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The Use of Nuclear Propulsion, Power and "In-Situ" Resources for Routine Lunar Space Transportation and Commercial Base Development

by

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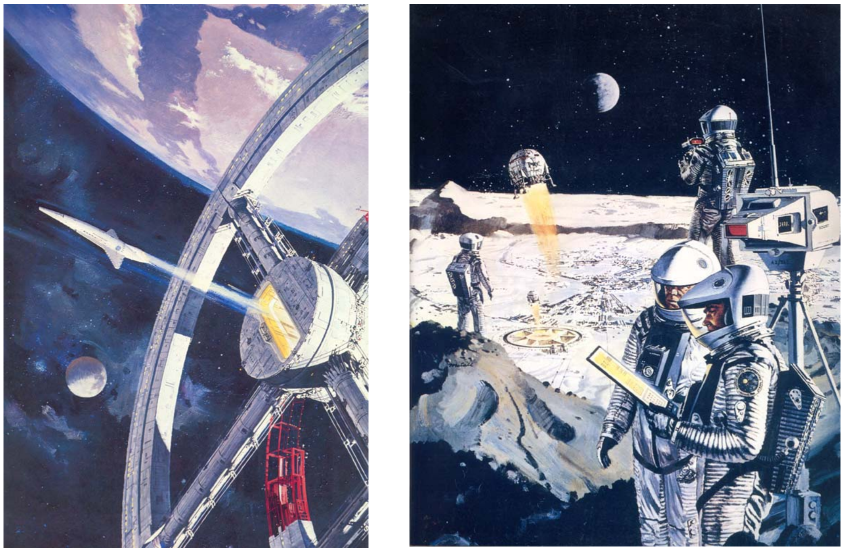
A Vision of the Future on the Moon "2100: A Space Odyssey?"



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Index Map Showing the Apollo 17 Landing Site and Major Geographic Features of Taurus-Littrow Region

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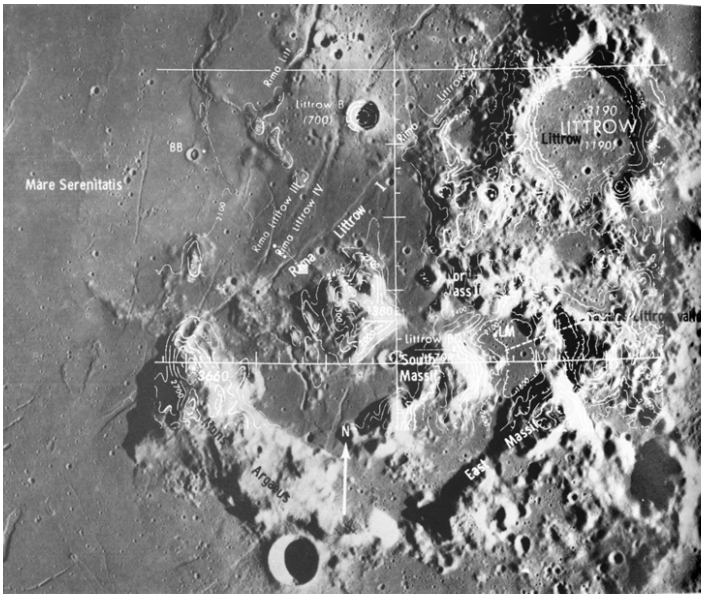

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Volcanic Glass from the Apollo 17 Mission to Taurus-Littrow is Attractive for LUNOX Production

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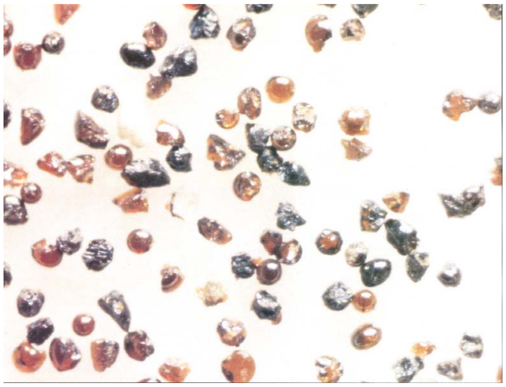
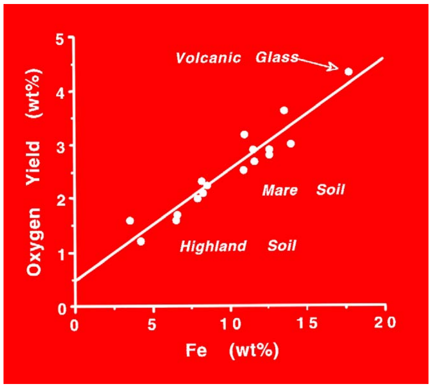


The best lunar oxygen ore found during the Apollo Program is the volcanic glass, ("orange soil") found at Taurus-Littrow. The glass beads are ~40 μm in diameter. The orange beads are clear glass, while the black beads cooled at bit more slowly and had a chance to crystallize.



Oxygen yield is directly related to iron abundance for the full range of soil compositions. Highest yields are from " FeO-rich" volcanic glass.

- **Oxygen production from "FeO-rich" volcanic glass is a 2 step process:**

$FeO + H_2$ -------> $Fe + H_2O$
(Hydrogen Reduction & Water Formation)

$2\ H_2O$ -------> $2H_2 + O_2$ (*LUNOX*)
(Water Electrolysis & Hydrogen Recycling)

Ref: Carlton Allen, "Prospecting for Oxygen on the Moon", Ad Astra, Nov. / Dec. 1996, pg. 34

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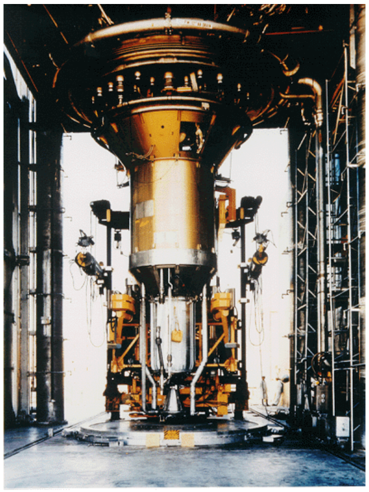
Rover / NERVA* Program Summary (1959-1972)

- **20 Rocket/reactors designed, built and tested at cost of ~$1.4 billion**
- **Engine sizes tested**
  - 50-250 klb_f
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (Graphite fuel)
- **I_{sp} capability**
  - 825-850 sec (hot bleed cycle)
- **Burn duration**
  - 62 min (NRX-A6 - single burn)
  - > 4 hrs (NRX-XE - 28 burns / accumulated burn time)
- **Engine thrust-to-weight**
  - ~3 for 75 klb_f NERVA
- **"Open Air" testing at Nevada Test Site**

** NERVA: Nuclear Engine for Rocket Vehicle Applications*



NERVA program experimental engine (XE) demonstrated 28 startup / shutdown cycles during tests in 1969.

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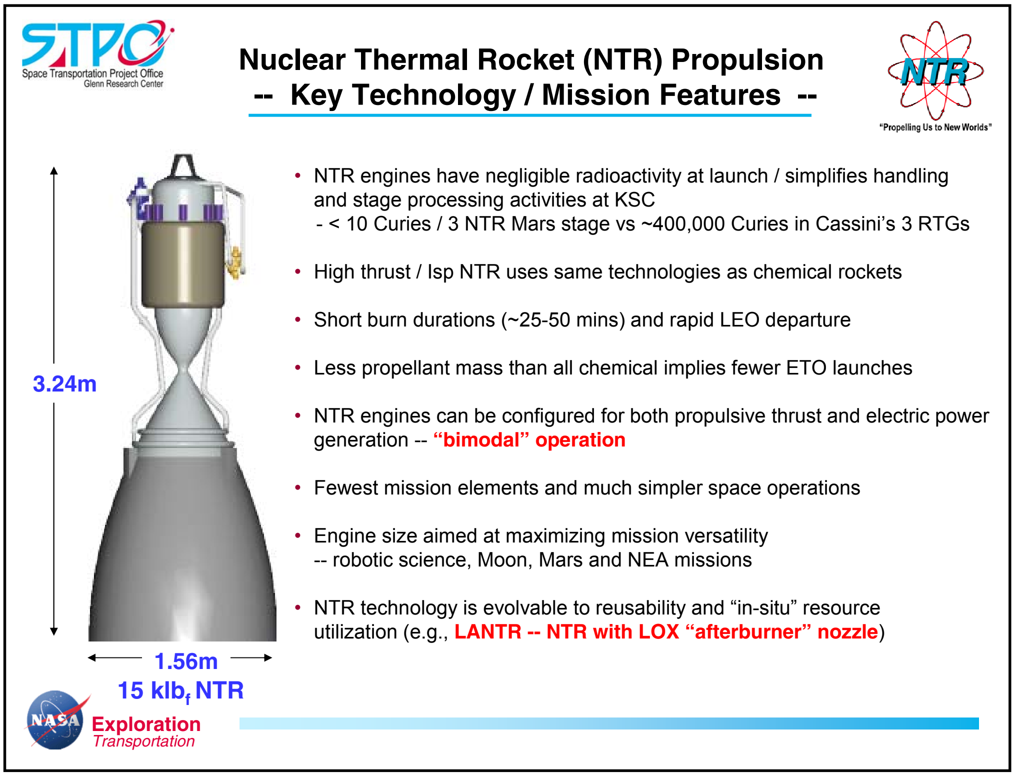
Nuclear Thermal Rocket (NTR) Propulsion

What's New?

Then (Rover/NERVA:1959–72)		**Now**
• **Engine sizes tested** – 50–250 klbf	**Smaller, Higher Performance**	• **"Current" focus is on smaller NTR sizes** – 5–15 klbf (Code S science–humans)
• **H_2 exit temps achieved** – 2,350–2,550K (Graphite)		• **Higher temp. fuels being developed** – 2,700K (Composite), 2,900K (Cermet) and ~3,100K (Ternary Carbides)
• **Isp capability** – 825–850 sec (hot bleed)	**Easier to test**	• **Isp capability** – 915–1005 sec (expander cycle)
• **Engine thrust-to-weight** – ~3 for 75 klbf NERVA		• **Advances in chemical rockets/materials** – ~3–6 for small NTR designs
• **Testing (Rover/NERVA)** – "Open Air" exhaust at Nevada test site	**Environmentally "Green"** **For Public Acceptance**	• **Small NTR allows full power testing in** – "Contained Test Facility" at INEL with "scrubbed" H_2 exhaust



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Nuclear Thermal Rocket (NTR) Propulsion
-- Key Technology / Mission Features --

15 klb$_f$ NTR

- NTR engines have negligible radioactivity at launch / simplifies handling and stage processing activities at KSC
  - < 10 Curies / 3 NTR Mars stage vs ~400,000 Curies in Cassini's 3 RTGs
- High thrust / Isp NTR uses same technologies as chemical rockets
- Short burn durations (~25-50 mins) and rapid LEO departure
- Less propellant mass than all chemical implies fewer ETO launches
- NTR engines can be configured for both propulsive thrust and electric power generation -- **"bimodal" operation**
- Fewest mission elements and much simpler space operations
- Engine size aimed at maximizing mission versatility
  -- robotic science, Moon, Mars and NEA missions
- NTR technology is evolvable to reusability and "in-situ" resource utilization (e.g., **LANTR -- NTR with LOX "afterburner" nozzle**)

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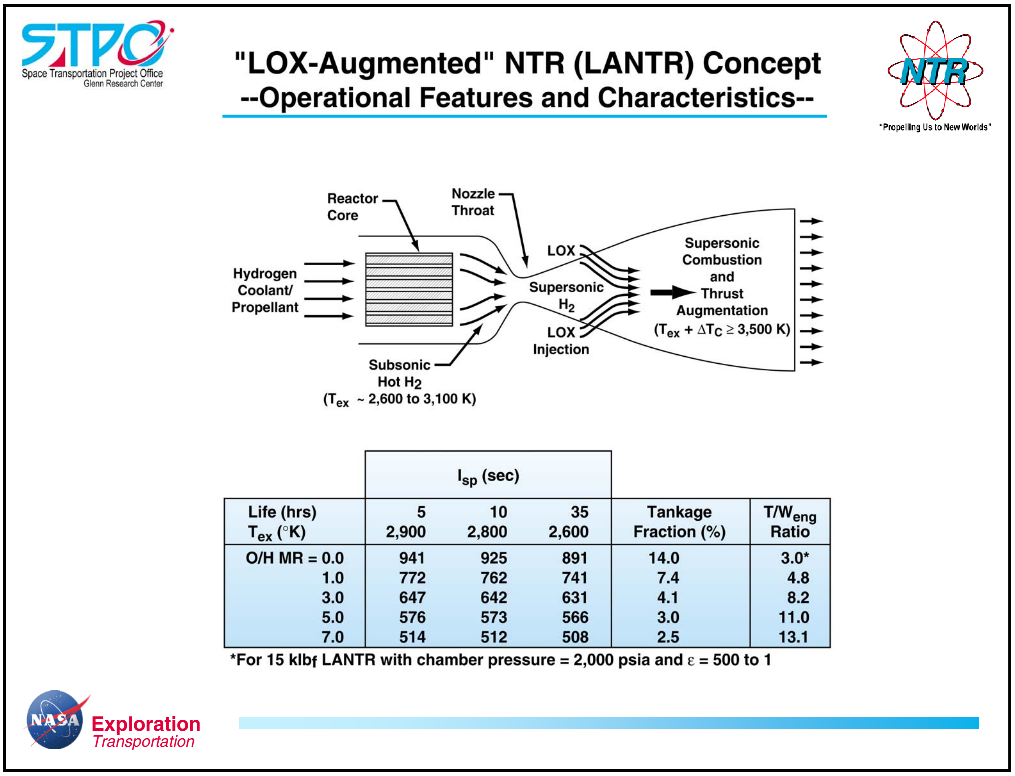

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"LOX-Augmented" NTR (LANTR) Concept
--Operational Features and Characteristics--

	I_{sp} (sec)				
Life (hrs) T_{ex} (°K)	5 2,900	10 2,800	35 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 15 klb$_f$ LANTR with chamber pressure = 2,000 psia and ε = 500 to 1

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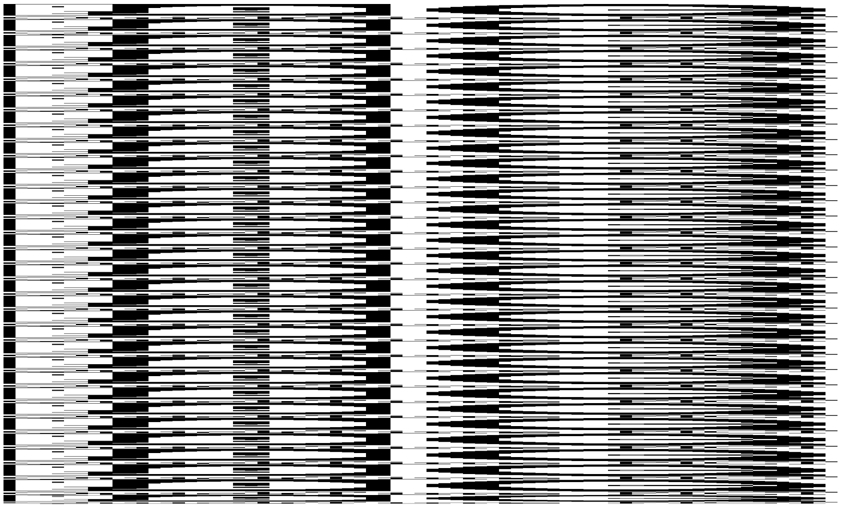
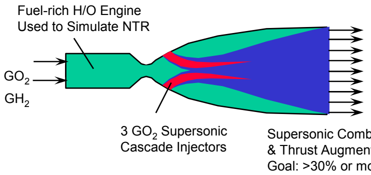
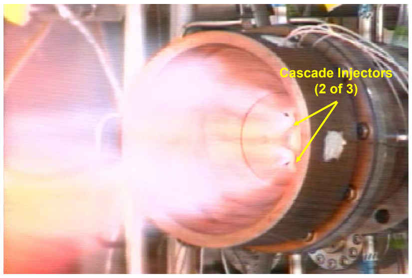
"LOX-Augmented" NTR (LANTR) Concept
--Engine, Vehicle and Mission Benefits--



"LOX-Augmented" Nuclear Thermal Rocket (LANTR)
"Afterburner" Nozzle Concept Demonstration





Baseline H/O Thrust: 2100 lbf at 1000 psia and MR = 1.5. With GO$_2$ injection into nozzle, measured thrust due to supersonic combustion is 3200 lbf (~52% thrust augmentation achieved at 50:1 and MR_L~3.0)

- **LANTR Concept and Benefits:**
  - "Afterburner" nozzle increases thrust by injecting & combusting GO$_2$ downstream of the NTR throat
  - Enables NTR with variable thrust and Isp capability by varying the nozzle O/H mixture ratio (MR)
  - Operation at modest MRs (<1.0) helps increase bulk propellant density for packaging in smaller volume launch vehicles
  - LANTR's bipropellant operation enables smaller, faster Moon / Mars vehicles when using extraterrestrial sources of H_2 and O_2

- **LANTR Test Program Objectives:** (Aerojet & GRC)
  - Measure thrust augmentation from oxygen injection and supersonic combustion using small, fuel-rich H/O engine with two different area ratio nozzles (@ 25:1 and 50:1) as "non-nuclear" NTR simulator.
  - Use results to calibrate reactive CFD assessment of bimodal LANTR engine

- **Status:** LANTR afterburner nozzle demonstrated
  - Oxygen injection into hot supersonic flow
  - Supersonic combustion in the nozzle
  - Elevated nozzle pressures measured
  - Benign nozzle wall environment observed
  - Increase O2 consumption rate with nozzle length
  - Thrust augmentation >50% measured

Implementation Approach for “LANTR-Based” Lunar Space Transportation System Architecture

- ***Objectives:***
  - Reduce “up-front” investment costs for “in-space” assembly infrastructure
  - Eliminate need for developing new ~130 t “Saturn V”-class HLLV -- major cost element of a lunar transportation system (LTS)
  - Maximize delivered payload to the surface on each lunar landing mission
  - Minimize LTS “recurring costs” so that commercialization and human settlement of the Moon can become practical

- ***Strategy:***
  - Utilize “all LH_2” NTR-powered LTV operating initially in an “expendable mode”
  - Expendable approach reduces support infrastructure, IMLEO / allows use of Shuttle-C or “Shuttle-derived” heavy lift vehicle (SDHLV) for Earth-to-orbit launch
  - Cargo missions precede piloted with surface payloads “dedicated” primarily to LUNOX production and habitation requirements
  - LUNOX used for refueling LLVs initially, then LANTR-powered LTVs
    - Transitioning to “reusable” LTS architecture at the earliest possible date improves life cycle costs
    - Accumulated cost savings reinvested “gradually” in support infrastructure

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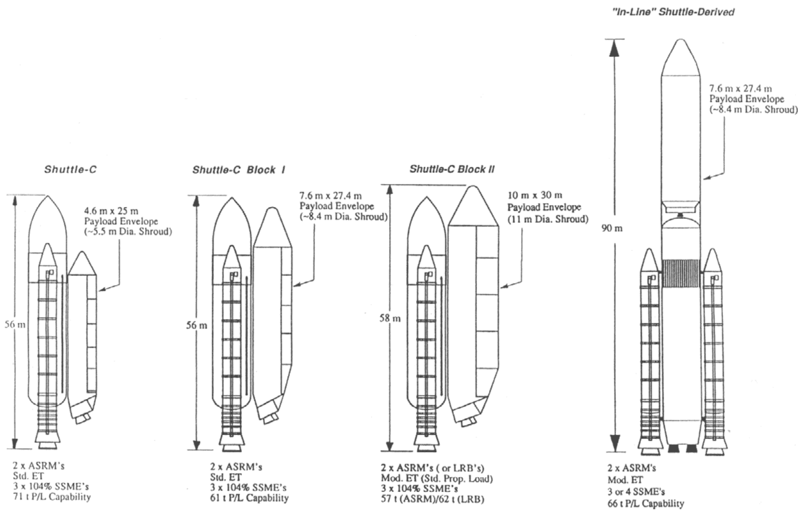
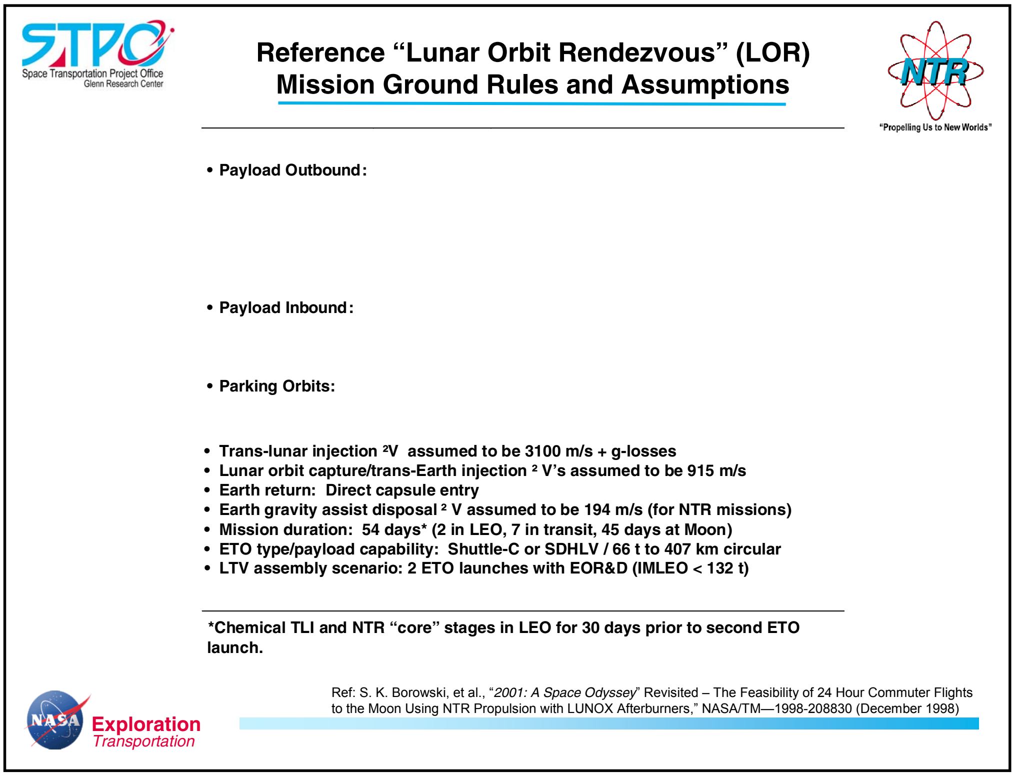
“Shuttle-Derived” Heavy Lift Vehicle (SDHLV) Options for Future Human Lunar Mission



Ref: S. K. Borowski, et al., “*2001: A Space Odyssey*” Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners,” NASA/TM—1998-208830 (December 1998)



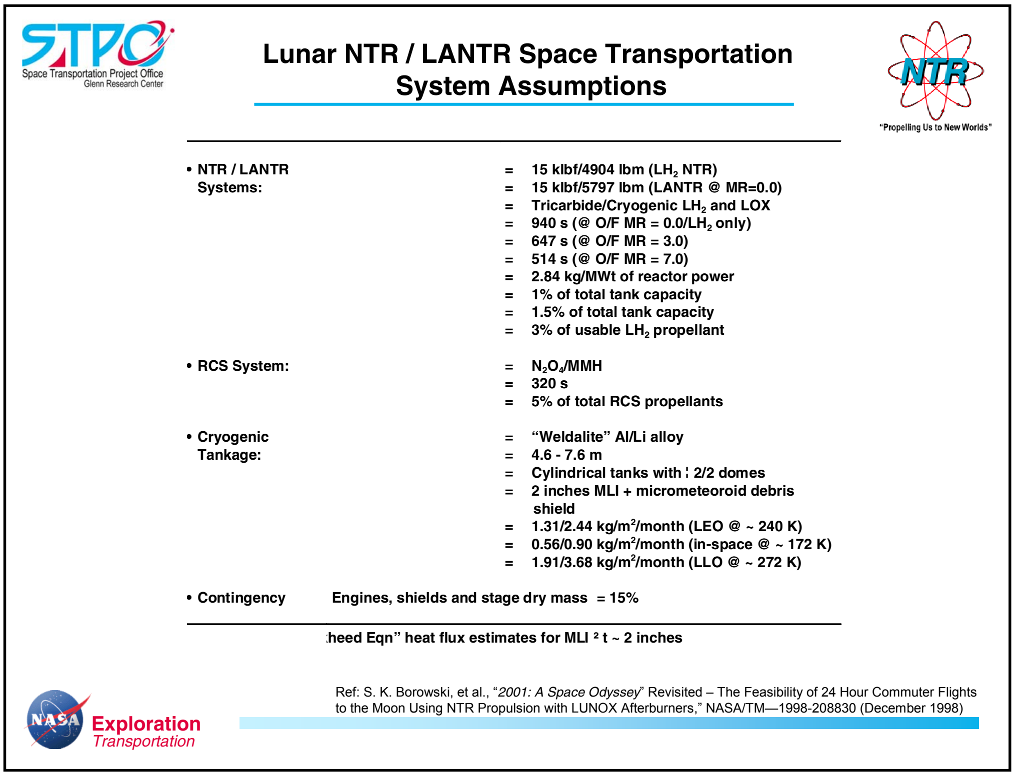
Reference "Lunar Orbit Rendezvous" (LOR) Mission Ground Rules and Assumptions

- **Payload Outbound:**
- **Payload Inbound:**
- **Parking Orbits:**

- **Trans-lunar injection ²V assumed to be 3100 m/s + g-losses**
- **Lunar orbit capture/trans-Earth injection ² V's assumed to be 915 m/s**
- **Earth return: Direct capsule entry**
- **Earth gravity assist disposal ² V assumed to be 194 m/s (for NTR missions)**
- **Mission duration: 54 days* (2 in LEO, 7 in transit, 45 days at Moon)**
- **ETO type/payload capability: Shuttle-C or SDHLV / 66 t to 407 km circular**
- **LTV assembly scenario: 2 ETO launches with EOR&D (IMLEO < 132 t)**

***Chemical TLI and NTR "core" stages in LEO for 30 days prior to second ETO launch.**

Ref: S. K. Borowski, et al., "*2001: A Space Odyssey*" Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners," NASA/TM—1998-208830 (December 1998)



Lunar NTR / LANTR Space Transportation System Assumptions

- **NTR / LANTR Systems:**
  = 15 klbf/4904 lbm (LH_2 NTR)
  = 15 klbf/5797 lbm (LANTR @ MR=0.0)
  = Tricarbide/Cryogenic LH_2 and LOX
  = 940 s (@ O/F MR = 0.0/LH_2 only)
  = 647 s (@ O/F MR = 3.0)
  = 514 s (@ O/F MR = 7.0)
  = 2.84 kg/MWt of reactor power
  = 1% of total tank capacity
  = 1.5% of total tank capacity
  = 3% of usable LH_2 propellant

- **RCS System:**
  = N_2O_4/MMH
  = 320 s
  = 5% of total RCS propellants

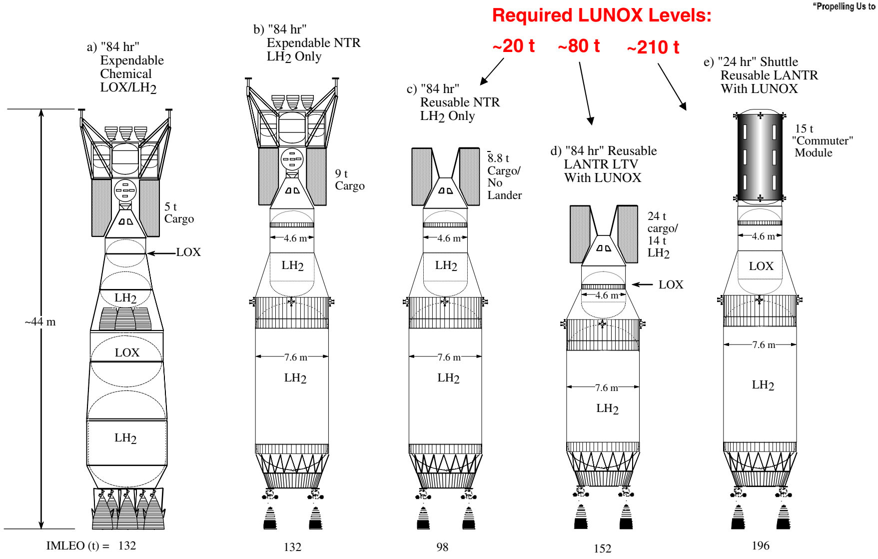
- **Cryogenic Tankage:**
  = "Weldalite" Al/Li alloy
  = 4.6 - 7.6 m
  = Cylindrical tanks with ¦ 2/2 domes
  = 2 inches MLI + micrometeoroid debris shield
  = 1.31/2.44 kg/m^2/month (LEO @ ~ 240 K)
  = 0.56/0.90 kg/m^2/month (in-space @ ~ 172 K)
  = 1.91/3.68 kg/m^2/month (LLO @ ~ 272 K)

- **Contingency** **Engines, shields and stage dry mass = 15%**

:heed Eqn" heat flux estimates for MLI ² t ~ 2 inches

Ref: S. K. Borowski, et al., "*2001: A Space Odyssey*" Revisited – The Feasibility of 24 Hour Commuter Flights to the Moon Using NTR Propulsion with LUNOX Afterburners," NASA/TM—1998-208830 (December 1998)

Evolution of NTR-Based Lunar Transportation System With LUNOX Development & Utilization



Ref: Borowski et al., NASA/TM--1998-208830

ΔV (TLI + LOI) ~ 4.1 km / s **~ 6.9 km / s**

LUNOX Production Requirements

- **24 Hour "1-way" Transits (15 t / 20 Passenger Transport Module):**

- LTV: (94.0 t LUNOX / mission*) x 52 weeks / year = 4888 t / year
- LLV: (28.8 t LUNOX / flight⁺) x (1 flight / LLV / week) x 4 LLVs x 52 weeks / year = 5990 t / year

Annual LUNOX Production Rate =10878 t / year

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*Assumes LUNOX Usage on "Moon-to-Earth" Transit only

⁺Assumes LLV Transports ~25 t of LUNOX to LLO and Returns to Lunar Surface with Empty 5 t "Mobile" LUNOX Tanker Vehicle

Lunar Mining Concept Comparisons

Comparison of Different Lunar Mining Concepts
—Plant Mass, Power and Regolith Throughput—

- **Hydrogen Reduction of "Iron-rich" Volcanic Glass:** (LUNOX Production @ 1000 t/yr)
  - Plant Mass (Mining, "limited" Beneficiation, Processing and Power) = 167 t
  - Power Requirements (Mining, "limited" Beneficiation and Processing) = 2.4 MWe
  - Regolith Throughput ("limited" beneficiation, direct processing of "iron-rich" volcanic glass ("orange soil") with 4% O_2 yield and MMR = 25 to 1) = $2.5x10^4$ t/yr
- **Lunar Helium-3 Extraction***: (5000 kg (5 t) He^3/year)
  - Mobile Miners (150 miners required each weighing 18 t/ each miner produces 33 kg He^3 per year) = 2700 t
  - Power Requirements (200 kW direct solar power/miner) = 30.0 MW
  - Regolith Throughout (processing and capture of Solar Wind Implanted (SWI) volatiles occurs aboard the miner) = $7.1x10^8$ t/yr

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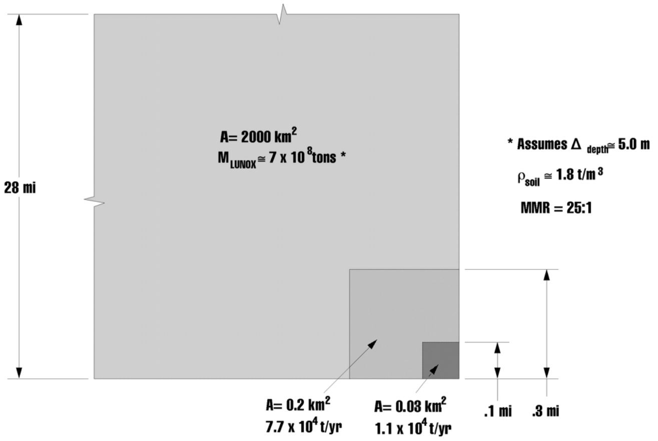
***NOTE:** The processing of lunar regolith for solar wind implanted He^3 for terrestrial fusion power also produces large quantities of volatile by-product. **For each metric ton (1000 kg) of He^3 mined, ~6100 t of H_2 and ~3300 t of H_2O are also produced! This activity would therefore provide very large supplies of LH_2 and LOX for LANTR, NEP/MPD and chemical engines.**

Mining Area & LUNOX Production Rates to Support "24 Hour" Lunar Commuter Flight

At the S.E. edge of the "Sea of Serenity" (Latitude: ~ 21° North / Longitude: ~29° East) lies a vast deposit of iron-rich volcanic glass beads tens of meters thick (one of many sites on Moon)



Could supply enough LUNOX for daily 24 hour commuter flights to Moon for next 9000 yrs.!

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Future Artificial Gravity Station (AGS) Using 500 kW_e Fission Power System

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Passenger Transport Module (PTM) Departing LEO Station for Docking with LANTR-powered Lunar Transfer Vehicle (LTV)

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“24 Hours” to the Moon Using LANTR
-- Leaving Orbit: “Aloha Earth” --

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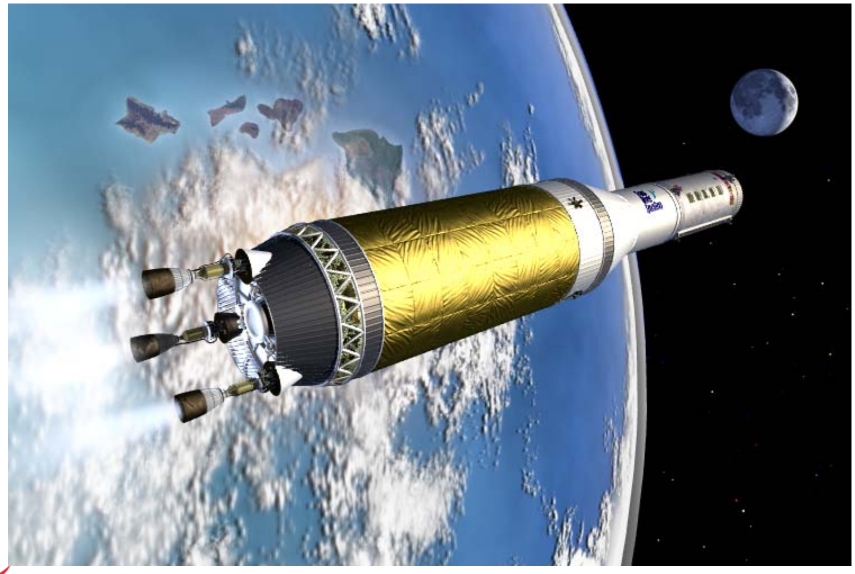

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LANTR “Afterburner” Nozzles in Operation During the LTV Earth Departure Phase

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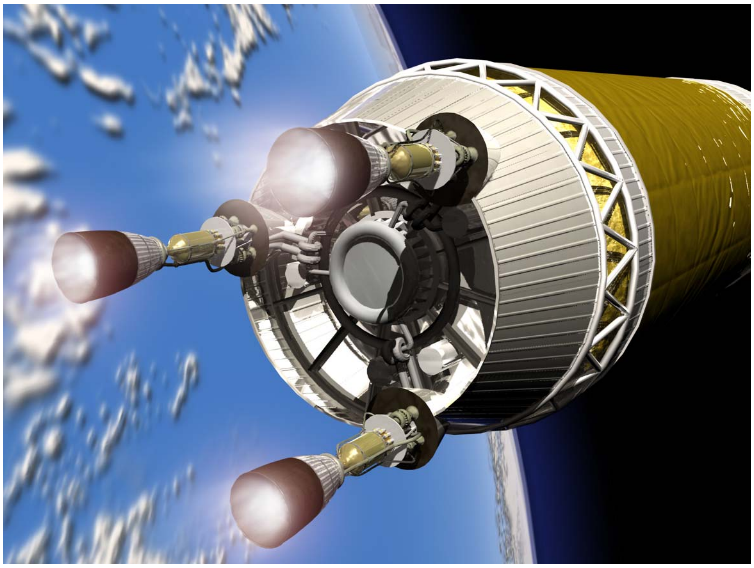

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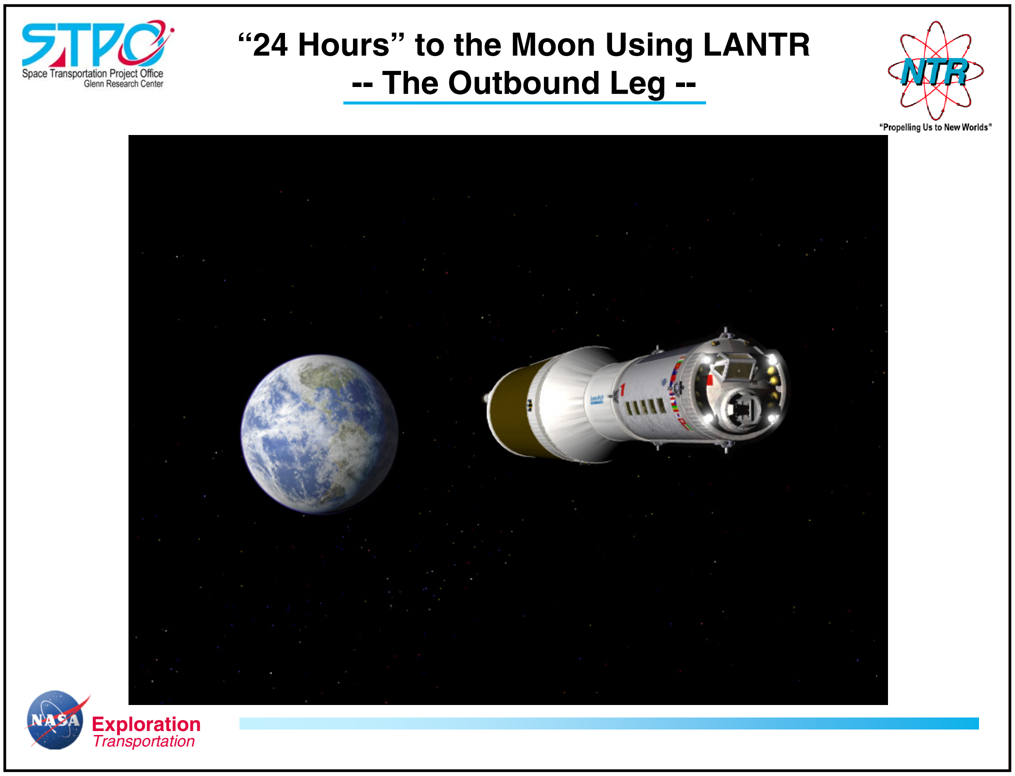

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“24 Hours” to the Moon Using LANTR
-- The Outbound Leg --

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Approaching the Western Rim
Destination: SE Edge of the “Sea of Serenity”
(Latitude: ~ 21° North / Longitude: ~29° East)

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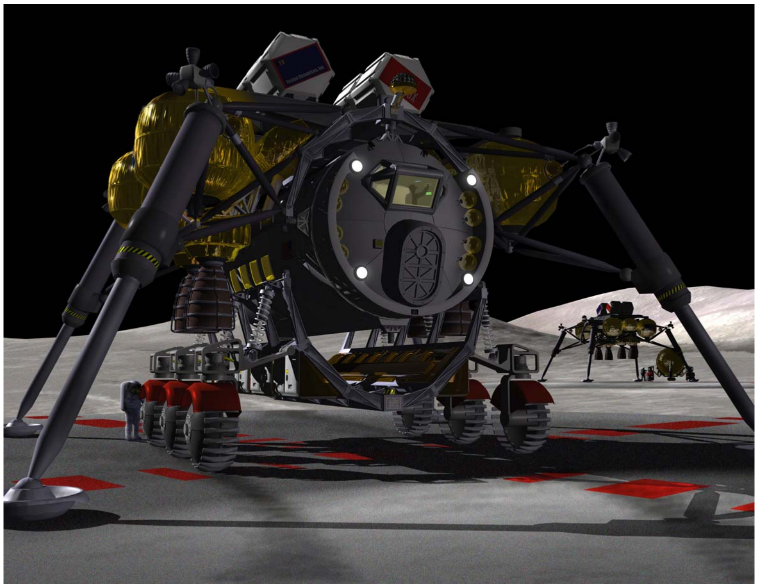
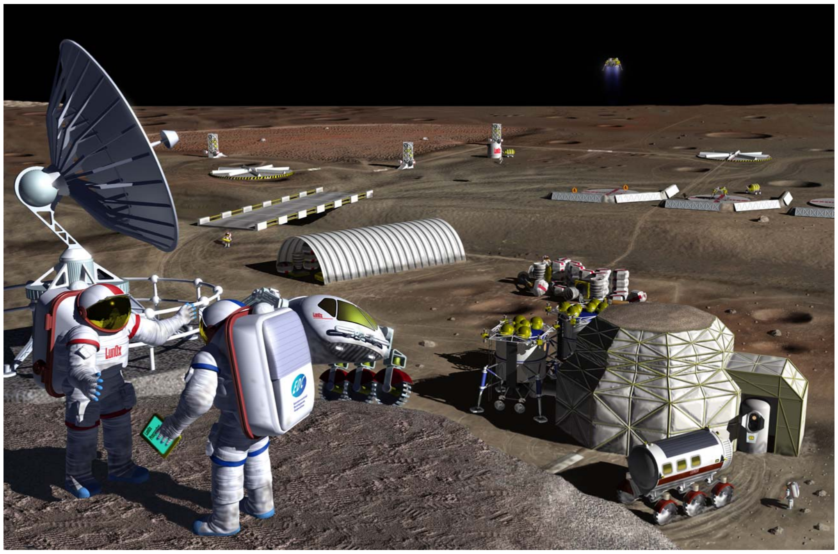
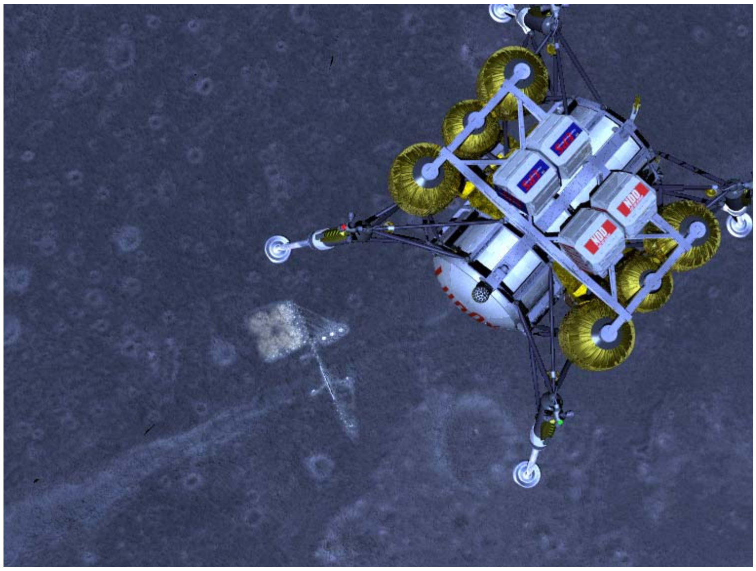
PTM Transfer from "Sikorsky-style" Lunar Landing Vehicle (LLV) to "Flat-bed" Electric Surface Transport



"Commercial" LUNOX Production Facility & Supporting Hardware

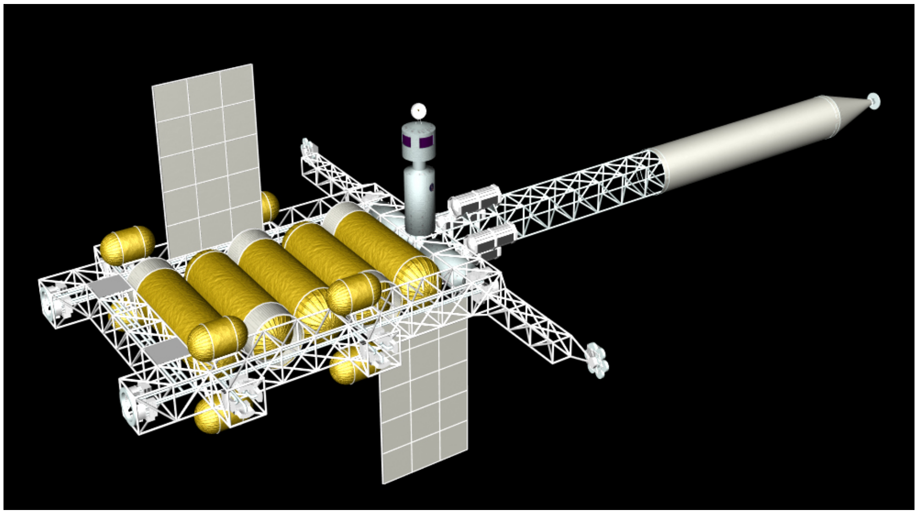


LUNOX Tanker LLV on Route to the Orbiting NEP Propellant Depot

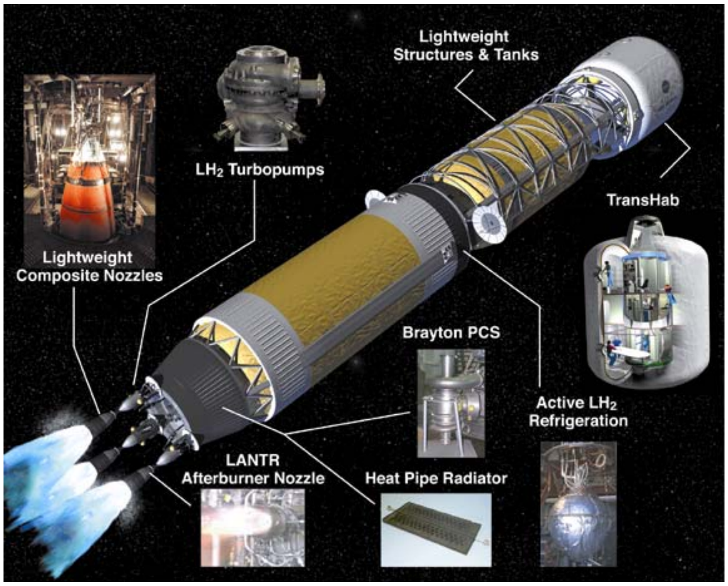


Human-tended NEP "Tanker/Propellant Depot"

Supporting 24 Hour Lunar Commuter Flights

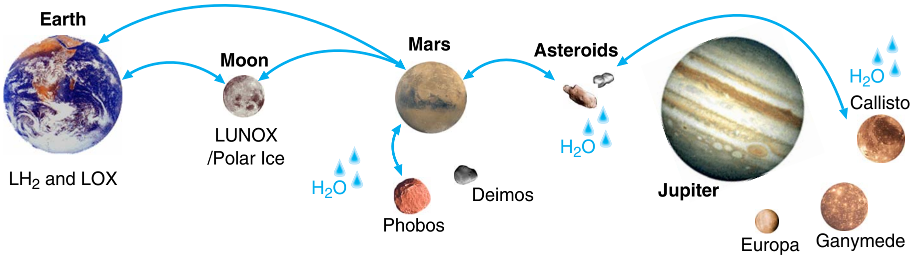


Significant Technology Development is Underway To Support Design Definition for Future Bimodal NTR Robotic and Human Missions



Human Exploration Possibilities Using NTR

High thrust and Isp, power generation and ISRU allow significant downstream growth capability--"Revolution through Evolution"



- **Mission possibilities:**
  - Reusable Lunar and Mars Transfer Vehicles
  - "24 Hour" Commuter Flights to the Moon
  - Reusable Mars Ascent/Descent Vehicles