydrogen exhaust temperatures (~2350-2550 K), sustained engine operation (over 60 minutes for a single burn) and restart capability--over 20 startups / shutdowns on the same engine.

What's new about NTR propulsion today that warrants a renewed investment in this technolgy ? The answer lies in a reduced size, higher performance engine that can be ground tested at full power in a "contained facility" meeting current environmental regulations. At present, Lewis Research Center is studying the benefits and development costs of a small (10-15 klbf) NTR engine that would use improved, high temperature, tricarbide fuel. The fuel, developed in the nuclear rocket program of the former Soviet Union known today as the Commonwealth of Independent States (CIS),[17] is capable of producing hydrogen exhaust temperatures in excess of 3100 K. Design studies, conducted by a joint US/CIS industry team[18,19] and funded by the Nuclear Propulsion Office between 1992-1993, produced a small advanced NTR engine with impressive parameters: thrust ~15 klbf, Isp~940-960 s, engine thrust-to-weight~3.1, and engine fuel lifetime of ~4.5 hours. Recent development schedule projections and cost estimates by Lewis Research Center and Idaho National Engineering Lab (INEL) indicate that a small 15 klbf NTR engine can be developed, tested in INEL's "Contained Test Facility" (CTF) with "scrubbed" H_2 exhaust, and integrated into a small flight stage in ~7 years at a cost of ~$2.5 billion including the first flight unit. Recurring stage cost for subsequent missions was estimated to be ~$150 million.

Although not the focus of this paper, an enhanced version of the NTR, which leverages the benefits of LUNOX, is being pursued at Lewis which combines conventional LH_2-cooled NTR and supersonic combustion ramjet (scramjet) technologies to form a LOX-augmented NTR (LANTR) engine.[4] The LANTR concept (Figure 5) utilizes the large divergent section of the NTR nozzle as an "afterburner" into which LOX is injected and supersonically combusted with reactor-heated hydrogen emerging from the LANTR's choked sonic throat--"scramjet propul-



	I_{sp} (sec)				
Life (hrs) T_C (°K)	5 2,900	10 2,800	30 2,600	Tankage Fraction (%)	T/W_{eng} Ratio
O/H MR = 0.0	941	925	891	14.0	3.0*
1.0	772	762	741	7.4	4.8
3.0	647	642	631	4.1	8.2
5.0	576	573	566	3.0	11.0
7.0	514	512	508	2.5	13.1

*For 15K lbf LANTR with chamber pressure = 2,000 psia and ε = 500 to 1

Fig. 5 Schematic / Characteristics of LOX-Augmented NTR

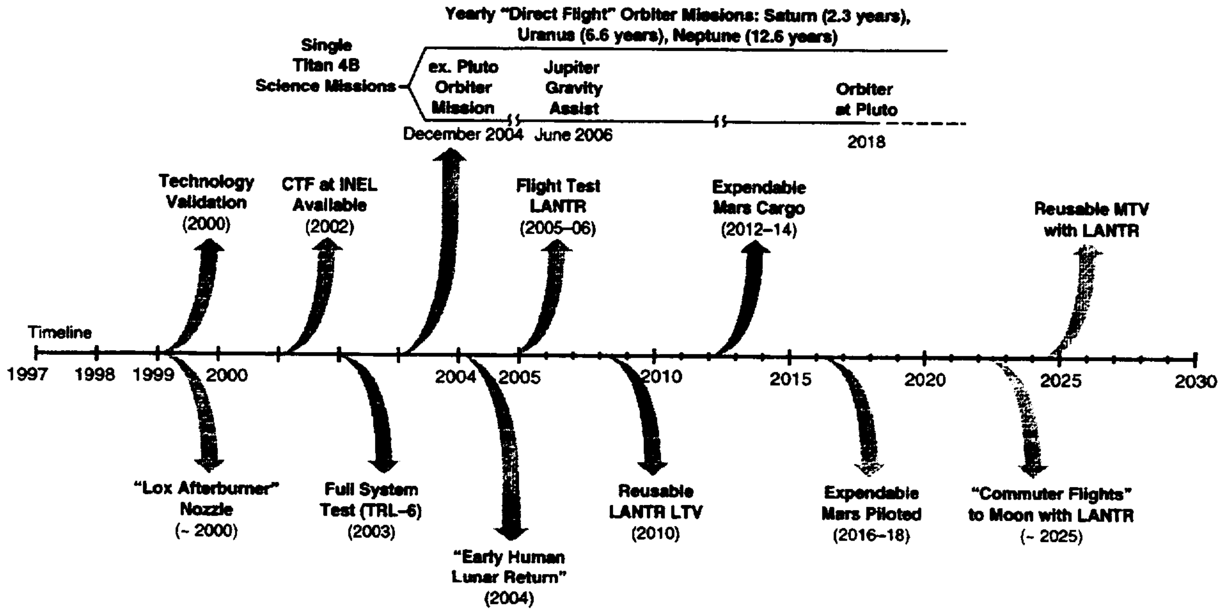


Fig. 6 NTR Development / Utilization Road Map

sion in reverse." By varying the LOX-to-LH_2 mixture ratio (MR), the LANTR engine can operate over a wide range of thrust and Isp values while the reactor produces a relatively constant power output. Thrust augmentation means that "big engine" performance can be obtained using smaller, more affordable, easier to test NTR engines. The increased use of high-density LOX in place of low-density LH_2 also reduces hydrogen tank volume. This feature provides important flexibility to vehicle designers allowing small LANTR-based transfer stages to be configured to accommodate "mass- and/or volume-constrained" launch vehicles.[20] Finally, once LUNOX becomes available in LLO to "reoxidize" LANTR-based transfer stages, "low cost" lunar transportation will become commonplace along with a host of other mission possibilities. A possible "road map" detailing the near term development and ultimate utilization of both conventional and LOX-augmented NTR systems is illustrated in Figure 6.

LUNAR MISSION / TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

The ground rules and assumptions for the reference and alternative lunar mission scenarios examined in this study are summarized in Table 1. Provided are details on outbound and return payloads, parking orbits, mission velocity change (ΔV) requirements and duration, and launch vehicle characteristics. In addition to the primary ΔV maneuvers indicated, midcourse correction maneuvers (ΔV = 30 m/s) are also performed using either storable or gaseous O_2 / H_2, bipropellant RCS systems. Tables 2 and 3 detail assumptions for the NTR-powered TLI stage and the chemical propulsion LERV, respectively, on primary and secondary propulsion, cryogenic tankage, thermal protection and boiloff rates, primary structure, and contingency factors used in this study.

An aluminum-lithium alloy "Weldalite" (F_{tu} = 111 ksi, ρ = 0.0976 lbm/in^3 = 2700 kg/m^3) has been used for the cryogenic LOX and LH_2 tanks and a graphite / epoxy composite IM7/977-2 (F_{tu} =91 ksi, ρ = 0.057 lbm/in^3 = 1577 kg/m^3) for non-pressurized primary structures. Wall thicknesses for the LH_2/LOX tanks were calculated based on a 35 / 50 psi internal pressure and included hydrostatic loads using a "4 g" load factor along with a safety factor of 1.5. A 2.5% ullage was also assumed in this study.

A 1.5 inch helium-purged, multilayer insulation (MLI) system (at 50 layers per inch) is assumed for thermal protection of the TLI stage LH_2 tank while 2 inches are applied to the LERV's LOX and LH_2 tanks. These insulation thicknesses reduce boiloff to acceptable levels and also satisfy the "ground

Table 1. Reference Lunar Mission Ground Rules and Assumptions

• Payload Outbound:	3.40 - 4.50 t	Crew Capsule
	0.45 t	Crew (2) and Suits
	0.05 - 0.30 t	Surface payload
• Payload Inbound:	3.40 - 4.50 t	Crew Capsule
	0.45 t	Crew (2) and Suits
	0.01 - 0.05 t	Lunar Samples
• Parking Orbits:	185 km	Circular (Earth departure)
	110-300 km	Circular (lunar arrival/departure)

- Trans-lunar injection ΔV: 3145 m/s + g-losses
- Lunar orbit capture / trans-Earth injection ΔV: 1050 m/s
- Lunar descent / lunar ascent ΔV: 2000 m/s / 1900 m/s
- Direct lunar descent / direct ascent and Earth return ΔV: 2510 m/s
- NTR TLI stage disposal ΔV: 30 m/s (lunar swingby and gravity assist)
- Mission duration: 12-14 days (2-4 in LEO, 7 in transit, 3 days at/on Moon)
- Launch vehicle type: Space Shuttle and Titan IVB
- Payload Delivery Capability: 25.4 t and 21.6 t to 28.5 deg. inclination
- LTS assembly scenario: Space Shuttle then Titan IVB launches with EOR & D (IMLEO: ~ 40 to 45 t)

Table 2. NTR TLI Stage System Assumptions

• NTR System:	Thrust / Weight	= 15 klbf / 4904 lbm
	Fuel / Propellant	= Tricarbide / Cryogenic LH_2
	Isp	= 940 s (@ 2900 K) / 960 s (@ 3025 K)
	External Shield Mass	= 2.76 kg/MWt of reactor power
	Flight Reserve	= 1% of usable LH_2 propellant
	Trapped Residuals	= 1% of total tank capacity
	Cooldown (effective)	= 3% of usable LH_2 propellant
• RCS System:	Propellant	= N_2O_4/MMH
	Isp	= 320 s
	Tankage	= 5% of total RCS propellants
• Cryogenic Tankage:	Material	= "Weldalite" Al/Li alloy
	Diameter	= 4.6 m
	Geometry	= Cylindrical tank with $\sqrt{2}/2$ domes
	Insulation	= 1.5 inches MLI + micrometeoroid debris shield
	LH_2 Boiloff*	= 1.75 kg/m²/month (LEO @ ~ 240 K)
		= 10.73 kg/day (for 12.4 m tank length)
		= 11.74 kg/day (for 13.6 m tank length)
• Primary Structure:	Materials	= "Weldalite" Al/Li and Graphite/Epoxy Composite
• Contingency:	Engine, shield , and stage dry mass = 15%	

* Assumes 3 x "Lockheed Eqn" heat flux estimates for MLI Δt < 2 inches

hold" thermal protection requirements for "wet-launched" LH_2 tanks of 1.5 inches.[21] The installed density of the 1.5 inch MLI system is ~2.05 kg/m^2, and the resulting LH_2 boiloff rate from the TLI stage while in LEO is ~1.75 kg/m^2/month (based on an estimated heat flux of ~0.294 W/m^2 at a LEO sink temperature of ~240 K). For the LERV, maximum boiloff rates for LOX and LH_2 have been estimated assuming a lunar surface temperature of ~394 K (equivalent to "early afternoon" on the Moon). At this temperature, the estimated heat flux is ~1.1 W/m^2 and the boiloff rates for LH_2 and LOX are ~6.51 and 13.26 kg/m^2/month, respectively. Also shown in Table 3 are boiloff rates for the LERV propellants in LEO, cislunar space and LLO. Lastly, a 0.25 mm thick sheet of aluminum (corresponding to ~0.682 kg/m^2) is included in the total tank weight estimates to provide protection against micrometeoroids and regolith backscatter from engine exhaust during landing and takeoff.

LUNAR MISSION SCENARIO DESCRIPTION

The reference lunar scenario examined in this study assumes a split mission architecture involving both cargo and piloted missions operated initially in an "expendable mode" in order to maximize payload delivered to the Moon on each mission, maintain a "two launch" mission capability (IMLEO limited to ~40 - 45 t), and reduce the LTS size and cost. The piloted mission employs a "lunar direct" flight profile[9,22] and assumes the availability of LUNOX for lander refill and Earth return. The mission flight profile is illustrated in Figure 7. The Space Shuttle and Titan IVB, with a combined payload delivery capability to LEO of ~45 t, are used to deliver the LTS elements to the 185 km (100 n. mi.) staging orbit. The LERV's "wet" lander stage and crew capsule with a combined mass of 20 t are delivered first in the orbiter's payload bay "side-by-side." Once in orbit the capsule is installed atop the lander and the

Table 3. LERV Transportation System Assumptions

• Primary Propulsion:	Total Thrust	= 12.5 - 15.0 klbf
	Propellant	= LOX/LH_2
	Isp	= 450 s (@ O/H MR = 5.2)
		= 465 s (@ O/H MR = 6.0)
	Flight Reserve	= 1% of usable propellant
	Trapped Residuals	= 1% of total tank capacity
• RCS System:	Propellants	= N_2O_4/MMH and GO_2/GH_2
	Isp	= 320 s and 400 s
	Tankage	= 5% of total propellants (storable)
• Cryogenic Tankage:	Material	= "Weldalite" Al/Li alloy
	Geometries	= Cylindrical with $\sqrt{2}/2$ domes/spheres
	Insulation	= 2.0 inches MLI + micrometeoroid debris shield
	LH_2/LOX Boiloff*	= 1.31 / 2.44 kg/m^2/month (LEO @ ~ 240K)
		= 0.56 / 0.90 kg/m^2/month (in-space @ ~ 172K)
		= 1.91 / 3.68 kg/m^2/month (LLO @ ~ 272K)
		= 6.51 /13.26 kg/m^2/month (LS @ ~ 394K)
• Primary Structure:	Materials	= "Weldalite" Al/Li and Graphite/Epoxy Composite
• Contingency:	Dry Stage Mass	= 15%

*Assumes 3x "Lockheed Eqn" heat flux estimates for MLI $\Delta t \leq$ 2 inches

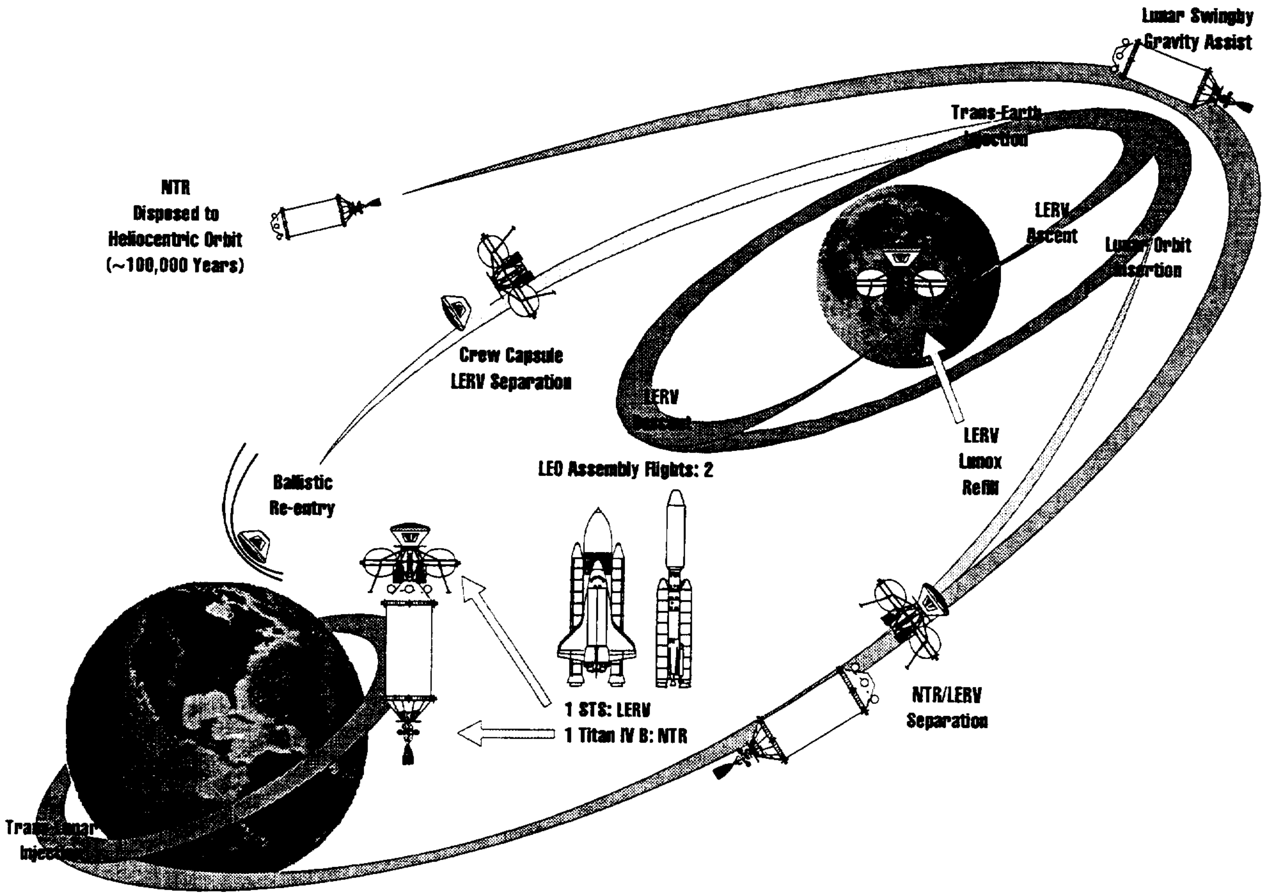


Fig. 7 Reference "Lunar Direct" Mission Scenario Using NTR, LERV and LUNOX

integrated LERV's systems are checked out. Next, the NTR-powered TLI stage, also weighing ~20 t, is launched to LEO by the Titan IVB where Earth orbit rendezvous and docking (EOR&D) with the LERV results in the integrated spacecraft shown in Figures 7 and 8.

Over the next 1 to 2 days, the integrated LTS is checked out in preparation for the TLI launch window. At the appropriate time the NTR engine is powered up and performs a sustained 28 minute TLI burn which sends the coupled spacecraft on a trajectory to the Moon. Gravity losses for the "single burn" Earth departure scenario are estimated to be ~205 m/s. Following an appropriate cooldown period (~5 hours) for the NTR engine, the piloted LERV and TLI stage separate with the LERV continuing on its nominal mission while the NTR stage executes a retargeting maneuver with its RCS system to perform a "trailing edge" lunar swingby. The resulting lunar gravity assist is used to deliver the "spent" NTR stage to a long-lived (~10^5 year) heliocentric orbit with minimal risk of Earth reencounter.

Following a 3.5 day transit, the LERV uses its four LOX/LH_2 engines to propulsively capture into a temporary parking orbit around the Moon. Pausing here allows time for navigational updates and phasing alignment over the desired landing site, and most importantly, time to communicate with the LUNOX production facility and its tanker vehicle to verify that all is ready for the LERV's arrival. Should equipment problems arise on the surface, the LERV would abort the landing and return to Earth using the remaining onboard landing propellant (equivalent ΔV=2000 m/s).

At the appropriate time, the LERV, with its 2 person crew, deorbits and lands on the lunar surface--an event which would be televised worldwide by cameras onboard the waiting LUNOX tanker. The LERV consists of a "state-of-the-art" Apollo-style capsule mounted atop a combination service module / lunar lander. It lands on the lunar surface with its LOX tanks essentially "empty" but within a reasonable distance of the LUNOX production facilities predeployed on an earlier cargo flight. The LERV does carry sufficient LH_2 fuel for the return trip back to Earth however. Shortly after landing, the crew's first major activity is to remotely activate and direct the nearby surface tanker to transport and refill the LERV's LOX tank with ~7 t of LUNOX supplied by the production facility. Once reoxidized, the LERV is ready to leave should an emergency situation arise over the next 3 days. Because the LERV is only designed to support its crew for 3 days on the lunar surface, extended staytimes will require a surface habitation facility be delivered on an earlier cargo mission. Near the end of the surface stay, the crew with its samples, ascends to a temporary lunar phasing orbit, then performs the trans-Earth injection (TEI) burn for the trip back. Near Earth, the crew module separates from the lander stage and performs a direct Earth entry while the lander stage is expended in cislunar space via an Earth fly-by.

LTS VEHICLE DESCRIPTIONS / COMPARISONS

The relative size and mass of the NTR transfer stage and chemical LERV with and without LUNOX usage is shown in Figure 8. Table 4 summarizes LERV system assumptions and mass breakdown both in LEO and on the lunar surface (IMLS) prior to Earth return. The mass elements include the suited crew, surface-landed payload (S/PL), the LERV's return crew capsule (LERC), and lunar landing stage, and returned lunar samples or payload (R/PL). The required amounts of Earth-supplied LOX and LH_2, as well as, quantities of LUNOX for ascent and Earth return are also shown.

Figure 8a shows the reference piloted vehicle configuration for the "LUNOX scenario" discussed above. After EOR&D, the total vehicle length and mass is ~25 meters and ~40 t, respectively. The TLI stage itself is ~18.7 m long but can easily be accommodated by the Titan IVB booster with a 76 foot (~23.2 m) long payload fairing. The NTR-powered TLI stage uses a single 15 klbf engine, dual turbopumps for improved reliability, and ternary carbide fuel elements. At the hydrogen exhaust temperature and nozzle inlet pressure of 2900 K and 2000 psia, respectively, the specific impulse is ~940 s using a nozzle expansion ratio of 300 to 1. Other elements of the NTR TLI stage include: (1) an external radiation shield for crew protection; (2) a 4.6 m diameter by 12.4 m long LH_2 tank; (3) a forward cylindrical adaptor housing the RCS, avionics, auxiliary power, and docking systems; (4) forward and aft cylindrical band skirts; and (5) a conical thrust structure. The TLI stage "dry" mass is ~7 t which includes ~3.64 t for the 15 klbf NTR and shield. The LH_2 and RCS propellant loads total ~13 t. Included in this total is propellant to perform a small (~30 m/s) "trailing edge" lunar swingby maneuver for stage disposal after LERV separation. The stage is also provided with an ~4 kilowatt electric (kW_e) fuel cell auxiliary power system which can provide the stage with ~2 kW_e average power for up to 5.5 days. Table 5 summarizes the mass properties of the TLI stage shown in Figures 7 and 8a.

The reference LERV uses four new throttleable LOX/LH_2 engines (each at ~6 klbf with 4:1 throttling) which operate at an O/H mixture ratio MR = 5.2 and Isp = 450 s. The LERV lander stage is set at 15 % of the "wet" LERV mass in LEO. Preliminary weight estimates of individual subsystem elements show this assumption to be conservative and to provide ample mass margin. In total, the mass of the crew capsule and "dry" lander stage is ~7.5 t or ~37.5% of the LERV's initial mass in LEO, and this weight can be redistributed as necessary if dictated by future analysis. In addition to the crew, the LERV also transports ~0.3 t of equipment (~0.22 t for an "Apollo-style" lunar rover and ~0.08 t of science equipment) to the lunar surface. Power for the LERV during most of the 12 day mission is supplied by two 4 kW_e fuel cells which provide ~3 kW_e average power, as well as, consumable water for the crew and coolant for the active thermal control system. Fuel cell reactants totaling ~0.36 t, at an O/H ratio of 8 to 1, are stored within the LERV's propellant tanks. The LERV transports ~1.34 t of LH_2 to the lunar surface (with ~40 kg being lost to boiloff over the 3 day lunar stay) and refills its LOX tank with ~7 t of LUNOX to return the LERV with its ~4.5 t crew capsule and ~0.5 t of crew and lunar samples back to Earth. The LOX, LH_2 and storable RCS propellant loads are ~8.38, 2.95 and 0.34 t, respectively, for a total IMLEO for the LERV of ~20 t which includes ~0.16 t for the LERV's TLI stage adaptor. The same LERV lander and TLI stage are also capable of delivering ~6.6 t of lunar surface payload on "1-way" cargo missions. This is sufficient to

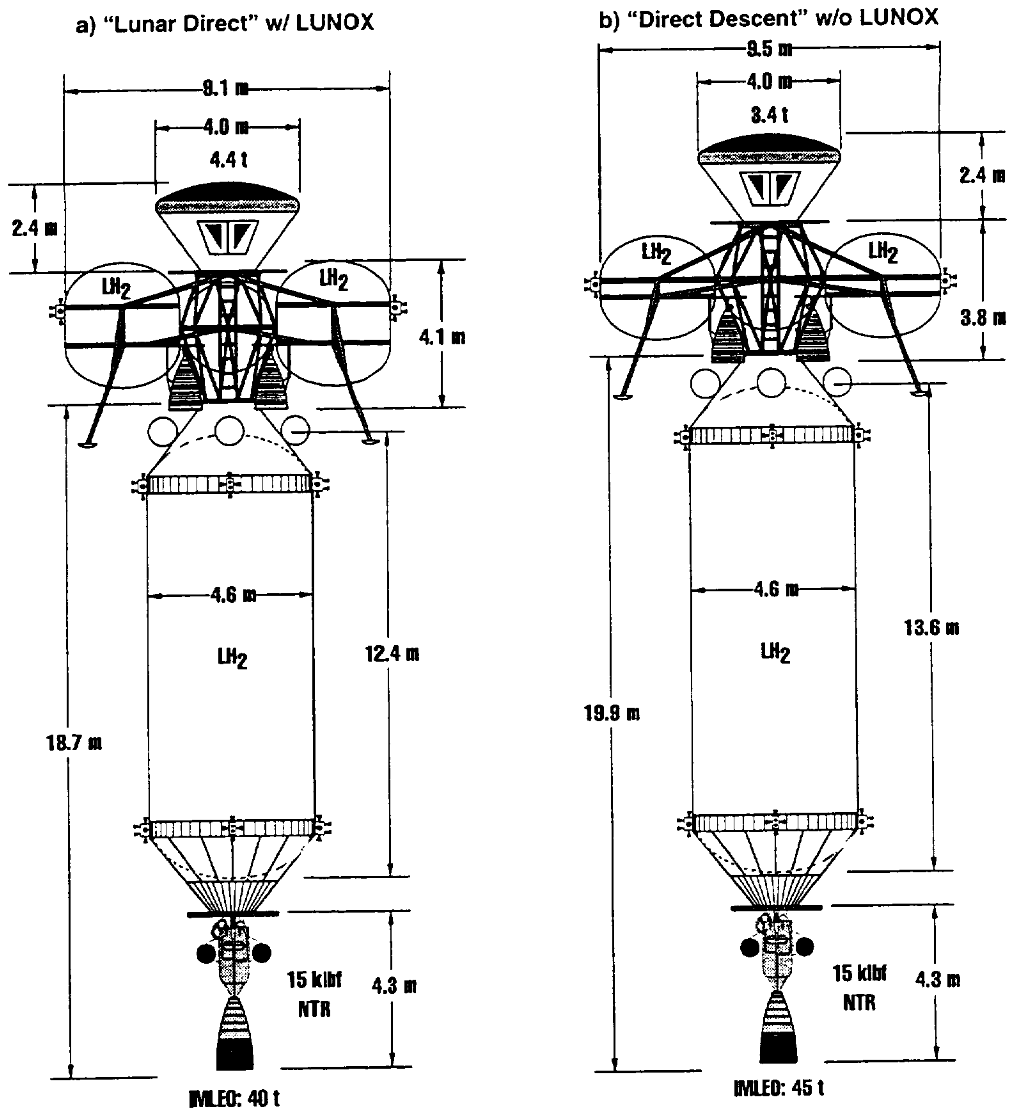


Fig. 8 Relative Size/Mass of NTR Stage and LERV With / Without LUNOX

accommodate all of the envisioned surface elements needed to support the piloted LUNOX mission scenario.

Without LUNOX, the LERV must carry its own return LOX resulting in a substantial reduction in mission capability. To stay within the IMLEO limit of ~45 t provided by the Shuttle and Titan IVB, a "direct descent" trajectory profile[23] must be adopted (see Figure 9) to reduce the total mission ΔV requirements (see Table 1). While direct descent can improve performance in the cargo flight mode, it is a higher risk trajectory profile for piloted missions and does not provide for a "free return" abort. Lunar surface site accessibility and lighting conditions flexibility is also degraded. Propulsion system performance and vehicle size must also be increased (see Figure 8b). For the TLI stage, the NTR fuel temperature is increased to ~3025 K to achieve a higher Isp of ~960 s. However, for a given reactor power level, this increase comes at the expense of a decrease in thrust to ~14.7 klbf. The TLI stage length and mass also increase in order to accommodate the larger LH_2 propellant load (~14.4 t) needed to send a heavier LERV (~23.4 t) to the Moon.

For the LERV's LOX/LH_2 chemical engines, the chamber pressure and mixture ratio are increased to achieve a Isp of ~465 s. A gaseous O_2/H_2 RCS with Isp of ~400 s is also assumed. This increase in

Table 4. LERV System Assumptions and Mass Characteristics

• Mission Profile:	Lunar Direct w/LUNOX	Direct Descent wo/LUNOX
• Propellant:	LOX/LH_2	LOX/LH_2
• MR/Isp:	5.2 / 450 s	6.0 / 465s
• IMLEO/IMLS:	20.0 t / 16.25 t	23.56 t / 13.17 t
• Crew (2) & Suits:	0.45 t	0.45 t
• $M_{S/PL}$:	0.30 t	0.05 t
• M_{LERC}:	4.42 t	3.36 t
• $M_{stage/adaptor}$:	3.0 t / 0.16 t	3.5 t / 0.16 t
• $M_{RCS\ prop}$:	0.19 t / 0.15 t	0.18 t / 0.06 t
• M_{LOX}:		
- Outbound	8.38 t	8.59 t
- Inbound	-	4.88 t
- LS boiloff	-	0.04 t
• M_{LH2}:		
- Outbound	1.61 t	1.43 t
- Inbound	1.30 t	0.81 t
- LS boiloff	0.04 t	0.04 t
• M_{LUNOX}:	6.78 t	-
• $M_{R/PL}$:	0.05 t	0.01 t

performance cannot compensate, however, for the extra 5 t of return LOX and the heavier lander stage required to carry it. The result is a decrease in the available mass and therefore capability of crew capsule (from ~4.4 to 3.4 t) , as well as, in payload delivered to the lunar surface (see Table 4). With no lunar rover and only ~50 kg of science equipment available to the astronauts, EVA activities will be limited to short distances away from the LERV similar to that on the Apollo 12 and 14 missions. Returned lunar samples will also be limited to ~10 kg, substantially less than that returned on the earlier Apollo missions. Although an initial 2004 human lunar return mission appears doable without LUNOX, subsequent flights would greatly benefit from its use and help to restore lost mission versatility and vehicle robustness.

Table 5. TLI Stage Mass Properties

Stage Element	Mass (kg)
Structure	607
Propellant Tank	1065
Thermal Protection System	508
Avionics and Power	293
Reaction Control System	227
NTR Assembly	
15 klbf NTR	2224
External Shield	940
Propellant Feed/TVC	171
Contingency (15%)	905
Dry Mass	6940
LH2 Propellant	12741
RCS Propellant	100
Wet TL I Stage Mass	19781

OTHER MISSION APPLICATIONS FOR THE NTR

Investing wisely in "high leverage" technologies with growth capability and applications to more ambitious human missions beyond the 2004 lunar return discussed here is an important point not to be overlooked. The small NTR stage is an excellent example of a wise technology investment for NASA for with it a wide range of missions become possible (see Figure 10). In less than 6 months after humans return to the Moon (see Figure 6), the same small NTR stage could be used to dispatch a robotic orbiter mission to Pluto using a single Titan IVB launch and a Jupiter gravity assist opportunity available in June 2006. Direct flight, "short transit time" orbiter missions to Saturn (2.3 years), Uranus (6.6 years), and Neptune (12.6 years) are also possible each year.[24]

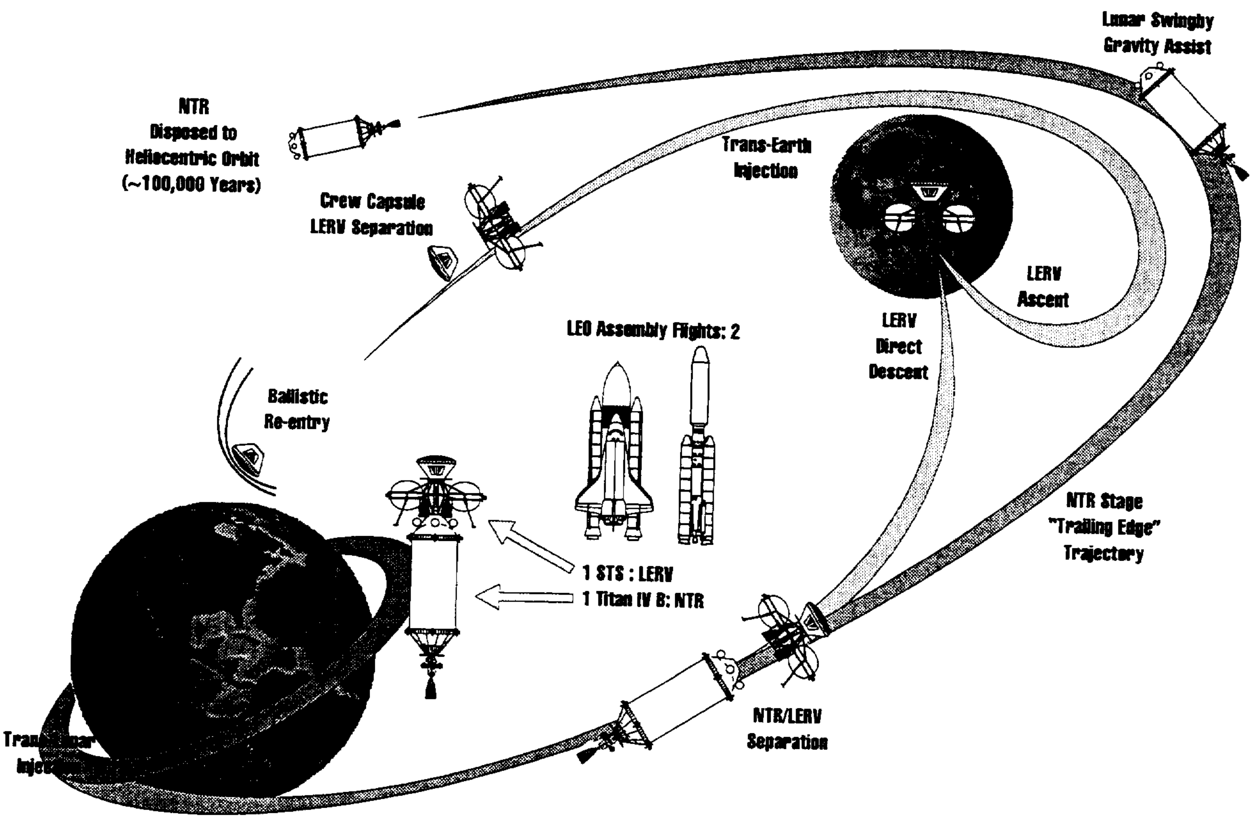


Fig. 9 Alternative “Direct Descent” Mission Scenario Using NTR and LERV Only

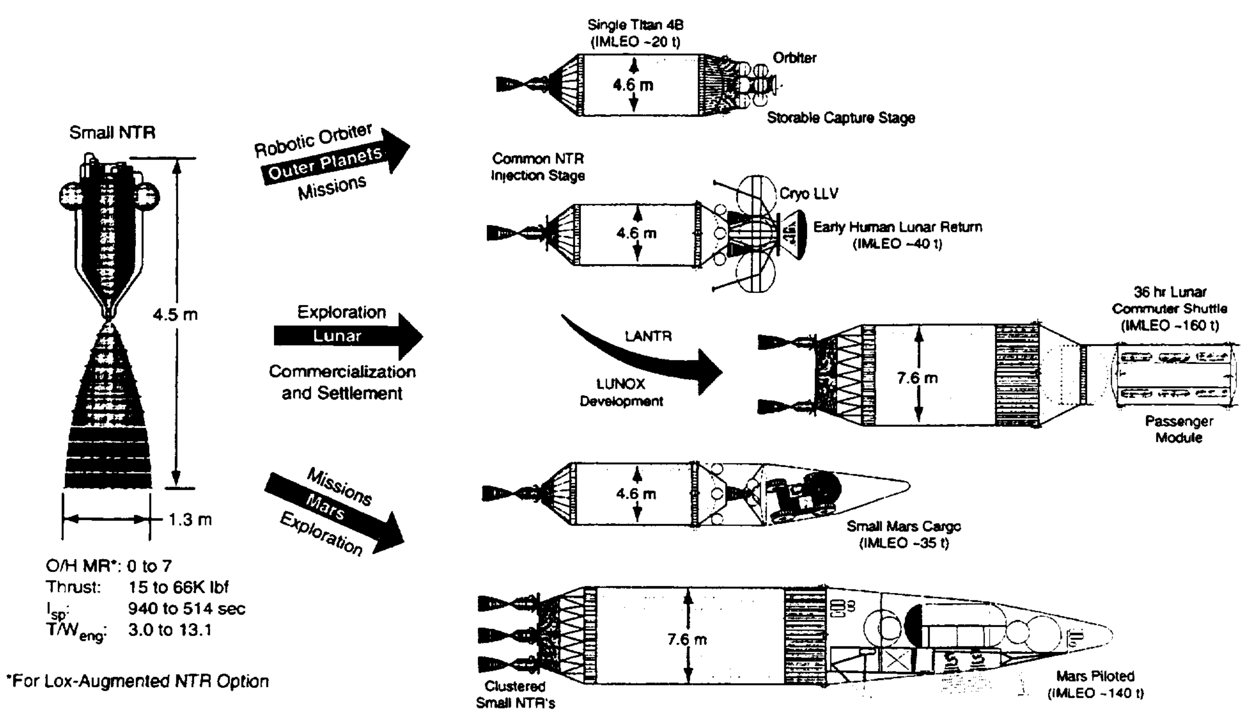


Fig. 10 Small NTR Mission Versatility: “One Size Fits All”

How far can we go with LANTR propulsion?

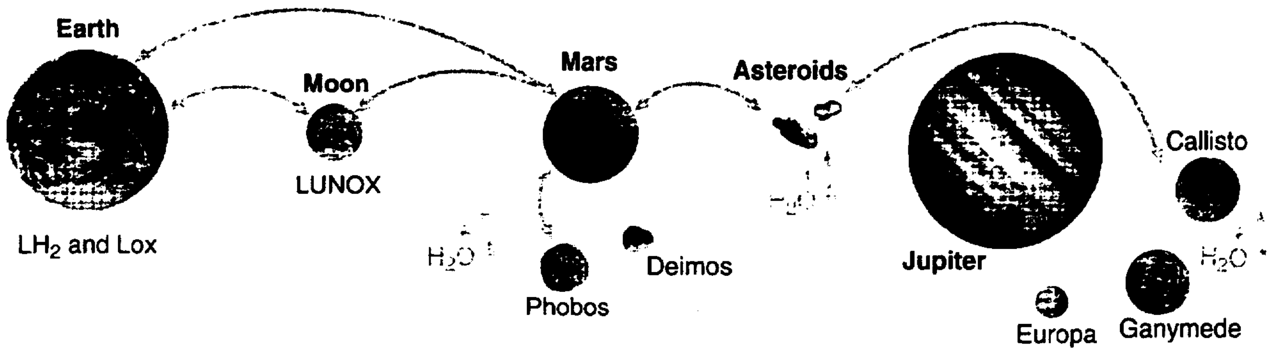


Fig. 11 Human Expansion Possibilities With LOX-Augmented NTR (LANTR)

In preparation for the human exploration of Mars, small Mars cargo missions capable of delivering up to 10 t of surface payload can be carried out using the Titan IVB-launched small NTR stage for trans-Mars injection and the Space Shuttle for launching the Mars payload with its biconic-shaped aero-capture and descent system. Higher capacity cargo and Mars piloted missions would use the same 15 klbf NTR engine in a clustered arrangement to provide the optimum mission thrust level. A cargo version of the current Space Shuttle (Shuttle C) or an "in-line" Shuttle-derived vehicle with a lift capability of ~70 t to LEO would probably be utilized for these missions to avoid the substantial LEO asembly requirements using "volume-limited" smaller capacity (~20 t-class) launch systems such as the reusable launch vehicle (RLV).

With time, initial outposts on the Moon and Mars will grow to centralized bases and settlements with a substantial human presence. LUNOX production facilities on the lunar surface will supply propellant depots in low lunar orbit and in turn a "LOX-augmented" NTR (LANTR)-powered LTS which will "revolutionize" cislunar space travel. Commuter flights[25] to and from the Moon with "one-way" trips of 36 to 24 hours will become commonplace using LANTR-powered passenger shuttles. On Mars, reusable LANTR-powered landers, operating from specially prepared landing sites, will transport significant quantities of payload to and from a Phobos station and propellant depot. The Phobos depot would also provide reusable LANTR-powered Mars transfer vehicles with their return propellant allowing them to transport more high value cargo to Mars instead of bulk propellant and expended lander / aerobrake hardware mass.

Beyond the Moon and Mars lies the asteroid belt and the Jupiter system (see Figure 11) where large quantities of water are believed to exist. Water ice has been detected on Ceres, the largest of the main-belt asteroids, and the Galilean satellites, Europa, Ganymede, and Callisto, are known to possess large amounts of water ice on their surfaces from the Voyager missions. Using ISRU and LANTR technologies, extraterrestrial sources of LOX and LH_2 can be developed and utilized to facilitate human expansion into the Solar System . While such missions and capabilities are wondrous to imagine what is most exciting to the authors is the fact that these technologies could be developed in the next 10 to 15 years!

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13. ABSTRACT ***(Maximum 200 words)***

The feasibility of returning humans to the Moon by 2004, the 35th anniversary of the Apollo 11 landing, is examined assuming the use of existing launch vehicles (the Space Shuttle and Titan IVB), a near term, advanced technology space transportation system, and extraterrestrial propellant--specifically "lunar-derived" liquid oxygen or LUNOX. The lunar transportation system (LTS) elements consist of an expendable, nuclear thermal rocket (NTR)-powered translunar injection (TLI) stage and a combination lunar lander/Earth return vehicle (LERV) using cryogenic liquid oxygen and hydrogen (LOX/LH_2) chemical propulsion. The "wet" LERV, carrying a crew of 2, is configured to fit within the Shuttle orbiter cargo bay and requires only modest assembly in low Earth orbit. After Earth orbit rendezvous and docking of the LERV with the Titan IVB-launched NTR TLI stage, the initial mass in low Earth orbit (IMLEO) is ~40 t. To maximize mission performance at minimum mass, the LERV carries no return LOX but uses ~7 t of LUNOX to "reoxidize" itself for a "direct return" flight to Earth followed by an "Apollo-style" capsule recovery. Without LUNOX, mission capability is constrained and the total LTS mass approaches the combined Shuttle-Titan IVB IMLEO limit of ~45 t even with enhanced NTR and chemical engine performance. Key technologies are discussed, lunar mission scenarios described, and LTS vehicle designs and characteristics are presented. Mission versatility provided by using a small "all LH_2" NTR engine or a "LOX-augmented" derivative, either individually or in clusters, for outer planet robotic orbiter, small Mars cargo, lunar "commuter", and human Mars exploration class missions is also briefly discussed.

14. SUBJECT TERMS

Space shuttle; Titan IVB; Nuclear thermal rocket; NTR; LOX-augmented NTR; LUNOX; Human lunar return; Cryogenic lander/Earth return vehicle; LERV; Lunar direct

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