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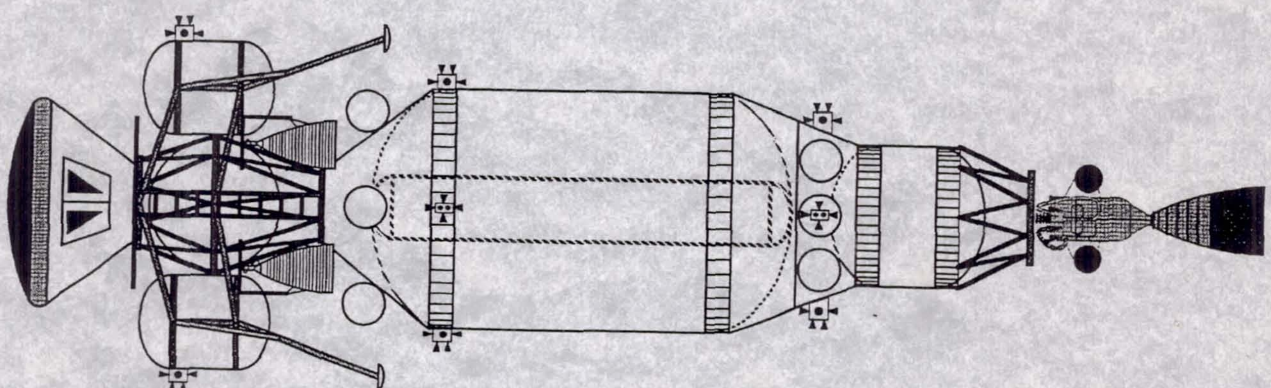
Human Lunar Mission Capabilities Using SSTO, ISRU and LOX-Augmented NTR Technologies— A Preliminary Assessment

Stanley K. Borowski
Lewis Research Center
Cleveland, Ohio



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HUMAN LUNAR MISSION CAPABILITIES USING SSTO, ISRU AND LOX-AUGMENTED NTR TECHNOLOGIES --A PRELIMINARY ASSESSMENT

Stanley K. Borowski *
NASA Lewis Research Center
Cleveland, OH 44135

ABSTRACT

The feasibility of conducting human missions to the Moon is examined assuming the use of three "high leverage" technologies: (1) a single-stage-to-orbit (SSTO) launch vehicle, (2) "*in-situ*" *resource utilization* (ISRU)--specifically "lunar-derived" liquid oxygen (LUNOX), and (3) LOX-augmented nuclear thermal rocket (LANTR) propulsion. Lunar transportation system elements consisting of a LANTR-powered lunar transfer vehicle (LTV) and a chemical propulsion lunar landing / Earth return vehicle (LERV) are configured to fit within the "compact" dimensions of the SSTO cargo bay (diameter: 4.6 m/length: 9.0 m) while satisfying an initial mass in low Earth orbit (IMLEO) limit of ~60 t (3 SSTO launches). Using ~8 t of LUNOX to "reoxidize" the LERV for a "direct return" flight to Earth reduces its size and mass allowing delivery to LEO on a single 20 t SSTO launch. Similarly, the LANTR engine's ability to operate at any oxygen/hydrogen mixture ratio from 0 to 7 with high specific impulse (~940 to 515 s) is exploited to reduce hydrogen tank volume, thereby improving packaging of the LANTR LTV's "propulsion" and "propellant modules". Expendable and reusable, piloted and cargo missions and vehicle designs are presented along with estimates of LUNOX production required to support the different mission modes. Concluding remarks address the issue of lunar transportation system costs from the launch vehicle perspective.

INTRODUCTION

Future human exploration missions to the Moon will require an "economical" lunar transportation system (LTS) providing efficient "*access to and through space*." Utilizing locally available resources--specifically "iron oxide (FeO)-rich" mare soils and impact / volcanic glass-- to produce LUNOX will also be key to minimizing IMLEO, the size and number of LTS elements, and the cost for each lunar mission. At present, NASA is focusing considerable resources on the construction of the international space station (ISS) and on development and demonstration of a reusable, single-stage-to-orbit (SSTO) vehicle[1] to replace the current Space Shuttle in the post-2005 timeframe. It is envisioned that an industry-developed and-operated SSTO would have an average flight rate of ~40 missions per year with ~50% of these flights procured by NASA to provide logistics resupply to the ISS.

Planning future human missions to the Moon and Mars is also beginning anew--albeit in a less dramatic fashion than the previous Space Exploration Initiative[2]--in response to the "Human Exploration and Development of Space" (HEDS) component of NASA's just released strategic plan.[3] Activities are focusing on the development of key "high leverage" technologies and systems, their demonstration on precursor missions, and on the identification of viable mission architectures that could be supported by NASA in the future given the expected tight budgets and the trends toward commercialization.

This paper addresses the feasibility of conducting human lunar missions using SSTO, ISRU and LOX-augmented nuclear thermal rocket (LANTR) technologies/systems. For "*access to space*," the lure of the SSTO is its full reusability, improved operability, high flight rate and reduced launch costs estimated at ~40 M$ per flight.[4] Its lift capability is limited, however, and varies from ~25 klbm (~11.3 t) to 45 klbm (~20.4 t) depending on the

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*Ph.D./Nuclear Engineering, Senior Member AIAA

low Earth orbit (LEO) altitude and its inclination. The SSTO's cargo bay volume is also small (~50 to 75% that of the current Space Shuttle) which makes packaging of payload and LTS elements a particular challenge.

The development of LUNOX production, storage and tanker transport / transfer technologies and systems for "reoxidizing" expendable lunar landing/Earth return vehicles (LERVs) initially, and then reusable, lunar landing and transfer vehicles (LLVs and LTVs) is expected to dramatically reduce IMLEO requirements, the number of SSTO launches and the cost of delivering payload to the lunar surface. For example, with ~7 kilograms of mass required in LEO for each kilogram of mass landed on the lunar surface, the ability to reoxidize an LERV with ~8 tons of LUNOX for a "direct Earth return" mission would save three 20 t-class SSTO launches compared to an "all Earth-supplied" mission requiring twice that number.

To improve "*access through space*," a LANTR-based LTV mission scenario has been assumed. The ability to alter the engine's thrust and specific impulse (Isp) by varying the liquid oxygen-to-liquid hydrogen (LOX/LH_2) mixture ratio (MR) in LANTR's "LOX-afterburner" nozzle leads to small engines (both in terms of physical size and reactor power output) capable of providing "big engine" performance. Supersonic combustion of LOX with reactor preheated hydrogen emerging from the engine's sonic throat also results in higher Isp values than LOX/LH_2 chemical engines operating at the same mixture ratio (~100 s at MR = 6). Lastly, the increased use of high-density LOX in place of low-density LH_2 reduces hydrogen tank volume and improves LTV component packaging within the "volume-constrained" SSTO cargo bay.

This paper describes results of preliminary system and mission analysis conducted by Lewis Research Center for NASA Headquarters' Advanced Concepts Office over the past two months. The paper first discusses the relevant technologies and describes their characteristics. Mission and transportation system ground rules and assumptions are then presented along with a description of the reference lunar mission scenario. Next, a comparison of different LTS element options--both for the LERV and LTV--is provided and the requirements/performance gains from transitioning from an expendable to reusable LTS architecture are discussed. The paper concludes with a discussion of lunar transportation system and launch vehicle costs.

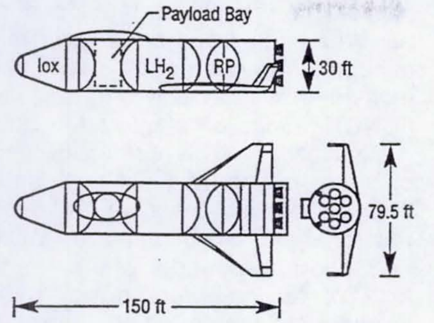
SSTO, LUNOX, AND LANTR TECHNOLOGY DESCRIPTION

The SSTO Reusable Launch Vehicle

In January 1993, NASA initiated a comprehensive "in-house" study called "Access to Space." The goals of the study were to identify attractive options for the next generation of U.S. launch vehicles which would: (1) allow major reductions in the cost of space transportation (by at least 50%); (2) provide an order of magnitude increase in crew flight safety; and (3) substantially improve overall system operability. The study examined three major architectural options which included: retaining and upgrading the current Space Shuttle and expendable launch vehicle fleet (Option 1); developing new expendable vehicles using conventional technologies (Option 2); and developing new reusable vehicles using advanced technology (Option 3). A conservative "launch needs" mission model was defined and used in the study.[4] It included all U.S. civilian (NASA), defense and commercial missions anticipated during the period 1995 through 2030, but did not consider future human missions to the Moon and Mars--a major omission.

In its final summary report[4] issued in January 1994, NASA concluded that a fully reusable, pure-rocket SSTO (SSTO-R) launch vehicle was the most attractive/beneficial option for development. The preferred Option 3 reference vehicle described in the "Access to Space Study" Summary Report[4] is shown in Figure 1. It is a vertical takeoff, horizontal-landing winged concept with a circular cross-section fuselage for structural efficiency (other configurations are presently being examined under NASA-supported industry contracts). It uses aluminum-lithium (Al/Li) cryotanks, graphite composite material for all non-pressurized primary structure and a tripropellant ($LOX/LH_2/RP$) propulsion system employing seven RD-704 engines. The payload bay is located horizontally between the forward LOX tank and the LH_2 tank positioned in the vehicle's midsection. The crew cabin is situated on top of the vehicle next to an airlock/work-station area which provides crew access to both the payload bay and the ISS through an overhead hatch. A "LOX/LH_2" version of the SSTO-R would have an overall length and diameter ~15% larger than its tripropellant counterpart and a gross liftoff weight (GLOW) of ~2.48 million pounds (~1125 t).

The reference SSTO-R cargo bay is 15 feet (~4.6 m) in diameter and 30 feet (~9.15 m) long. A



Payload*	Flight Crew	Final Orbit
25 klbm	None	Station: 220 nmi circ @ 51.6°
15.5 klbm	2 Person	Station: 220 nmi circ @ 51.6°
45 klbm	None	100 nmi circ @ 28.5°
32 klbm	None	220 nmi circ @ 28.5°
24 klbm	None	100 nmi circ @ 90°

* Includes Payload and ASE

Vehicle:

GLOW:	1.96 Mlb
Dry Mass:	159.5 klb
Propellant Mass:	1.74 Mlb
Propellant Type:	Lox/LH_2/RP
Main Engine Type/No.:	RD–704/7
Vac Thrust (ea.) Mode 1/2:	441.4/175.5 klb
Vac ISP Mode 1/2:	407/452
Area Ratio:	74:1
OMS Engine Type/No.:	New Lox/LH_2
Vac Thrust (ea.):	6 klbf
Vac Isp:	462 s
Area Ratio:	100:1
Cryo Tanks	Al-Li
Primary Structure:	Gr-Composite
Control Surfaces:	ACC
TPS:	ACC/TABI/AFRSI
Payload Bay—Usable Volume	15 ft D × 30 ft L

Notes:
- Vertical takeoff/horizontal landing
- 15 percent dry weight margin
- Option for carrying two on-orbit operations crew for 7 days
- Option for carrying four S.S. *Freedom* rotation crew in payload bay
- Option for carrying high energy transfer stage for Atlas class (5k lb) GEO missions

Fig. 1 Characteristics of Reference SSTO Launch Vehicle (Ref. 4)

"stretched" tripropellant vehicle configuration with a 45 foot (13.7 m) long payload bay and capable of delivering ~20 t to LEO (185 km/28.5 degrees inclination) was also developed. Because of the tripropellant vehicle's smaller LH_2 tank, the 45 foot bay could also be placed longitudinally in the vehicle. The 45 foot SSTO-R design could also accommodate the larger DOD Titan IV-class payloads. As a result, this vehicle option showed the lowest annual operating costs (~1.4 B$/year), as well as cost per launch (~38 M$) and per pound of payload to LEO (~920 $/lbm) of the three options examined (see Table 1).

Table 1. Summary of Launch Vehicle Option Costs (Ref. 4)

* Current Space Shuttle capability (no ASRM)
** In the out-years
• Constant FY94 dollars; no "new ways of doing business."

		Current Program	Option 1 (Retrofit + ELV Fleet)	Option 2 (Lg. + Sm. Veh. + Delta)	Option 3 (SSTO-R, 30-ft Bay + Titan)	Option 3 (SSTO-R, 45-ft Bay)
Costs	Technology	0	Incl. in DDT&E	$0.4B	$0.9B	$0.9B
	DDT&E (Incl. Technology)	0	$2.4B	$11.1B	$17.6B	$18B
	Production	0	$5.6B	$2.0B	$18.1B	$18.7B
	Operations (Out-Years)	$6.4B/yr	$6.1B/yr	$4.0B/yr	$2.6B/yr	$1.4B/yr
	Life-Cycle Costs	$233B	$230B	$192B	$198B	$169B
Operations Cost Metrics**	Average $/Launch (Shuttle Replacement)	$322M (STS)*	$293M (STS)*	$85M (Sm.) $205M (Lg.)	$41M	$38M
	$/lb of Payload (Fleet Average for Mission Model)	$7,488/lb	$6,814/lb	$6,100/lb	$3,900/lb	$2,100/lb
	$/lb of Payload (Full Veh., to LEO, 28°)	$6,850/lb (STS)*	$6,234/lb (STS)*	$3,900/lb (Sm.) $1,600/lb (Lg.)	$980/lb	$920/lb
	$/lb of Payload (to the Space Station)	$12,880/lb	$11,720/lb	$3,700/lb (Lg.)	$1,600/lb	$1,500/lb

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 MR=6) with a source of return propellant oxidizer reduces the size and mass of the LERV, as well as, the LTV which delivers it to low lunar orbit (LLO). 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 reults suggest that iron- and titanium-rich soils and iron-rich glasses, in particular, would be attractive feedstocks 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. This is very important because reduced mining and benefication of bulk regolith can lower the mass and power requirements of a LUNOX production plant.

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[8] 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 facilty before power generation begins. Subsequent flights would deliver high duty-cycle, electric vehicles for loading and handling regolith and transporting LUNOX from the production site to the LERV (see Figure 2).

The mass and power requirements for a lunar ilmenite reduction facility producing ~24 t of LUNOX per year (enough for 3 piloted missions) have been estimated[8,9] at ~17.3 to 20.7 t, and ~40 to 80 kW_e, respectively, with system mass and power variations depending on specific assumptions. A breakdown of system element masses for Jooston's[8] 20.7 t estimate includes the LUNOX plant (7.3 t), and nuclear reactor system (5.1 t), 2 regolith loaders (3.5 t), and haulers (1.9 t), and 2 LUNOX tanker vehicles (2.9 t).

The LOX-Augmented NTR (LANTR)

The recently proposed LANTR propulsion concept[10,11] represents an innovative combination of conventional LH_2-cooled NTR and supersonic combustion ramjet (scramjet) technologies. The LANTR engine (see Figure 3) 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 propulsion 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. As the MR varies from 0 to 7, the engine thrust - to - weight ratio for a 15 klbf NTR increases by ~ 440%--from 3 to 13--while the Isp decreases by only ~45%--from 940 to 515 seconds.

The ability to vary LANTR engine performance with MR also results in important engine-, vehicle-, and mission-benefits. Thrust augmentation allows "big engine" performance to be obtained using smaller, more affordable, easier to test NTR engines. Burn times are also shortened which extends engine life and improves "life cycle costs"--an important consideration in reusable mission architectures.

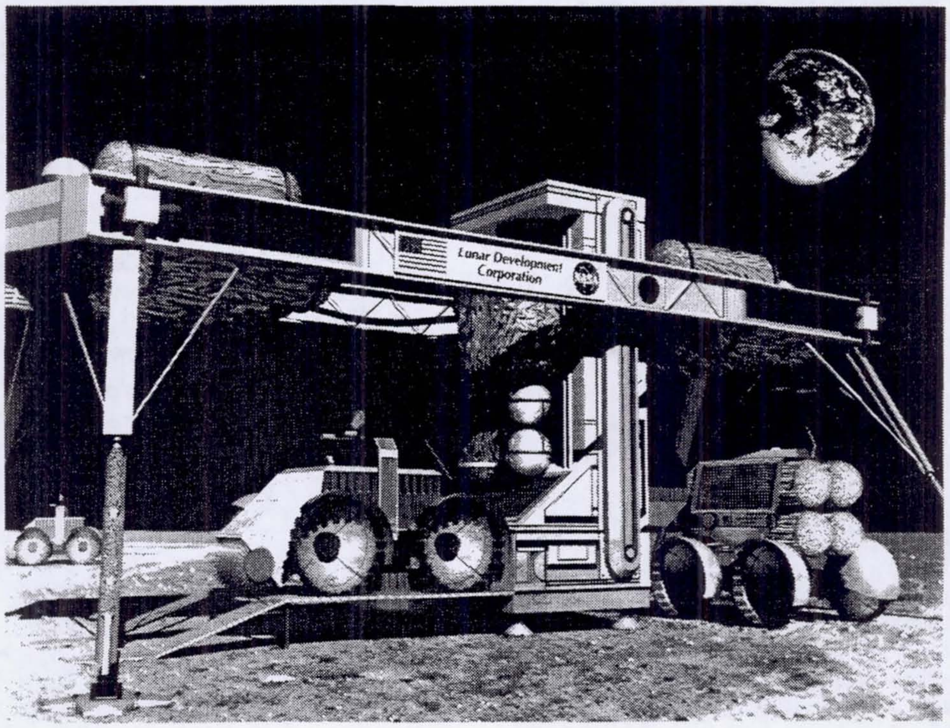
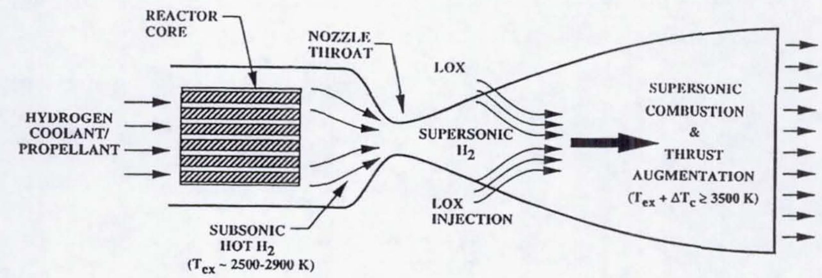


Fig. 2 "LUNOX" Facility and Teleoperated Support Vehicles



	Isp (sec)				
Life (hrs.) T_c ($^\circ$K)	5 2900	10 2800	30 2600	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 15 klbf LANTR with chamber pressure = 2000 psia and ϵ = 500 to 1

Fig. 3 Schematic/Characteristics of LOX-Augmented NTR

Increasing the MR reduces the hydrogen mass and volume and decreases the LH_2 tank size and mass. 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. Compactness is especially important for LANTR deployment using the SSTO because of its small cargo bay dimensions.

Finally, once LUNOX becomes available in LLO to reoxidize the LANTR LTV, transition to a "reusable" mission architecture can occur, with formerly expendable vehicles delivering significant quantities of payload to LLO on each round trip cargo, as well as piloted mission. These capabilities are discussed in detail in the sections which follow.

LUNAR MISSION / TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

The ground rules and assumptions for the reference lunar mission examined in this study are summarized in Table 2. Provided are details on outbound and return payloads, parking orbits, mission velocity change (ΔV) requirements and duration, and SSTO characteristics. In addition to the primary ΔV maneuvers indicated, midcourse correction maneuvers are also performed using a storable, bipropellant RCS system. Table 3 details assumptions for the LANTR LTV on primary and auxiliary 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 structure in accordance with assumptions used for the SSTO-R reference configuration. Wall thicknesses for the LH_2 tanks were calculated based on a 35 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 50 psi internal pressure was assumed for LOX tanks with wall thicknesses of ~0.05 inches.

A two inch helium-purged, multilayer insulation (MLI) system (at 50 layers per inch) is assumed for thermal protection of the LANTR's LOX

Table 2. Reference Lunar Mission Ground Rules and Assumptions

• Payload Outbound:	17.4-18.2 t	"Wet" LERV	"expendable mode" *
	0.6 t	Crew (3) & suits	
	1.0-0.2 t	Surface payload	
	6.8 t	LTV crew module	"reuse mode" **
	0.8 t	Crew (4) & suits	
	2.0 t	Surface payload	
• Payload Inbound:	6.8 t	LTV crew module	
	0.8 t	Crew (4) & suits	
	0.5 t	Lunar samples	
	0.1 t	LERV lunar samples	
• Parking Orbits:	185-407 km	Circular (Earth departure)	
	300 km	Circular (lunar arrival/departure)	

- Trans-lunar injection / Earth orbit capture ΔV: 3155 m/s + g-losses / 3100 m/s
- Lunar orbit capture / trans-Earth injection ΔV: 915 m/s
- Lunar descent / direct ascent and Earth return ΔV: 2000 m/s / 2900 m/s and capsule entry
- Lunar orbit disposal ΔV: 860 m/s (for expendable LANTR scenario)
- Mission duration: $\leq$54 days* (2 in LEO, 7 in transit, $\leq$45 days at Moon)
- Launch vehicle type / payload capability: SSTO / 20 t to 185 km circular
- LTS assembly scenario: 3 SSTO launches with EOR&D (IMLEO $\leq$ 60 t)

* "Wet" LERV carries return fuel but requires LUNOX for direct ascent/Earth return
** In "reuse mode" surface-based LLV picks-ups/returns crew & payload/sample

Table 3. LANTR Transportation System Assumptions

• LANTR System:	Propellants	= Cryogenic hydrogen and oxygen
	Isp	= 940 s (@ O/F MR = 0.0 / LH_2 only)
		= 607 s (@ O/F MR = 4.0)
		= 545 s (@ O/F MR = 6.0)
	External Shield Mass	= 2.84 kg/MWt of reactor power
	Flight Reserve	= 1% of total tank capacity
	Residuals	= 1.5% 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	= 2.7 m (LOX)/4.6 m (LH_2)
	Geometry	= Cylindrical tank with 2/2 domes
	Insulation	= 2 inches MLI + micrometeoroid debris shield
	LH_2/LOX Boiloff*	= 1.31/2.44 kg/m²/month (LEO @ ~ 240 K)
		= 0.56/0.90 kg/m²/month (in-space @ ~ 172 K)
		= 1.91/3.68 kg/m²/month (LLO @ ~ 272 K)
• Primary Structure:	Material	= Graphite/Epoxy Composite
• Contingency:	Engine, shield , and stage dry mass = 15%	

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

and LH_2 cryogenic tanks. This insulation thickness exceeds the "ground hold" thermal protection requirements for "wet-launched" LH_2 tanks which need a minimum of 1.5 inches of helium-purged insulation.[12] The installed density of the "2 inch MLI system" is ~2.62 kg/m^2, and the resulting LH_2 boiloff rate in LEO is ~1.31 kg/m^2/month (based on an estimated heat flux of ~0.22 W/m^2 at a LEO sink temperature of ~240 K). In lunar orbit, where the sink temperature and heat flux are estimated to be ~272 K and 0.32 W/m^2, respectively, the LH_2 boiloff rate increases by ~46% to 1.91 kg/m^2/month. The corresponding boiloff rates for LOX are also shown in Table 3. Finally, a 0.25 mm thick sheet of aluminum (corresponding to ~0.682 kg/m^2) is included in the total tank weight estimates to account for micrometeoroid protection.

LUNAR MISSION ARCHITECTURE DESCRIPTION

The reference lunar scenario examined in this study assumes a split mission architecture involving both cargo and piloted missions operating initially in an "expendable mode." The piloted mission employs a "lunar direct" flight profile and assumes the availability of LUNOX for lander refill and Earth return.[8,13] The mission flight profile is illustrated in Figure 4. Three SSTO flights, each with a payload capability of ~20 t, are used to deliver the LTS elements consisting of the LANTR-powered LTV and its payload--the piloted lunar landing / Earth return vehicle (LERV) to LEO. Here the elements are assembled into an integrated spacecraft via a series of rendezvous and docking maneuvers (see Figures 4 and 5b).

After 2 days in LEO for system checkout, a "single burn" trans-lunar injection (TLI) maneuver is performed which sends the coupled LTV/LERV on a trajectory to the Moon. Following a 3.5 day transit, the LANTR engine performs a second burn to achieve lunar orbit insertion (LOI). After a brief waiting period in LLO for proper landing site phasing, the LERV with its 3 person crew separates from the LANTR stage, deorbits and lands on the lunar surface. Shortly afterwards, the LANTR performs a short (~0.6 minute) final burn to depart LLO and send the spent stage on a "long-term disposal" trajectory into heliocentric space.

The LERV consists of a "*scaled-up*" Apollo capsule mounted atop a combination service module/lander vehicle which uses either LOX/LH_2 or LOX/liquid methane (CH_4) chemical engines. It lands on the lunar surface with its LOX tanks essentially "empty" but carries sufficient fuel (LH_2 or

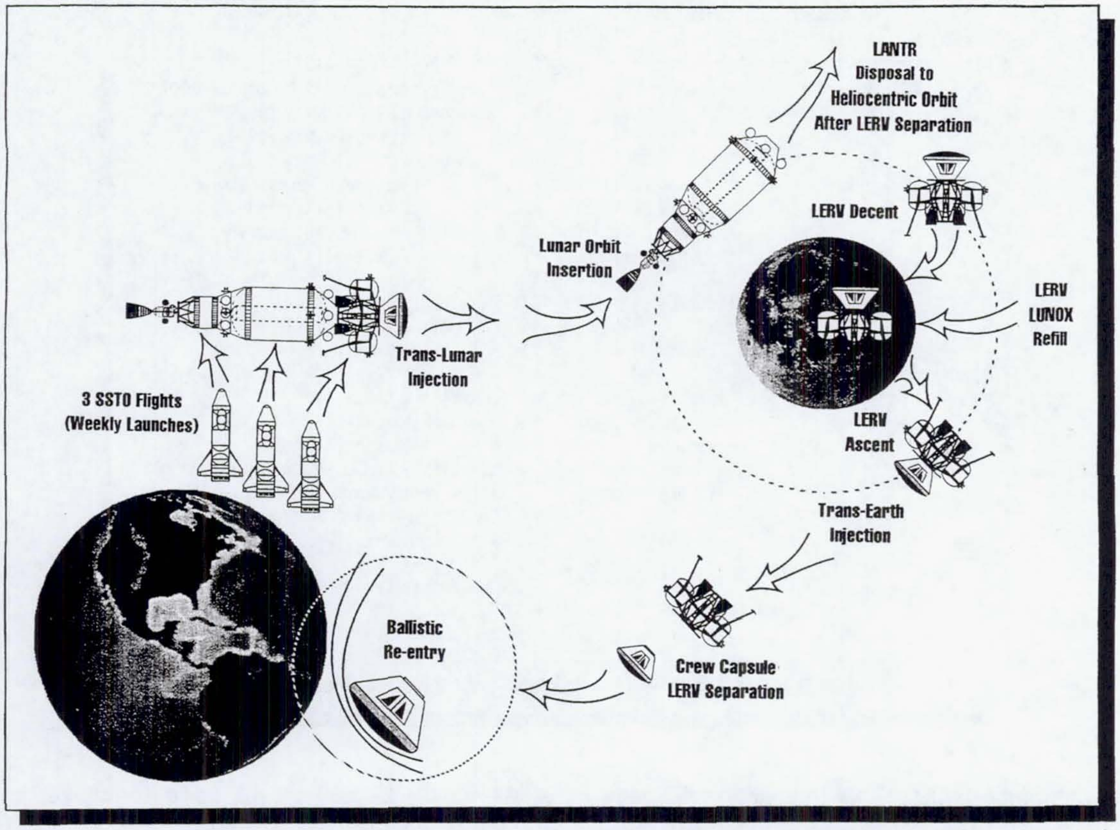


Fig. 4 Reference Piloted Mission Scenario Using SSTO, LANTR and LUNOX Technologies

CH_4) for the return trip to Earth. Because of the limited life support capabilities of the LERV, the crew is sustained for extended periods by a surface habitation facility delivered on earlier cargo missions, as are the LUNOX production equipment and surface exploration equipment.[8] Near the end of the surface stay, the crew uses the surface tanker to transport and refill the LERV's LOX tank with ~8 t of LUNOX supplied by the production facility. Once reoxidized, the LERV, with crew and samples, ascends to a temporary lunar phasing orbit, then performs the trans-Earth injection (TEI) burn for the trip back. Near Earth, the lander stage is jettisoned and the crew module reenters ballistically.

LTS VEHICLE DESCRIPTIONS / COMPARISONS

The relative size and mass of various NTR/LANTR-powered LTV and chemical LERV combinations are shown in Figure 5. Table 4 summarizes LERV system assumptions and its mass breakdown both in low lunar orbit (IMLLO) and on the lunar surface (IMLS) prior to Earth return. The mass elements include the 3 crew, surface-landed payload (SP/L), the LERV's return crew capsule (LERC), and lunar landing stage, and returned lunar samples/payload (RP/L). The required amounts of LOX and fuel (either LH_2 or CH_4) for landing, as well as, quantities of LUNOX and fuel for ascent and Earth return are also shown.

To provide a point of comparison with the reference SSTO-launched and LANTR-powered vehicles, Figure 5a shows a LOX/LH_2 LERV and "all LH_2" NTR LTV configuration that uses the Space Shuttle orbiter and a Titan IV launch vehicle, respectively, for their delivery to LEO. The LERV's "wet" lander stage and crew capsule have a combined mass of 20 t and are carried in the orbiter's payload bay "side-by-side." Once in orbit the capsule is installed atop the lander and the integrated LERV's systems are checked out.

Next, a 20 t "all LH_2" NTR-powered LTV is launched to LEO for Earth orbit rendezvous and docking (EOR&D) with the LERV. A Titan IV booster, with an 86 foot (~26.2 m) long payload fairing, is

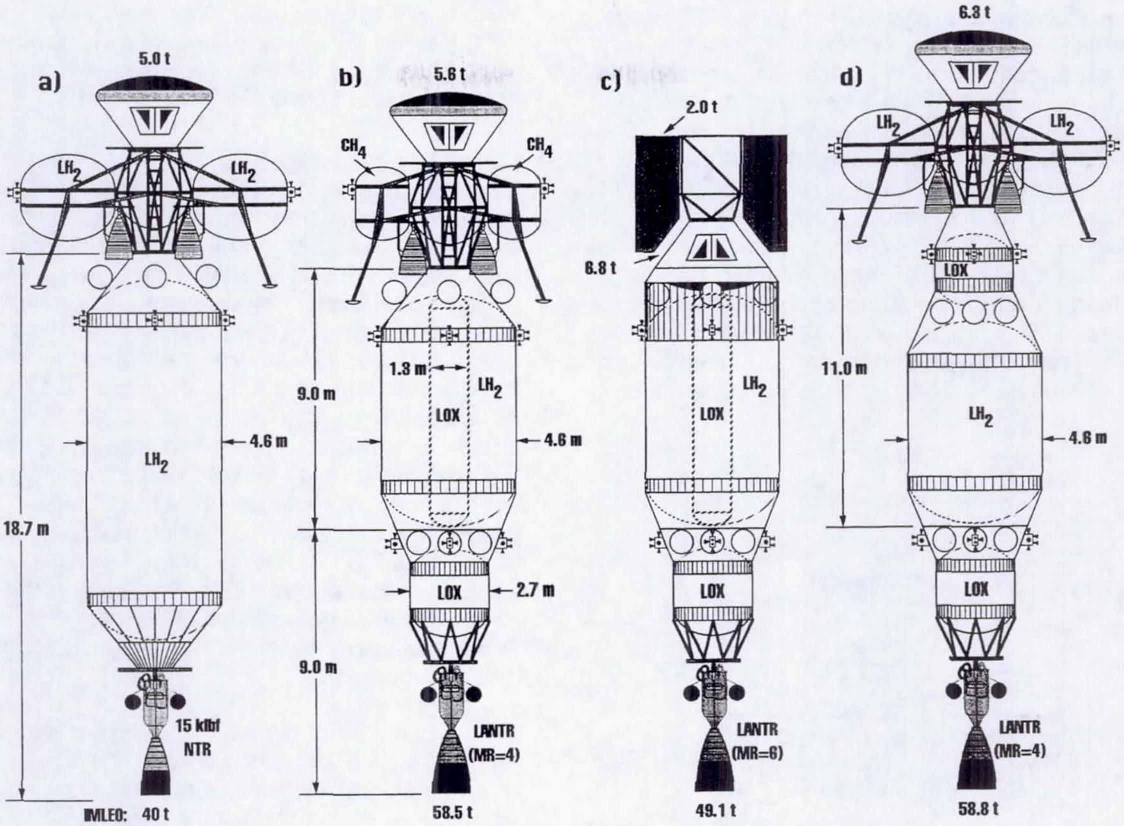


Fig. 5 Relative Size/Mass of NTR, LANTR and LERV Vehicles

Table 4. LERV System Assumptions and Characteristics

• Propellant:	LOX/LH_2	LOX/LH_2	LOX/CH_4
• MR / Isp:	6.0 / 465 s	6.0 / 465s	3.5 / 375 s
• IMLLO / IMLS:	16.0 /16.8 t	19.0 t	18.5 t
• Crew (3) & suits:	0.6 t	0.6 t	0.60 t
• $M_{SP/L}$:	0.4 t	1.04 t	0.20 t
• M_{LERC}:	5.0 t	6.29 t	5.60 t
• M_{stage}:	3.0 t (15% IMLEO)	2.85 t (15% IMLS)	1.85 t (10% IMLS)
• M_{LOX}:	5.0 t	5.93 t	6.82 t
• M_{fuel}: - landing - ascent / return	0.84 t 1.16 t	0.99 t 1.31 t	1.14 t 2.30 t
• M_{LUNOX}:	6.95 t	7.85 t	8.05 t
• $M_{RP/L}$:	0.10 t	0.10 t	0.10 t

used to accommodate the 18.7 m long NTR stage. Total vehicle length after EOR&D is ~25 meters (see Figure 6). In contrast to the reference scenario, the NTR LTV performs a single 28 minute TLI burn only, leaving the LERV to accomplish the LOI burn. The added LOX/LH_2 propellant consumption results in a lower initial mass in low lunar orbit (IMLLO) of ~16 t (see Table 4) and a reduced capability crew cab weighing ~5.0 t. The LERV lander stage mass is set at 15% of the "wet" LERV mass in LEO. The same mass fraction and mission approach was proposed by General Dynamics[14] in 1993 except that their scenario used a "Centaur-derived" TLI stage with a new, single 35 klbf LOX/LH_2 chemical engine. It also

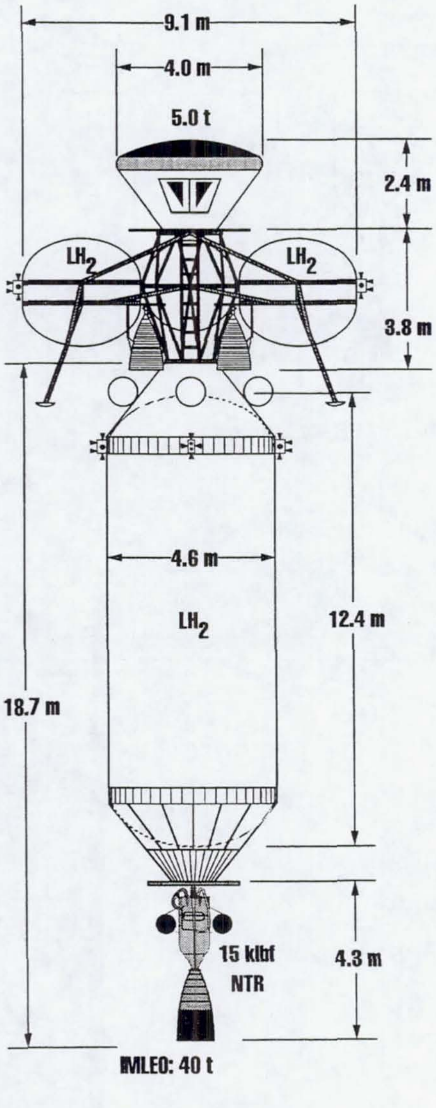


Fig. 6 NTR LTV and LERV Dimensions Using Shuttle and Titan IV Launch Vehicles

assumed a lighter weight "2 person" crew capsule (at ~3.3 t) and had a total IMLEO in excess of the "40 t limit" because of the use of a chemical TLI stage and the absence of LUNOX utilization.

The "all LH_2" NTR 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 system, avionics and auxiliary power, and docking system; (4) forward and aft cylindrical band skirts; and (5) a conical thrust structure. The TLI stage "dry" mass is ~7.0 t which includes ~3.64 t for the 15 klbf NTR and shield. The RCS and LH_2 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.

Because of the high launch cost estimates for the Titan IV (~190-375 M$) and the Space Shuttle (~450-550 M$) systems, future lunar transportation costs could be substantially reduced if LTS elements can be efficiently packaged within the SSTO cargo bay. The most restrictive configuration is the 30 ft cargo bay. Figure 5b shows a "3 element" vehicle configuration. The first SSTO flight delivers the "*propulsion module*" consisting of a small LANTR engine (producing 15 klbf at MR = 0) and a LOX tank which is 2.7 m in diameter and 3.0 m long and has a maximum capacity of ~15 t. The propulsion module also contains: (1) a forward conical adaptor section (housing half of the total RCS propellant and hardware required for the lunar mission, modest avionics and auxiliary power, and docking system); (2) two cylindrical band skirts; and (3) aft thrust structure. The propulsion module "dry" mass is ~5.0 t and consists primarily of the LANTR engine at ~2.7 t and its external radiation shield at ~1.1 t. The propulsion module total mass and length are ~20 t and 9.0 m, respectively. By contrast, a propulsion module with a LH_2 tank the same size as the LOX tank would contain only ~1 t of LH_2 and thus be far less mass-efficient than the present design.

The second SSTO launch one week later, delivers a 20 t "*propellant module*" to LEO containing the LH_2 tank, its forward and aft adaptors and docking systems, and the remainder of the RCS, avionics and auxiliary power. To stay within the "9 m length limit " of the SSTO, the remaining oxygen required for the mission is contained within a "double-walled" and insulated internal LOX tank the same length as that of the LH_2 tank at ~8.0 m. Its diameter is only 1.3 m, however, compared to 4.6 m for that of the LH_2 tank. The LH_2 and internal LOX tanks contain ~6.5 t and 10.0 t of fuel and oxidizer, respectively, but can accommodate up to ~7.3 t of LH_2 and ~11.1 t of LOX depending on mission requirements. The 9 m long "propellant module" has a dry mass of ~3.3 t and RCS, LH_2 and LOX propellant loads of 0.3, 6.5, and 9.9 t, respectively.

After successful rendezvous and docking between the propulsion and propellant modules, the third and final SSTO launch delivers the LERV and its crew. Because of volume constraints, a LOX/CH_4 LERV is utilized and launched with the crew capsule positioned sideways next to the lander. Its maximum mass is limited to ~18.5 t to stay within the payload delivery capability of the LANTR-powered LTV and the total "mission-mass-limit" of 60 t. The LERV's LOX/CH_4 engines operate at a MR = 3.5 and Isp = 375 s (see Table 4), and although their performance is less than the LOX/LH_2 system, methane is more easily stored on the Moon implying less boiloff and tank insulation mass. The LERV transports ~2.3 t of "return methane" to the lunar surface and refills its LOX tank with just over 8 t of LUNOX to return the LERV with its 5.6 t crew capsule and ~0.7 t of crew and lunar samples back to Earth. The same LANTR LTV and LERV landing stage can deliver ~8.7 t of lunar surface payload on "1-way" cargo missions.

When the crew capsule is mounted to the landing stage and the LERV mated to the LANTR LTV, the total spacecraft length and mass is ~24.2 m and 58.5 t, respectively (see Figure 7). The LANTR engine operates at a MR = 4 (Isp ~607 s) which increases the thrust output by a factor of ~3.2--from 15klbf (at MR = 0) to ~48.4 klbf. With this "enhanced" engine thrust-to-weight capability, g-losses drop to less than 50 m/s and the TLI burn duration is ~11.2 minutes compared to ~28 minutes for the "all LH_2" NTR system (Figure 5a). In fact, the total burn duration for the TLI, LOI and LLO disposal manuevers is just over 14 minutes --half that of the "all LH_2" NTR TLI stage.

Because the reactor fuel lifetime in the LANTR engine is ~5 hours at a hydrogen exhaust temperature of 2900 K, the LANTR LTV is capable of performing many lunar missions in its lifetime, thereby reducing LTS recurring costs. Once LUNOX becomes available in LLO to "reoxidize" the expendable LANTR LTV (Figure 5b), the mission architecture can transition to a "reusable mode" with the same LANTR-powered LTV transporting a 6.8 t

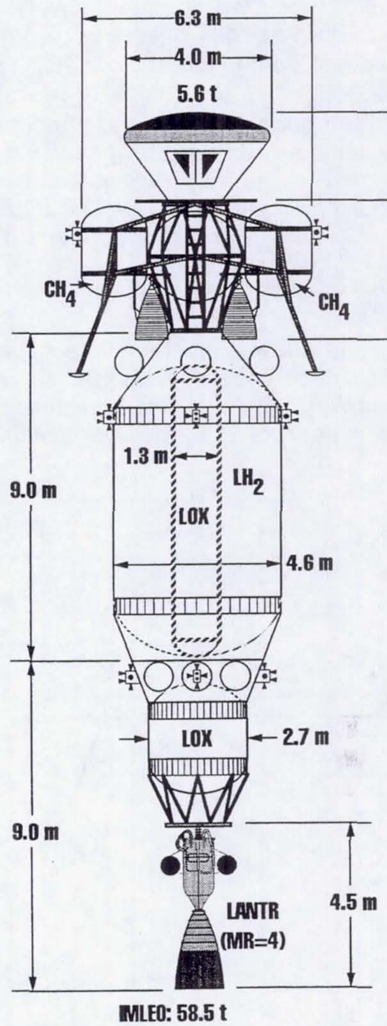


Fig. 7 LANTR LTV and LERV Dimensions Using "9 m Cargo Bay" SSTO

crew module plus 2 t of surface payload to LLO (see Figure 5c). Crew and cargo would then be ferried to the lunar surface by reusable LLVs that are now maintained and refueled at an established lunar outpost. In the "cargo-delivery mode," the crew capsule would be removed allowing the LANTR LTV to deliver ~12 t of cargo and "Earth-supplied LH_2" to LLO on each round trip mission. The required IMLEO for the reusable cargo mission is ~52.4 t.

In the "reuse mode," the LANTR engine operates with a MR=6 (Isp~545 s and thrust~61 klbf) both outbound and back to stay within the LOX and LH_2 propellant limits of the LTV again demonstrating the versatility of the LANTR concept. The piloted and cargo vehicles would require refilling in LLO with

~17.1 and 9.7 t of LUNOX, respectively, before returning to Earth. Also with total mission burn times for the piloted and cargo missions of ~15.2 and 12.9 minutes, respectively, the LANTR-powered LTV would be able to perform ~20 round trip piloted and or cargo missions over its reactor operational lifetime thereby improving lunar transportation costs. Refueling and reoxidizing of the LANTR LTV in LEO would be accomplished at a propellant depot resupplied by a "tanker version" of the SSTO.

Figure 5d shows an alternative expendable piloted configuration possible using the "45 ft cargo bay" SSTO option. With ~13.5 m of available length to work with instead of 9 m, the supplemental LOX

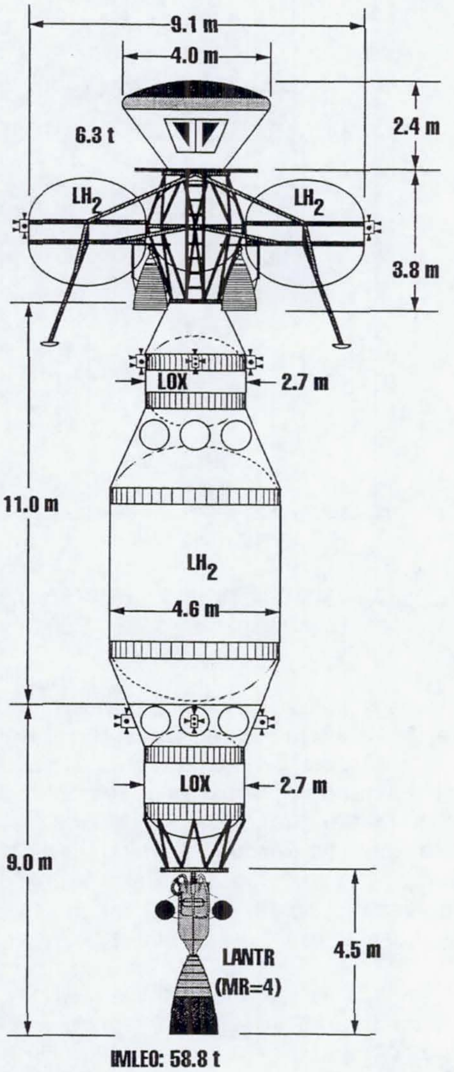


Fig. 8 LANTR LTV and LERV Dimensions Using "13.5 m Cargo Bay" SSTO

tank in the propellant module can be removed from inside the LH_2 tank improving safety and simplifying the design, construction and cost of the propellant module. The propellant module length is ~11 m and includes a 7 m long LH_2 tank and an ~2.5 m long LOX tank at the same diameter as the propulsion module LOX tank. The LANTR LTV has an overall length ~2m longer than the configuration shown in Figure 5b but it is slightly lighter since the "double-walled" internal LOX tank is replaced by a single-walled version. The larger payload bay also makes it possible to deploy a larger, more capable LOX/LH_2 LERV carrying a 6.3 t crew capsule (see Figure 8) while staying within the 60 t IMLEO limit. On "1-way" cargo missions, the LOX/LH_2 lander stage can deliver ~9.2 t of surface payload which is sufficient to accommodate all of the envisioned surface elements[8] needed to support the piloted mission.

CONCLUDING REMARKS ON TRANSPORTATION SYSTEM COSTS

While detailed LTS system (LANTR LTV and LERV) and operational costs are not yet available for determining the economics of the transportation system discussed here, some preliminary statements can be made on the basis of launch vehicle options and costs. Because LANTR engine use provides flexibility in packaging the LTV, it appears that viable human lunar missions are possible using SSTO and modest orbital assembly (Earth orbit rendezvous and docking of no more than three SSTO payloads). If SSTO launch costs of ~40M$ can be truly realized, then 3 SSTO launches costing ~120 M$ could support higher performance lunar missions than the 2 launch scenario using the Space Shuttle and Titan IV vehicles costing ~640 M$--a factor of 5 reduction in costs. With past studies[8] showing cost of payload to the lunar surface at ~100 k$/kg (~8 times higher than the cost to LEO), it can be inferred that delivery costs to the lunar surface of ~20 k$/kg may be possible using SSTO, ISRU and LANTR technologies. It can also be easily argued that quoted SSTO costs are only estimates at this time while the the cost for Shuttle and Titan IV reflect actual operational costs. The technology challenges of the SSTO are substantial but so are the economic rewards. Without it, human lunar missons still appear possible using Shuttle,Titan IV, ISRU and NTR / LANTR technologies but at substantially higher costs.

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Stanley K. Borowski

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National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

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13. ABSTRACT *(Maximum 200 words)*

The feasibility of conducting human missions to the Moon is examined assuming the use of three "high leverage" technologies: (1) a single-stage-to-orbit (SSTO) launch vehicle, (2) *"in-situ" resource utilization* (ISRU)--specifically "lunar-derived" liquid oxygen (LUNOX), and (3) LOX-augmented nuclear thermal rocket (LANTR) propulsion. Lunar transportation system elements consisting of a LANTR-powered lunar transfer vehicle (LTV) and a chemical propulsion lunar landing/Earth return vehicle (LERV) are configured to fit within the "compact" dimensions of the SSTO cargo bay (diameter: 4.6 m/length: 9.0 m) while satisfying an initial mass in low Earth orbit (IMLEO) limit of ~60 t (3 SSTO launches). Using ~8 t of LUNOX to "reoxidize" the LERV for a "direct return" flight to Earth reduces its size and mass allowing delivery to LEO on a single 20 t SSTO launch. Similarly, the LANTR engine's ability to operate at any oxygen/hydrogen mixture ratio from 0 to 7 with high specific impulse (~940 to 515 s) is exploited to reduce hydrogen tank volume, thereby improving packaging of the LANTR LTV's "propulsion" and "propellant modules". Expendable and reusable, piloted and cargo missions and vehicle designs are presented along with estimates of LUNOX production required to support the different mission modes. Concluding remarks address the issue of lunar transportation system costs from the launch vehicle perspective.

14. SUBJECT TERMS

LOX-augmented NTR; LANTR; LUNOX; Single-stage-to-orbit; SSTO; ISRU; Lunar transportation system; Lunar landing/Earth return vehicle; LERV; LTV

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