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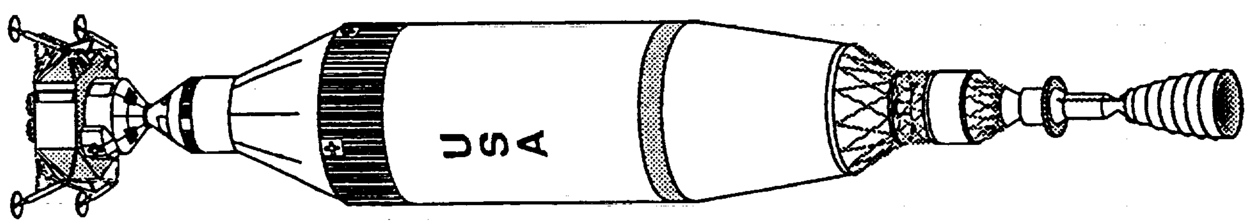

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THE RATIONALE/BENEFITS OF NUCLEAR THERMAL ROCKET PROPULSION

FOR NASA'S LUNAR SPACE TRANSPORTATION SYSTEM

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ABSTRACT

The solid core nuclear thermal rocket (NTR) represents the next major evolutionary step in propulsion technology. With its attractive operating characteristics, which include high specific impulse (~850-1000 s) and engine thrust-to-weight (~4-20), the NTR can form the basis for an efficient lunar space transportation system (LTS) capable of supporting both piloted and cargo missions. Studies conducted at the NASA Lewis Research Center indicate that an NTR-based LTS could transport a fully-fueled, cargo-laden, lunar excursion vehicle to the Moon, and return it to low Earth orbit (LEO) after mission completion, for less initial mass in LEO than an aerobraked chemical system of the type studied by NASA during its "90-Day Study." The all-propulsive NTR-powered LTS would also be "fully reusable" and would have a "return payload" mass fraction of ~23 percent-- twice that of the "partially reusable" aerobraked chemical system. Two NTR technology options are examined-- one derived from the graphite-moderated reactor concept developed by NASA and the AEC under the Rover/NERVA (Nuclear Engine for Rocket Vehicle Application) programs, and a second concept, the Particle Bed Reactor (PBR). The paper also summarizes NASA's lunar outpost scenario, compares relative performance provided by different LTS concepts, and discusses important operational issues (e.g., reusability, engine "end-of-life" disposal, etc.) associated with using this important propulsion technology.

INTRODUCTION

The Space Exploration Initiative (SEI) outlined by President Bush on July 20, 1989, the 20th anniversary of Apollo 11, calls for a return to the Moon "to stay" early in the next century, followed by a journey to Mars using systems "space tested" in the lunar environment. Establishing and sustaining a permanent outpost on the Moon will require the development of an efficient, reusable, lunar space transportation system for moving humans and substantial quantities of cargo in cislunar space.

To date, National Aeronautics and Space Administration (NASA) studies[1,2] have assumed the development and availability of a new, advanced liquid oxygen/liquid hydrogen (LOX/LH_2) fueled chemical space engine for LTS primary propulsion. Returning piloted and cargo lunar transfer vehicles (LTVs) would also carry an aerobrake through the entire lunar mission for use in final capture into LEO. Without aerodynamic braking at Earth return, "all propulsive" chemical LTVs would require initial starting masses in low Earth orbit (IMLEO) on the order of 275 -300 metric tons (t) (1 t=1000 kg). The higher IMLEO range corresponds to a more "Apollo-like" expendable mission mode with significant jettisoning of expended stages and/or propellant tank mass.

The solid core NTR represents the next major evolutionary step in propulsion technology[3] and is ideally suited to performing either piloted, cargo, or combination lunar missions. With its factor of two advantage in Isp over chemical propulsion and its high engine thrust-to-weight capability, a fully reusable, "all propulsive," single stage NTR-powered LTV is possible. Operating in the "combined mode," a piloted LTV can deliver and return significant quantities of payload, while in the "courier mode," without cargo, the NTR LTV could leverage its propellant loading to reduce the "1-way" Earth-Moon transit time to less than

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WHY NTR FOR LUNAR MISSIONS?

- **Potential Performance Benefits**
  - High Isp and T/W_e allows both piloted and cargo missions
  - Enables single stage, fully reusable lunar transfer vehicle
  - Enables more demanding mission profiles (e.g., "courier" and polar orbit missions with significant plane change)
  - Reduces IMLEO/fewer Earth to orbit launches
- **Early Operations Experience**
  - NTR vehicle assembly
  - Refueling, rendezvous, and docking in radiation environment
  - Disposal of "end-of-life" engines
- **Technology Test Bed and "Dress Rehearsal" for Mars**
  - Interplanetary mission "in miniature" requiring major impulsive maneuvers and multiple engine restarts
  - Reduced performance requirements: ΔV, flight time/thrust time
  - Operations in "nearby" space environment
  - "Free Return" trajectory available without penalty

Fig. 1. Rationale for Lunar Missions with NTR

3 days. Functioning in the "cargo-mode," a robotic NTR stage could deliver self-landing lunar habitation modules to equatorial or lunar polar orbit staging nodes from which deployment to locations over the entire lunar surface would be possible.

In addition to these performance benefits, NTR usage for lunar missions will provide valuable operational experience and serve as a technology "proving ground" before undertaking more demanding interplanetary missions to Mars (see Figure 1).

This paper describes results of preliminary studies conducted at the NASA Lewis Research Center on the use of NTR for the "in-space" portion of the LTS. The paper first reviews NASA's current lunar outpost scenario and mission profile, and then discusses NTR technology options and "state-of-the-art" performance projections. Mission ground rules and technology assumptions are then presented and used in comparing transportation system options and alternative mission modes. Finally, a summary of the technical results and the conclusions reached in the study are presented.

SCENARIO OPTIONS FOR LUNAR OUTPOST DEVELOPMENT

NASA has three specific objectives in developing a lunar outpost: (1) to establish a permanent lunar base and manned presence on the Moon, (2) to learn to live and work in a non-terrestrial environment, and (3) to test technologies, systems, and operations required for the subsequent exploration of Mars.

The Lunar/Mars Exploration Project Office (LMEPO) at the Johnson Space Center has baselined a central lunar base concept that evolves in time to support substantial science and exploration objectives, as well as resource production for eventual self-sufficiency. The base is assumed to be located equatorially on the lunar nearside in the Sea of Tranquility.

The lunar space transportation system required to create the base, sustain its operation and growth, and provide for crew rotation consists of two principle vehicles. One is an "in-space" lunar transfer vehicle operating between established Earth and lunar staging nodes, and the second is a lunar excursion vehicle (LEV) for orbit to lunar surface transportation and return. The LTV concept featured in NASA's 90-Day Study[1] is a LOX/LH_2 fueled, partially reusable design with expendable trans-lunar injection (TLI) and lunar orbit capture (LOC) propellant tanks. The reusable core vehicle contains the propellant for trans-Earth injection (TEI) together with propulsion, avionics, crew module and aerobrake for Earth orbit capture (EOC). The LEV is sized to deliver 27 t to the lunar surface and return to lunar orbit when used as a "dedicated" autonomous cargo lander and ~33 t when expended after lunar landing. On piloted flights, the LEV also carriers a crew of 4 and a 30-day mission module so the payload is reduced to ~15 t. Figures 2 and 3 summarize the mission operations, LTV flight profile, and ΔV budget used during the 90-Day Study.

The centralized lunar base concept proposed by the LMEPO[4] has the advantage that resources can be concentrated at a particular site allowing the outpost's five major work areas supporting (1) habitation, (2) science, (3) launch and landing operations, (4) power production and distribution, and (5) in-situ resource utilization to be developed more rapidly. Significant surface activities and support equipment will be required to unload, transport, and assemble large cargo elements (e.g., habitation modules) at the particular work area. This activity can lead to considerable EVA time for the crew and base operational complexity. The outpost's dedicated location may also restrict the range of manned scientific sorties to distances not more than 50 km beyond the lunar base. "Global access" to other interesting sites on the Moon will therefore be limited.

A large number of alternative lunar base concepts were proposed in the 1960's for the post-Apollo program. These ranged in size from small facilities used for short-term occupancy by a few people to larger complexes established at sites of interest and occupied semi-permanently by large numbers of crew. Lunar Exploration Systems for Apollo (LESA)[5] is an example of the latter concept in which functionally different LESA modules, each with their own propulsion for lunar landing, could be used in a "building block" approach to form the nucleus of a permanent lunar base. Such

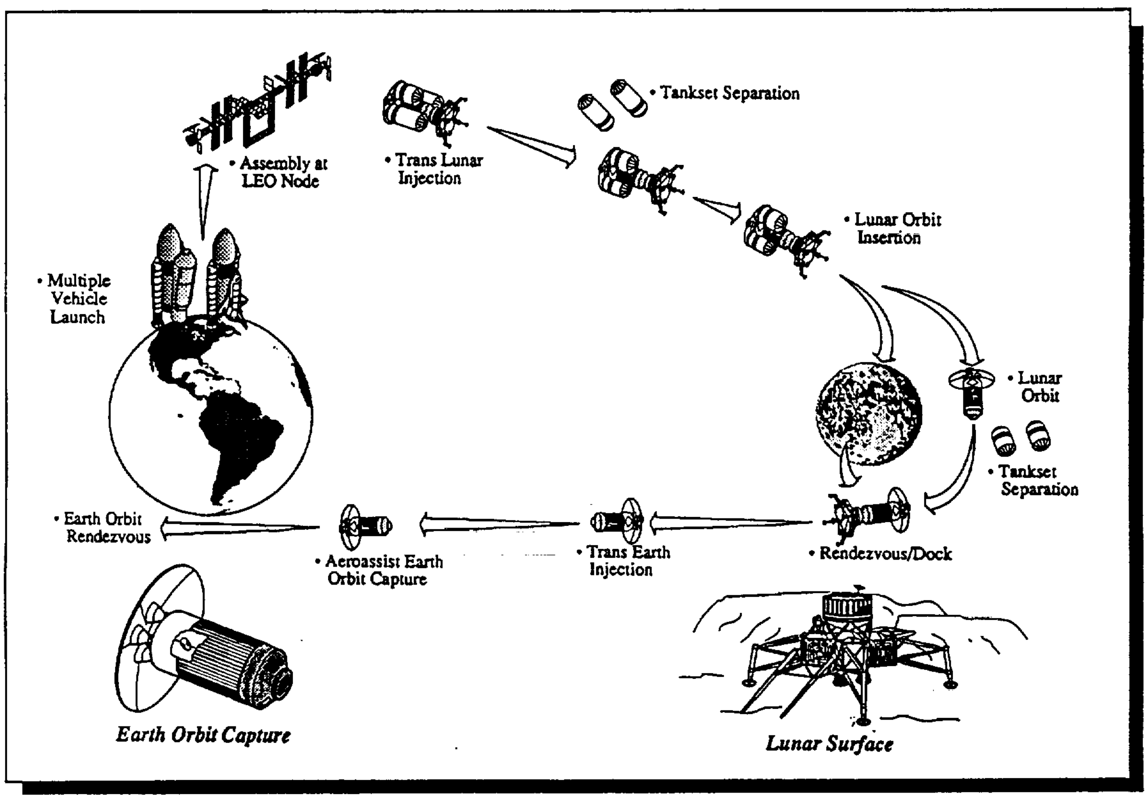


Fig. 2. NASA "90-Day Study" Lunar Outpost Scenario

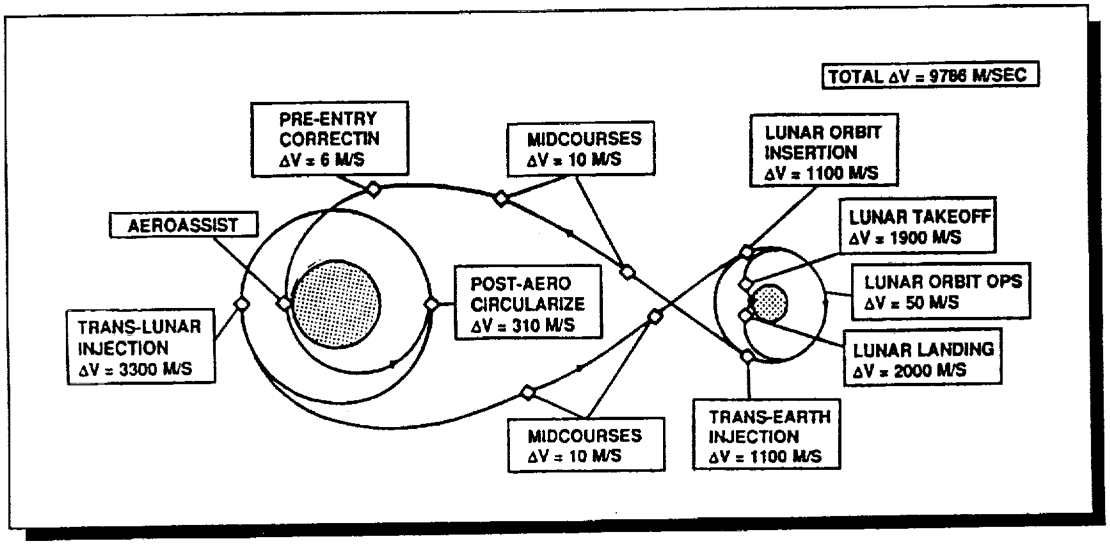


Fig. 3. Lunar Orbit Rendezvous Mission Profile and Aerobrake ΔV Budget

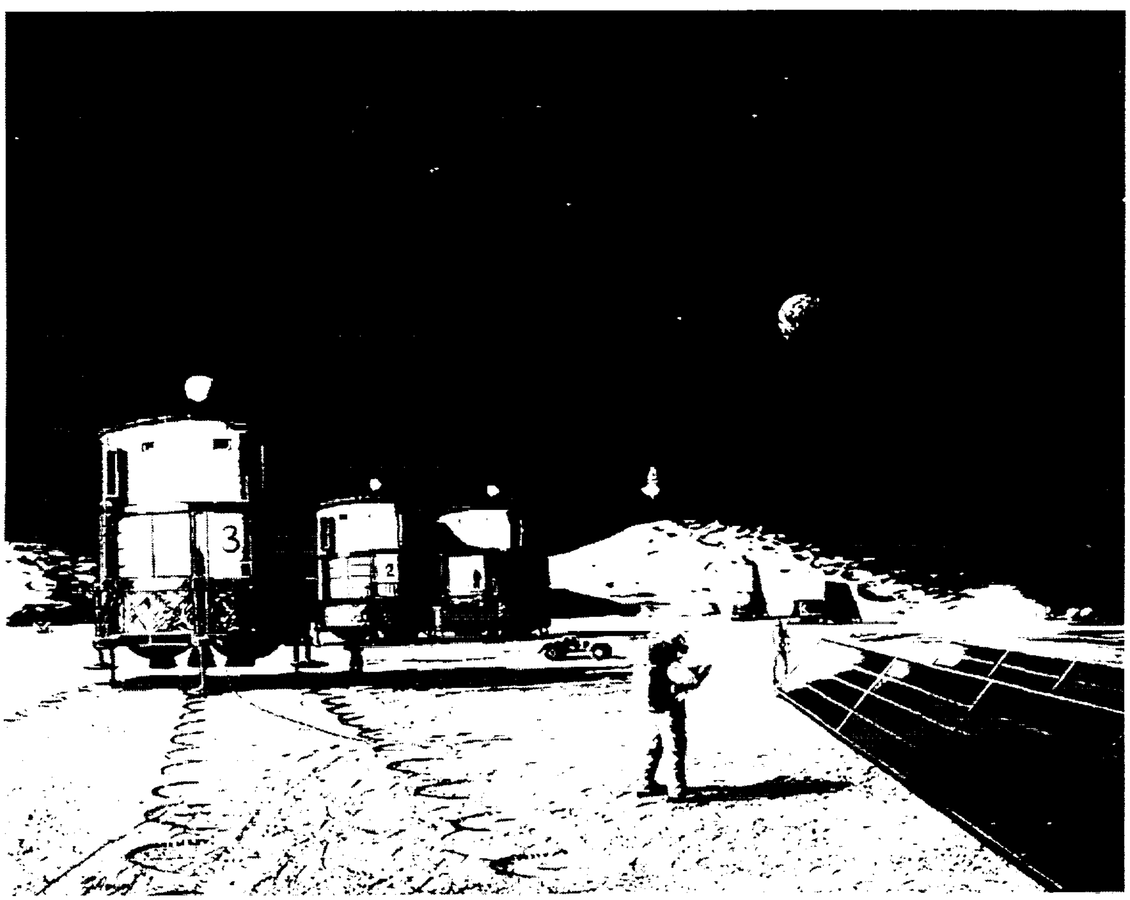


Fig. 4. Modular Approach to Lunar Base Assembly
(Courtesy of Martin Marrietta Astronautics)

modules could be totally constructed, outfitted and checked-out on Earth and delivered to the Moon by either piloted or robotic NTR transfer vehicles.

The LESA modular base concept is being revisited today and appears as a key component in the "Lunar/Mars Direct" architecture being proposed by Zubrin[6] of Martin Marrietta Company. Figure 4 depicts habitation modules being moved together to form a large contiguous pressurized volume. Articulated landing gear on each module provides capability for movement in both the vertical and horizontal directions, thereby enabling the individual modules to "walk" short distances for connection. Each module is ~8.5 m in diameter by ~10 m in length, and contains two complete decks, and provisions sufficient to accommodate a crew of 4 for one year without resupply. The "wet" hab module would have a mass of 40 t in low lunar orbit (LLO) of which ~14.5 t is LOX/LH_2 propellant used for lunar descent. Surface-to-orbit ascent and rendezvous with the LTV could be provided by a LEV of the type discussed earlier. An alternative mission mode would be to use an Earth Return Vehicle (ERV) fueled with storable bi-propellants (NTO/MMH) to provide a direct Earth return capability. The 19.5 t ERV (shown departing the lunar surface in Figure 4), together with its "wet" cryogenic lunar landing stage, would have a combined mass in LLO of ~33.5 t.

Operating in a "cargo mode," a single stage NTR vehicle could deliver single or multiple habitation/cargo modules to transportation nodes located in equatorial or lunar polar orbit (LPO). An equatorial parking orbit and surface base location has operational advantages which include surface-to-orbit abort opportunities every 2 hours along with a continuous abort-to-Earth capability. Locating a transportation node in LPO would not constrain base location and would provide access to the entire lunar surface. Surface-to-LPO abort opportunities would vary, however, from ~2 hours for higher latitude locations to ~14 days for mid-latitude locations, and abort-to-Earth opportunities would also occur ~ every 14 days.

NUCLEAR THERMAL ROCKET ENGINE CYCLES AND TECHNOLOGY OPTIONS

Nuclear thermal rocket systems function by raising hydrogen propellant to high pressure in a turbopump assembly, passing it through a high power reactor where it is heated to high temperatures, and then exhausting it through a nozzle at high speeds to generate thrust. By using low molecular weight hydrogen as the reactor coolant and propellant, the exhaust velocity (v_{ex}) and specific impulse ($Isp=v_{ex}/g$; $g=9.8$ m/s^2) of a NTR can be nearly twice that of conventional LOX/LH_2 fueled chemical rockets at comparable exhaust gas temperatures.

Engine Cycles

A variety of energy sources exist within a NTR for heating the turbine drive gas to the required levels. In the "hot bleed" cycle, a small percentage of heated hydrogen exiting the reactor core is diverted from the nozzle plenum chamber, cooled to the desired turbine inlet temperature, and then used to drive the turbopump assembly. The turbine exhaust can either be utilized for roll control or can be readmitted into the diverging portion of the nozzle for thrust generation. In the "full flow topping" or "expander" cycle, preheated hydrogen is routed to the turbopumps and then through the reactor core with the entire propellant flow being heated to design temperatures (see Figure 5). Hydrogen flowing from the pumps would be used to cool the nozzle, reflector, control rods, and support structure resulting in the necessary hydrogen preheating.

NERVA/NERVA-Derivative Technology

The feasibility of a hydrogen-cooled, graphite-core NTR was demonstrated by the Rover nuclear rocket program[7] begun at Los Alamos in 1955. Building on the technology base provided by this program, a joint NASA/AEC program was initiated in 1960 to develop a Nuclear Engine for Rocket Vehicle Application (NERVA).[8] Both programs were highly successful and demonstrated the practicality of reusable, high thrust, high specific impulse NTR systems (see Table 1). Despite program achievements, the Rover/NERVA programs were terminated in 1973, short of flight demonstration, because of decisions to delay NASA's post-Apollo program which envisioned the construction of lunar bases and piloted missions to Mars.

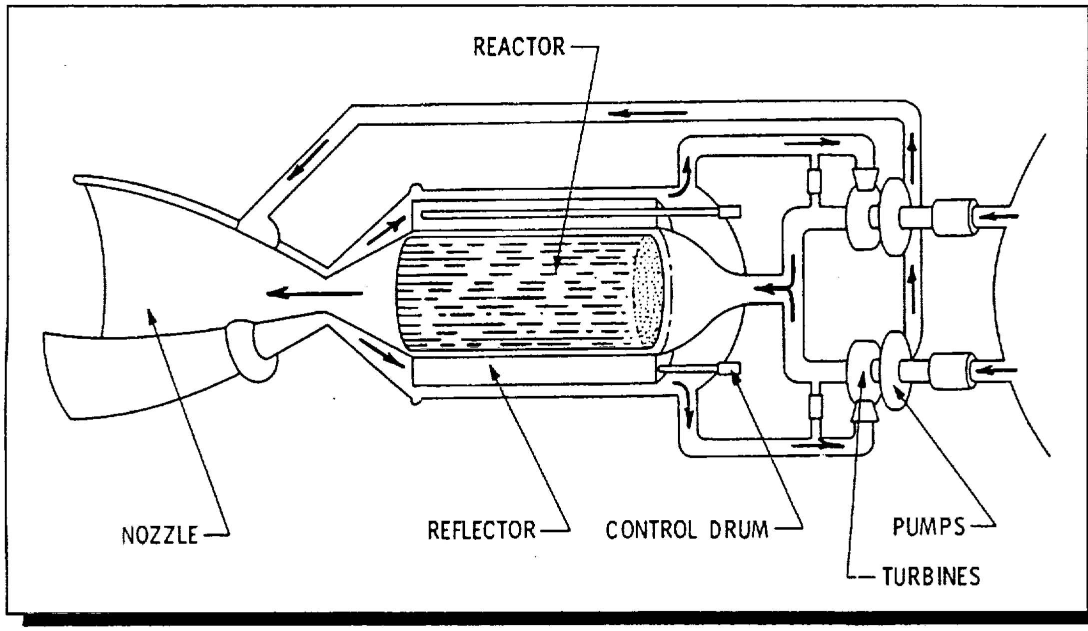


Fig. 5. Schematic of Dual Turbopump Expander Cycle NTR

Table 1. Rover/ NERVA Program Summary

- 20 Reactors designed, built, and tested between 1955 and 1973 at a cost of approximately $1.4 billion. (First reactor test: KIWI-A, July 1959).

- Demonstrated Performance

Power	~ 1100 (NRX Series) - 4100 (Phoebus-2A)
Thrust (klbf)	~ 55 (NRX Series) - 210 (Phoebus -2A)
Peak/Exit	
Fuel Temps. (K)	~ 2750/2550 (PEWEE)
Equiv. Specific Impulse(s)	~ 850 (PEWEE)
Burn Endurance	1-2 Hours
- NRX-A6	62 minutes at 1125 MWt (single burn)
- Nuclear Furnace	109 minutes accumulated (4 tests) at 44 MWt
Start/Stop	28 auto start-ups/shutdowns with XE

- Broad and deep database achieved/used in preliminary NERVA "flight engine" design (1972)

- Anticipated Performance

Burn Endurance	~ 10 hours (demonstrated in electric furnace tests at Westinghouse)
Specific Impulse	Up to 925s (composite)/up to 1020s (carbide fuels)

The basic components of the NERVA engine are shown in Figure 6. Particles of coated uranium carbide were dispersed in hexagonally-shaped graphite matrix fuel elements each having 19 axial coolant channels and coated with zirconium carbide to reduce the hydrogen/graphite reaction. Interspersed among the fuel elements were cooled support elements, attached to an upstream core support plate, to restrain the core in the direction of flow. An assembly of fuel and support elements was used to form the NERVA core with each fuel element producing approximately 1 to 1.2 megawatts of thermal power.

Performance projections for NERVA derivative reactor (NDR) systems utilizing higher temperature "composite" and "carbide" fuel forms and "state-of-the-art" nozzle and turbopump technologies indicate substantial improvements in both Isp and engine thrust-to-weight over the 1972 NERVA reference design (see Table 2). The composite and carbide fuels (with predicted temperature capabilities of 2500-2900 K and 2900-3300 K, respectively), underwent limited testing in the Nuclear Furnace[7] reactor in 1972 although at substantially lower temperatures. An advanced composite fuel was successfully tested by Westinghouse in an electric furnace for 10 hours at 2750 K with 64 temperature cycles.[9]

Particle Bed Reactor Technology

A compact, high power density reactor concept has been proposed by Brookhaven National Laboratory.[10] Referred to as the particle bed reactor, its distinguishing feature is the direct cooling of small (500-700 μm diameter) coated particulate fuel spheres by the hydrogen propellant. A representative fuel element is shown in Figure 7. The fuel is packed between two concentric porous cylinders, called "frits," which confine the fuel but allow coolant penetration. A number of these small annular fuel elements would be arrayed in a cylindrical moderator block to form the PBR core. Coolant flow is directed radially inward, through the packed bed and hot frit, and axially out the inner annular channel. Because of the large heat transfer area envisioned in a PBR element, bed power densities 2 to 10 times larger than the peak power densities demonstrated in the NERVA program may be possible. If such parameters can be achieved, NTRs with a smaller physical size and a substantially higher engine thrust-to-weight ratio-- on the order of 20-- may be possible.

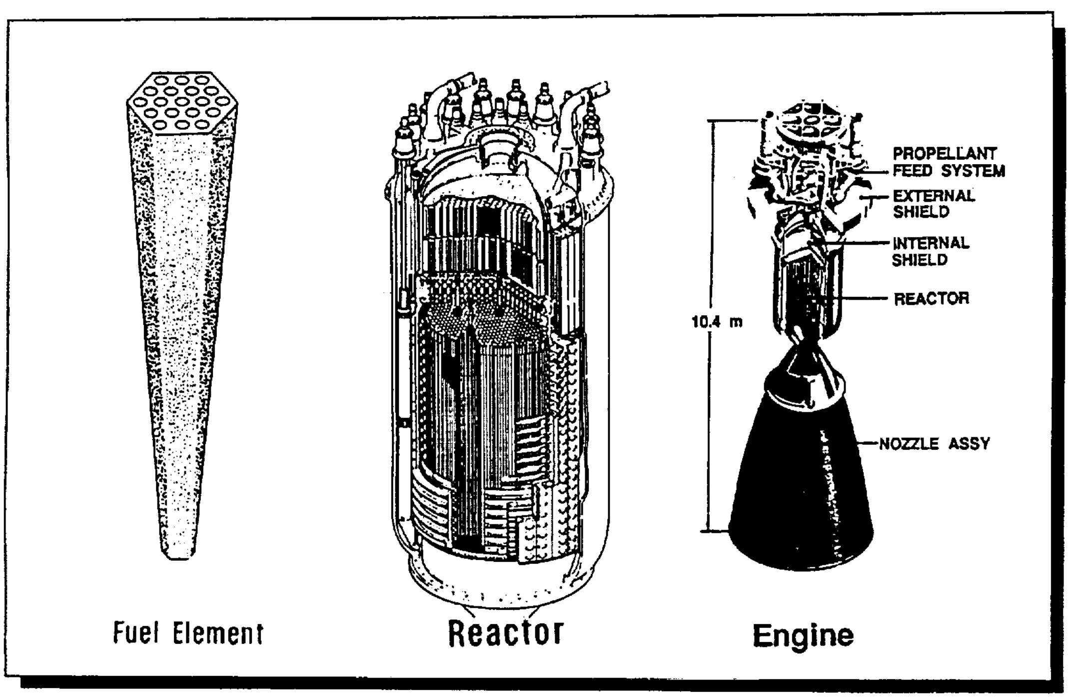


Fig. 6. Components of NERVA Engine

Table 2. Characteristics for 75 klbf NERVA-Type Engines

PARAMETERS	'72 NERVA**	"STATE-OF-THE-ART" NERVA DERIVATIVES**				
Engine Flow Cycle	Hot bleed/ Topping	Topping (expander)				
Fuel Form	Graphite	Graphite		Composite		Carbide
Chamber Temp. (K)	2350-2500	2500	2350-2500	2700		3100
Chamber Press (psia)	450	500	1000	500	1000	1000
Nozzle Exp.Ratio	100:1	200:1	500:1	200:1	500:1	500:1
Specific Impulse(s)	825-850/ 845-870	875	850-885	915	925	1,020
Engine Weight+(kg)	11,250	7,721	8,000	8,483	8,816	9,313
Engine Thrust/Weight (w/int. shield)++	3.0	4.4	4.3	4.0	3.9	3.7

** Engine weights contain dual turbopump capability for redundancy
+ w/o external disk shield
++Thrust-to-weight ratios for NERVA/NDR systems are ~5-6 at the 250 klbf level

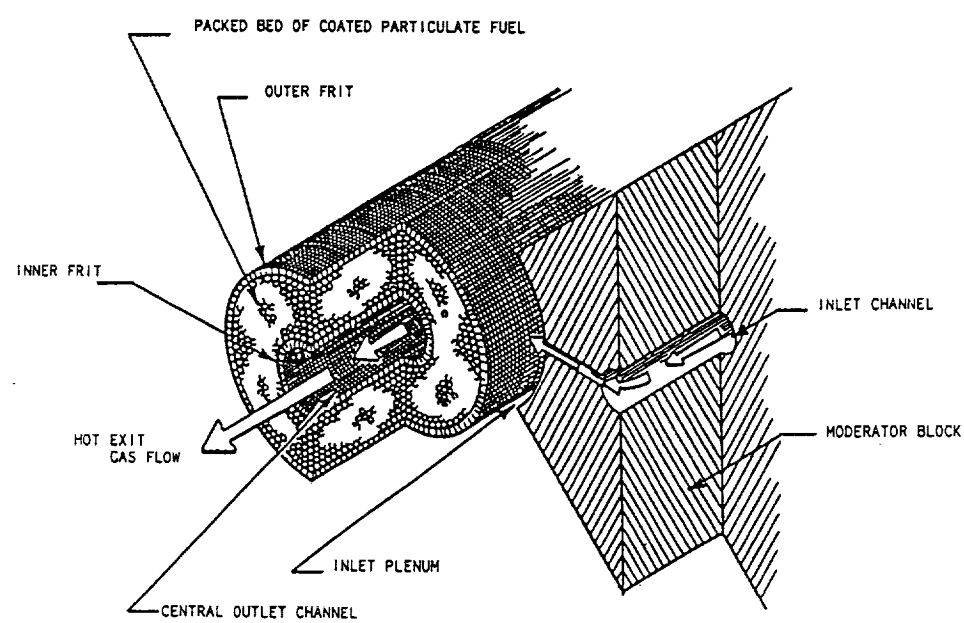


Fig. 7. PBR Fuel Element/Moderator Assembly

Table 3. Mission Ground Rules and Assumptions

• Payload Outbound:	31.83 t	"Wet" lunar excursion vehicle (LEV)
	14.67 t	LEV payload
	6.57 t	Lunar transfer vehicle (LTV) mission module and crew (4)
	1.85 t	LTV radiation shield
• Return Payload:	6.57 t	LTV mission module and crew (4)
	1.85 t	Water radiation shield (vented prior to EOC)
	9.40 t	"Dry" LEV (returned by lunar NTR vehicle)
• Parking Orbits:	407 km	Circular (Earth departure/arrival)
	300 km	Circular (Lunar arrival/departure)

- Trans-lunar injection ΔV assumed to be 3100 m/s + g-losses
- Lunar orbit capture/trans-Earth injection ΔV's assumed to be 1100 m/s
- Earth orbit capture ΔV assumed to be 3100 m/s
- Mission duration: 50 Days (11 in LEO, 7 in transit, 32 at Moon)
- Ref. Chem/AB vehicle partially reusable (LTV core and crew module)
- Lunar NTR vehicle fully reusable

Note: NASA "90-Day Study" Lunar Outpost Scenario/Option 5

MISSION/TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

The ground rules and modeling assumptions used in comparing the chemical aerobrake (chem/AB) and NTR systems are representative of those currently being used by the LMEPO and the NASA field centers involved in SEI studies. Table 3 details information on the makeup of outbound and return payload masses, parking orbits, mission velocity change (ΔV) requirements and duration, and assumed mission profiles for both systems. In addition to the 4 primary ΔV maneuvers, midcourse correction (MCC) and reaction control system (RCS) ΔV's are also included to simulate in-flight and orbital maneuvers.

The principle propulsion system, aerobrake, and tank mass assumptions made in this study are summarized in Table 4. The chem/AB system uses four 20 klbf LOX/LH_2 fueled advanced space engines (ASE) for LTV primary propulsion along with advanced, lightweight aluminum-lithium propellant tanks and an ~3.5 t aerobrake requiring partial "on-orbit" assembly.

The NTR technologies examined included NERVA (1972-vintage), NDR, and PBR concepts. Modest growth versions of a graphite matrix and composite fuel NDR were studied along with a high pressure/high nozzle expansion ratio (ε) version of the composite NDR, capable of delivering 925 s of specific impulse. (The advanced carbide fuel NDR was not considered in this study.) At this particular time, specific engine parameters for a "man-rated" PBR are not available. In their absence a specific impulse of 915 s and an engine thrust-to-weight of 20 has been assumed for analysis purposes. A thrust level of ~75 klbf was determined to be near optimum for the piloted lunar mission and was chosen as the baseline. A removable biological disk shield weighing ~4.5 t was also assumed on all piloted missions. This weight was obtained from NASA contractor studies of lunar NTR stages conducted during the 1960's and early 1970's. In estimating the total propellant requirements, allowances have been made for reserve and post-burn reactor cooldown.

Aluminum alloy 2219-T87 (F_{tu}=62 ksi, ρ=0.102 lbm/in^3=2827 kg/m^3) was used for the lunar NTR's LH_2 propellant tank construction. This selection is due to its favorable properties at cryogenic temperatures and its extensive use in cryogenic tank construction. It has a relatively high strength-to-density ratio, good toughness and availability, is weldable and low in cost. Alloy 2219-T87 plate is also presently used for the LOX/LH_2 tanks on NASA's space transportation system (the "Shuttle"). Tank thicknesses were calculated based on a 35 psi (241.3 kPa) internal pressure and include hydrostatic loads using a "3 g" load factor along with a safety factor of 1.5. A 2.5 percent ullage was also assumed.

Tank insulation on the NTR stage includes 0.5 inches of PVC closed cell foam (at 0.55 kg/m^2) for "wet" launching, and 2 inches of "Superfloc" high performance multilayer insulation[11] (at 30 layers/inch) with an installed density (including face sheets, pins, overlap and attachments) of ~0.976 kg/m^2. The cislunar space heating rate for the combination foam and insulation system described is ~0.378 W/m^2/s and results in a LH_2 boil-off rate for the NTR stage of ~2.23 kg/m^2/mth. Finally, one 0.4 mm sheet of aluminum (comparable to that used on NASA's Mariner 9 spacecraft) is assumed for micrometeroid protection.

COMPARISON OF TRANSPORTATION SYSTEM OPTIONS

One of the key aspects of the LTS featured in the 90-Day Study was its reusability. After aerocapture into LEO, the core LTV vehicle would be refueled and serviced, and then outfitted with expendable propellant tank sets and cargo for return to the Moon at the next opportunity. For the initial piloted mission, the return payload mass fraction (defined as mass returned to LEO/IMLEO) was ~7.6 percent. In FY'90, studies were initiated at NASA's Marshall Space Flight Center on a single crew module, integrated LTV/LEV concept, and mission scenario (shown in Figure 8) which returned all but two large TLI propellant tanks each weighing 5.1 t.

Table 4. Propulsion System, Aerobrake and Tank Mass Assumptions

- **Chemical**

	Propellant	Isp (sec)	Usage
- Primary*	LOX/LH_2	481 (ASE)**	Main impulse
- Auxiliary	Stor. biprop.	320	RCS/MCC

* Chem/AB: 4 ASE Engines (LTV)
** Thrust/engine: 89 kN (20 klbf)

- **NTR-LH_2 Propellant**

- Engine	Pc (psia)	ε (-)	Isp (sec)	Thrust (kN/klbf)	Engine T/W	Ext. Shield Mass(t)
'72 NERVA+	450	100:1	870	333/75	3.0	4.5
Graphite NDR*	500	200:1	875	333/75	4.4	4.5
Composite NDR*	500	200:1	915	333/75	4.0	4.5
Composite NDR*	1000	500:1	925	333/75	3.9	4.5
PBR**	-	-	915	333/75	20.0	4.5

\+ Assumes expander cycle @ 2500 K
* NDR - NERVA-derivative reactors (Graphite @ 2500 K and Composite @ 2700 K)
** PBR - Particle Bed Reactor

- Reserve/cooldown propellant/boiloff rates: 2%/3%/~2.23 kg/m^2/mth
- Aerobrake mass fraction: 20.8% = AB mass/total return mass (incl. AB)
- Tankage fraction: ~4.2-7.6% (Chem/AB) and ~12.5% (single tank NTR stage)

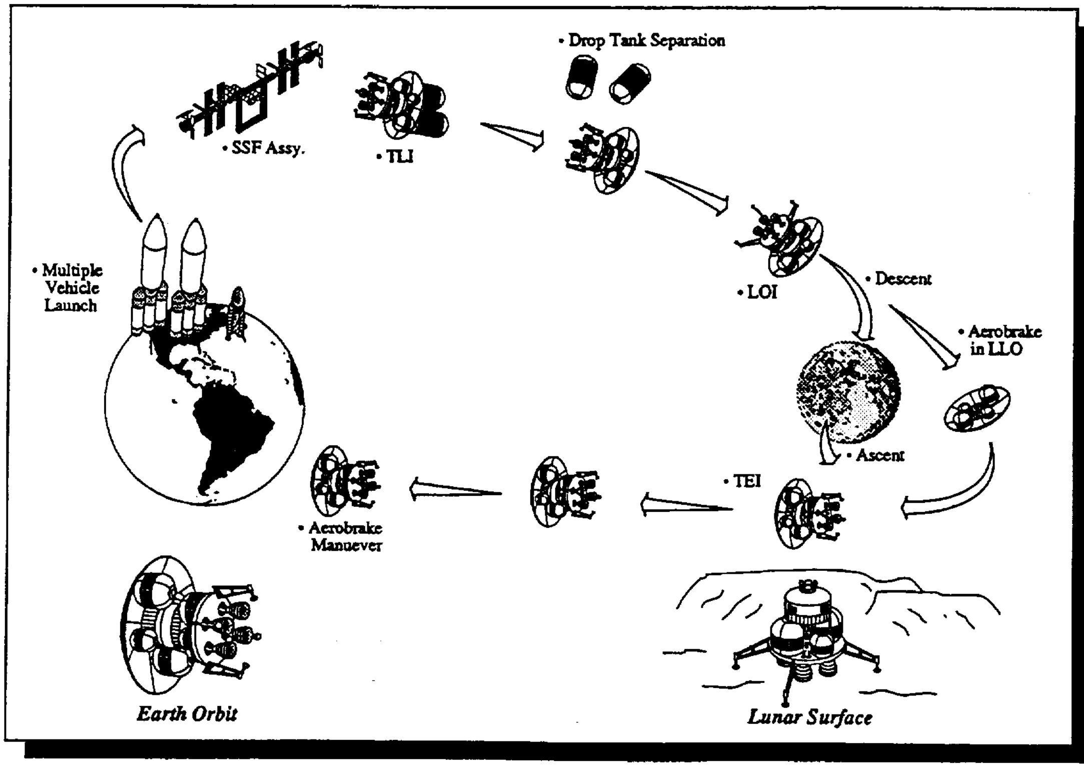


Fig. 8. FY'90 Single Crew Module/Propulsion Stage Scenario

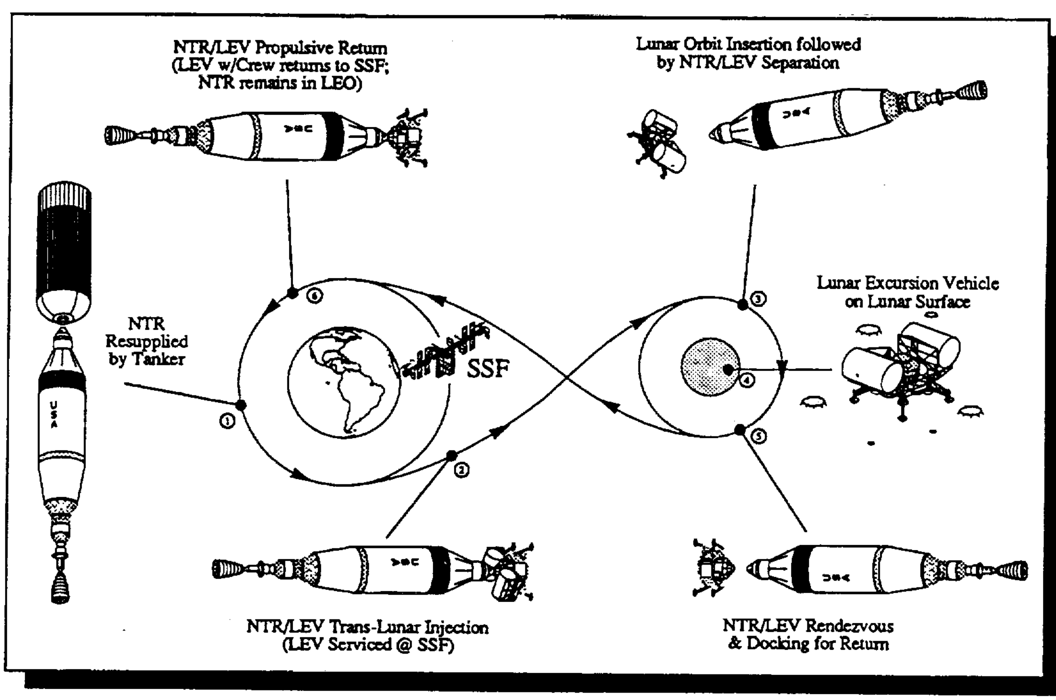


Fig. 9. Fully Reusable NTR Lunar Scenario

At the same time a "fully reusable," all propulsive NTR lunar scenario was proposed and preliminary stage point design work initiated at NASA's Lewis Research Center. Details of the scenario and a relative size comparison of the chem/AB and NTR vehicles are shown in Figures 9 and 10, respectively. The NTR scenario retains the option of separate crew modules and propulsion systems on both the LTV and LEV. This feature provides added crew safety and a powered-abort capability, using LEV propulsion, similar to that demonstrated during the Apollo 13 mission.

After rendezvous and docking in LLO, the LEV would be returned to LEO using the NTR stage. Once in LEO, the crew would transfer to the LEV and return to Space Station Freedom. The "radioactive" NTR and its stage would remain at an appropriate "stand-off" distance from Freedom between mission intervals. Preparation for follow-on missions would involve LH_2 refueling using a propellant tanker, resupply of RCS and fuel-cell reactants, and redocking of the "wet," cargo-laden LEV for subsequent transport.

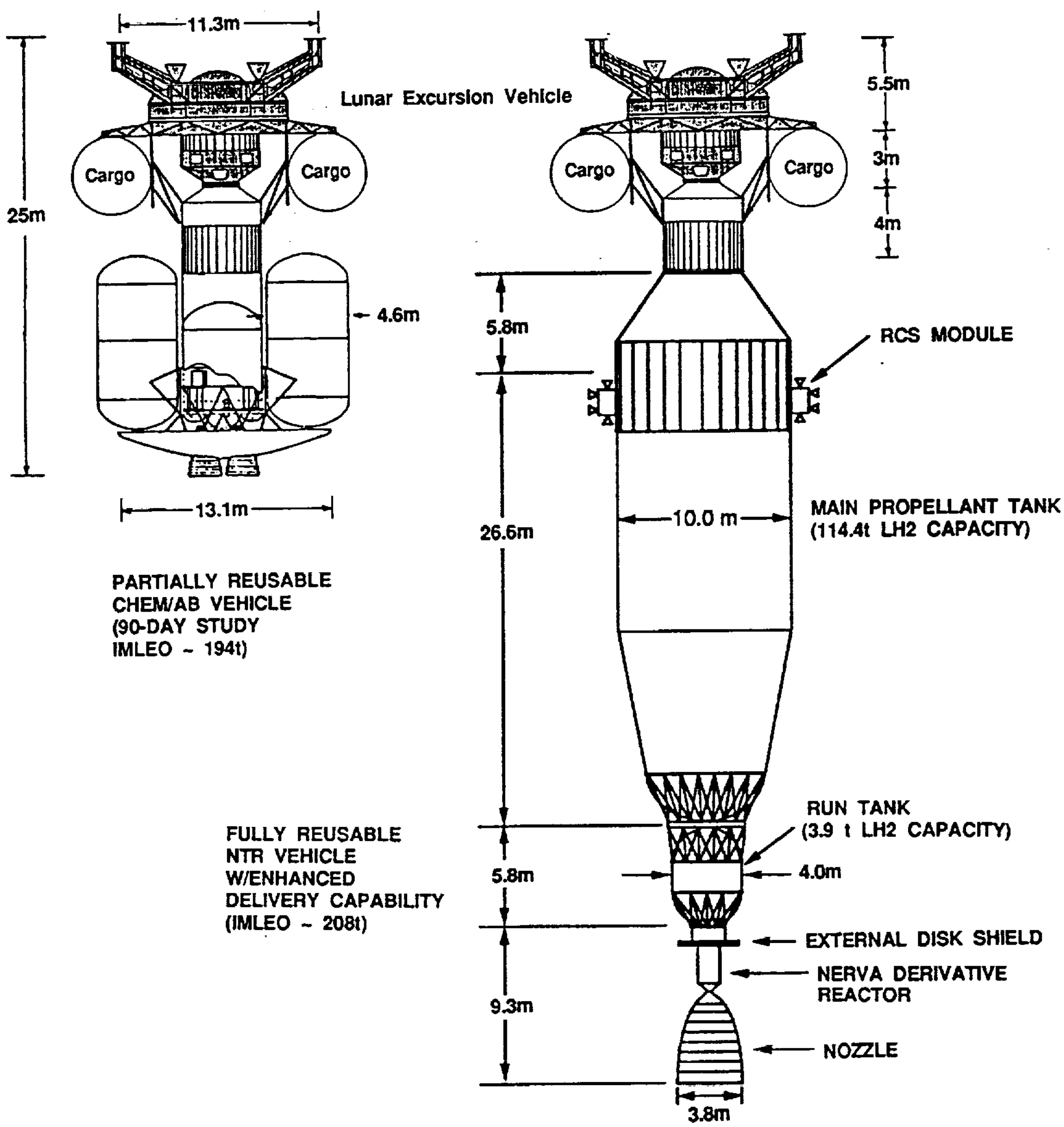


Fig. 10. Lunar Transportation Vehicle Size Comparison

The lunar NTR vehicle shown in Figure 10 is similar in configuration to earlier NTR lunar shuttle designs produced by NASA contractors[12,13] during the 1960's and early 1970's for lunar and interplanetary applications. It contains two distinct modules which can be assembled in space. The main propellant tank has a diameter of 10 m, a root 2 ellipsoidal forward dome, and a 10 degree conical aft section with an ~3.6 m spherical end cap radius. The tank's tapered end reduces forward radiation scattering to the crew and helps to reduce stage shielding requirements. A command and control, and RCS module would be located in the stage forward section to allow robotic cargo missions.

The "propulsion module" contains the NTR engine and a small run tank. The run tank has hemispherical forward and aft domes and a cylindrical barrel section ~4.0 m in diameter. The "wet" propulsion module has been sized both in dimensions and mass for deployment from the "Shuttle" cargo bay as a single autonomous unit. Using the 925 s high expansion ratio composite NDR as representative of the largest engine envelope envisioned (length ~11.8 m, nozzle diameter ~4.2 m), and allowing space allocation for a docking system and propellant transfer lines, the run tank length and LH_2 capacity are estimated to be ~5.8 m and 3.9 t, respectively. The run tank can therefore be used for engine startup and cooldown, and for short duration burns.

LUNAR OUTPOST COMPARISON RESULTS

The IMLEO requirements for the lunar outpost scenario assuming chem/AB and NTR-based LTVs are shown in Figure 11. The partially reusable chem/AB system featured in the 90-Day Study has an IMLEO of ~194 t. The fully reusable NDR systems, with IMLEO's varying from ~190 - 200 t, are comparable to the chem/AB system even with the assumption of the heavier 2219-T87 Al tank material. The thrust-to-weight ratio of 20 assumed for the PBR results in an IMLEO savings of ~15 percent and indicates the benefits to be gained by reducing engine weight.

Fig. 11. Lunar Outpost Comparison Results

CASE	IMLEO(t)
• "90-Day" Chem/AB Baseline* (Partially reusable, returns LTV core module and 4 crew)	193.9
• Lunar NTR vehicle (fully reusable, returns LTV and crew)	
- Graphite NDR (875/4.4)+	199.7
- Composite NDR (915/4.0)	191.2
- Composite NDR (925/3.9)	191.1
- PBR (915/20)	165.5
• FY'90 Chem/AB baseline (Partially reusable with TLI drop tanks)	233.6
• Lunar NTR vehicle (fully reusable, returns "dry" LEV also)	
- '72 NERVA (870/3.0)+	235.9
- Graphite NDR (875/4.4)	218.2
- Composite NDR (915/4.0)	207.9
- Composite NDR (925/3.9)	206.0
- PBR (915/20)	181.4

* NASA "90-Day Study" Lunar Outpost Scenario/Option 5
+ (Isp/engine thrust-to-weight)

The single crew module/single propulsion stage chem/AB concept baselined in the FY'90 NASA studies has an IMLEO of ~234 t. While an integrated LTV/LEV concept might appear to have a lower IMLEO requirement, the resulting crew module and propulsion stage which must be landed on the lunar surface and returned to LLO is heavier, as is the aerobrake, which must now capture the integrated vehicle along with its LOC/TEI propellant tanks back in LEO. By contrast, the NTR systems, with their higher Isp capability, have lower IMLEO requirements for the more demanding lunar missions. The IMLEO results shown in Figure 11 reflect the fully reusable NTR scenario depicted in Figure 9 which includes the return of the "dry" LEV to LEO for refurbishment, refueling and remanifesting. Even '72 NERVA has performance comparable to or better (considering the tankage assumptions) than the chem/AB systems. The NTR vehicle shown in Figure 10 depicts the composite NDR system with 915 s specific impulse. The NTR vehicle (without the LEV) has a "dry mass" of ~37.9 t and requires ~118.3 t of LH_2 in its main propellant and run tanks to cover the impulse, engine cooldown, boil-off, and reserve requirements of the mission.

OTHER FIGURES-OF-MERIT

While IMLEO is the most commonly used "figure-of-merit" for comparing different propulsion systems, there are other operational figures-of-merit which should be considered when comparing transportation system options like reusability, crew and mission safety, and technology maturity, operational margin and growth potential. Table 5 compares three transportation system options-- Apollo, chem/AB, and NTR-- against a number of operational parameters.

The Apollo program objectives of sending men to the Moon and returning them safely to Earth were successfully accomplished in an expendable mission mode with direct entry of the command module 6 t capsule. Peak "g-loadings" on the crew during re-entry were on the order of 7 g's. Single engines were the norm and were used reliably for all critical mission maneuvers, although backup propulsion options were available in abort modes.

The single crew module/single propulsion

Table 5. Lunar Transportation Systems Comparison

PARAMETERS	APOLLO		CHEM/AB	NTR
• IMLEO (t)	123*		234	208
• Mission Mode	Expendable		Partially Reusable	Fully Reusable
• Propulsion				
- Engine/#	J-2/1	SPS+/1	ASE/4	NERVA Derivative/1
- Propellant	LOX/LH2	Storables	LOX/LH2	LH2
- Total Thrust (klbf)	225	22	80	75
- Isp(s)	425	256	481	915
• Burn Duration/Engine (mins)				
- TLI	5.2	—	26.0/4	28.4
- LOC	—	6.3	4.9/4	7.2
- TEI	—	2.5	1.6/4	4.3
- EOC	Direct Entry		Aerocapture	9.2
• Earth Entry Velocity (km/s)/"g-loading"	11.2/≤7g		≤11.2/≤5g	0.5 g - 0.7 g (begin-end EOC)
• Return Mass Fraction (%)	4.8		11.5	23.4

* S-IVB Stage Prior to TLI with 44.7 t Payload - CSM, LEM and 3 crew
\+ Service module propulsion system

stage concept shown in Figure 8 has a return payload mass fraction of 11.5 percent. It also utilizes multiple engines to satisfy crew mission safety requirements and subjects the crew to lower g-loadings than those encountered by the Apollo astronauts.

The NTR transportation system shown in Figures 9 and 10 utilizes a single engine for all primary in-space propulsion maneuvers, similar to the Apollo mission profile. Also, like Apollo, it retains separate crew modules and propulsion systems on both the LTV and LEV which can provide added crew safety and potential abort capability. The longest single burn requirement during the lunar mission is under 30 minutes (during TLI), and the total mission burn duration of ~50 minutes is 12 minutes less than the 62 minute "continuous full-power burn" demonstrated by the NERVA program's NRX-A6 reactor in December 1967. With a 5 to 10 hour lifetime anticipated for the NDR system, propulsion module replacement will occur after every 5 missions.

Regarding crew comfort during final propulsive capture into LEO, the g-loadings experienced by the crew varies from ~0.5 to 0.7 g's from EOC start to finish. Lastly, an NTR-based LTS has good performance potential. The 915 s composite fuel NDR is 26 t lighter than its chem/AB counterpart and its return payload mass fraction of 23.4 percent is a factor of two higher.

ALTERNATIVE NTR MISSION MODES AND APPLICATIONS

The fully reusable, piloted NTR mission scenario, illustrated in Figure 9 utilizes the lunar orbit rendezvous (LOR) mission mode used during the Apollo program. The all-propulsive NTR flight profile requires 4 major impulsive burns (TLI, LOC, TEI and EOC), and cargo is returned to LEO in the form of the "dry" LEV. This particular scenario represents only one of a variety of possible lunar NTR flight profile options available for piloted and cargo missions to the Moon (see Figure 12).

Autonomous NTR stages can also employ a "4-Burn" scenario to deliver cargo to lunar orbit, such as an expendable lander with its surface payload. They can then return to Earth empty or have the option of bringing back a piloted or cargo payload in the LOR mission mode. If the lunar

Fig. 12. Lunar NTR Application Options

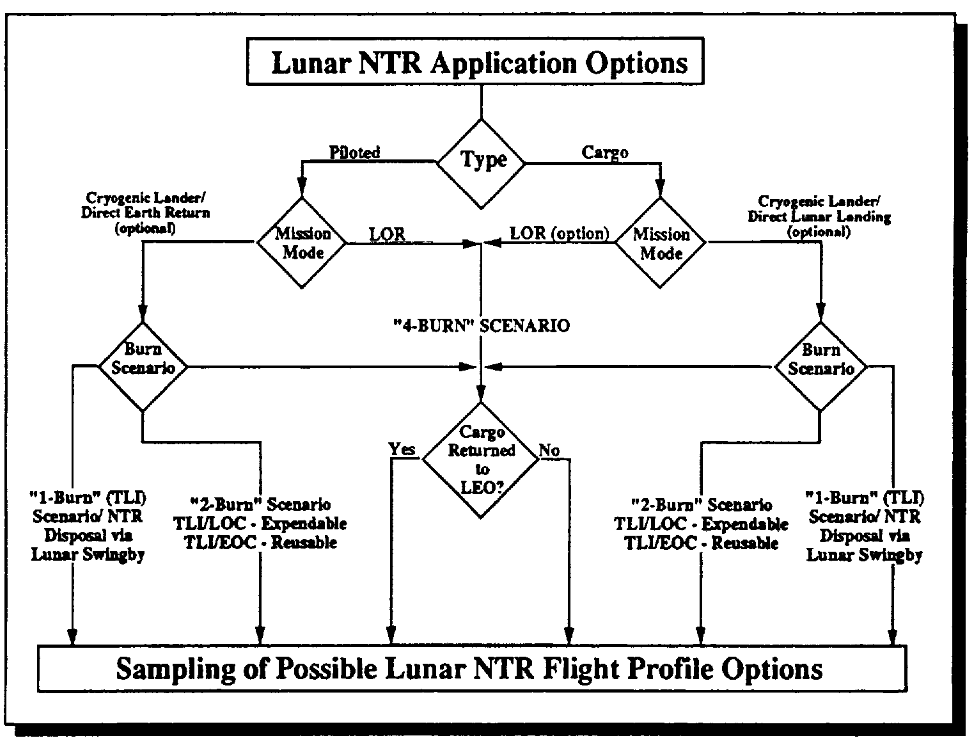


Table 6. Sensitivities to Alternative Mission Modes

NTR Application	IMLEO(t)/Tank LH_2 (t)*/Payload Mass Fraction** (%)	
	Customized Stage	Fixed Stage
• "4-Burn" Piloted ("Dry" LEV Returned to LEO)	← 207.9 / 114.4 / 25.5 →	
• "4-Burn" Cargo (Expendable Lander+ with Payload: 59.4t)	168.4 / 79.7 / 35.3	181.0 / 87.7 / 32.8
• "4-Burn" Cargo (Piloted Hab Module and ERV: 73.5t)	215.6 / 104.7 / 34.1	219.2 / 107.1 / 33.5
• "2-Burn" Cargo, Reusable with "Free Return" Trajectory (Piloted Hab and ERV: 82.9t)++	181.7 / 66.8 / 45.6	194.9 / 74.1 / 42.5
• "1-Burn" Cargo, Expendable using "Lunar Gravity Assist" (2 Hab and 1 ERV: 127.8t)++	230.7 / 71.3 / 55.4	238.9 / 74.4 / 53.5

* Propellant in Main Tank / does not include 3.9t of LH_2 in "Run Tank"
** "Outbound" Payload Mass Fraction
\+ "Wet" Expendable lander from the "90-Day Study" can deliver 33t to lunar surface
++ Piloted Hab(s) and ERV each have LOX/LH_2 cryo stage sized for direct lunar descent

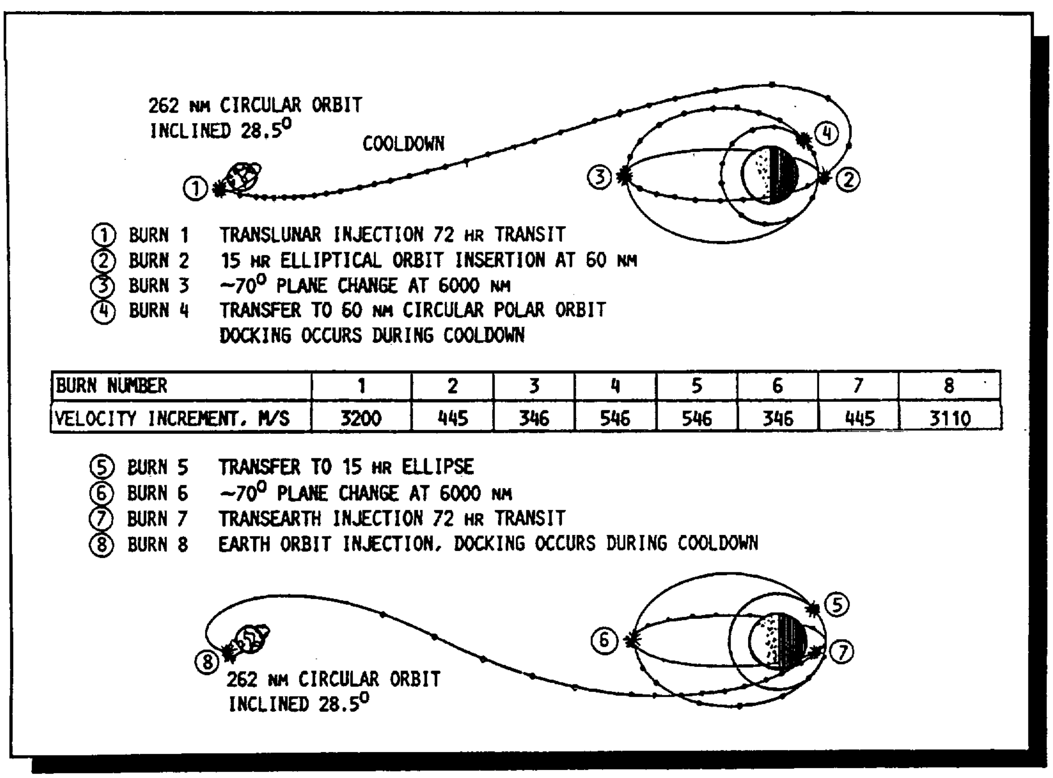
payload has its own cryogenic stage to allow a direct lunar landing, the NTR cargo vehicle can employ a simple "2-Burn" scenario. This option involves a "leading edge" encounter with the Moon to set up a "free return" trajectory to Earth. Some midcourse correction auxiliary propulsion, or "cooldown thrust," from the NTR itself would be used to optimize the Earth return conditions for capture back into LEO.

As "full power lifetime limits" are approached on the engine, the NTR cargo vehicle can be expended in lunar orbit after its final payload has been delivered. A more attractive disposal mode is associated with the "1-Burn" scenario shown in Figure 12. In this particular scenario, a lunar gravity assist maneuver is used to deliver the "end-of-life" NTR stage to a heliocentric orbit with minimal risk of Earth reencounter. After the TLI burn, the NTR stage would separate from the payload and its cryogenic stage, and retarget for a "trailing edge" lunar swingby to set up the gravity assist. The ΔV requirements for the maneuver are very modest-- on the order of 30 m/s. (A large number of disposal modes for lunar NTR mission applications have been identified and reported on elsewhere.[14])

Alternatives to the 90-Day Study LOR piloted mission mode are also shown in Figure 12. For example, an autonomous NTR stage could deliver to lunar orbit a combination payload consisting of a piloted habitation module and Earth Return Vehicle (ERV) of the type discussed previously and illustrated in Figure 4. The NTR stage could then return to Earth either empty or with a payload if operated in the LOR mission mode. Similarly, 1-Burn and 2-Burn scenarios are available in the piloted mission mode if the piloted payloads are equipped with cryogenic lander and/or braking stages, and an ERV capability is provided for the crew.

A comparison is made, for a variety of NTR applications, of the performance penalty incurred by using a fixed geometry NTR stage vs. a "customized" stage. The performance parameters on which the comparison is based are IMLEO, main tank propellant loading, and payload mass fraction (see Table 6). The NTR stage of Figure 10, with its composite fuel NDR, specific impulse of 915 s and engine thrust-to-weight of 4 is selected as the baseline configuration. To transport to LLO the 90-Day Study expendable LEV with its 33 t surface payload, the baseline stage requires only 88 t of LH_2 propellant in its 114.4 t capacity tank. The required IMLEO using the baseline stage is ~181 t compared to ~168 t using a smaller capacity tank customized for this particular mission. As the payload size goes up in the 4-Burn cargo scenario, the IMLEO difference between the customized and baseline stage decreases. Additionally, transporting larger payloads more effectively utilizes the propellant capacity of the baseline stage. Similar trends are indicated in the 2-Burn and 1-Burn scenarios. Of particular note is the attractive payload capability of the NTR cargo stage which can range from ~35 percent in the 4-Burn scenario to ~45 percent in the 2-Burn scenario with "free return" trajectory, and to ~55 percent in the 1-Burn expendable cargo mode with a "lunar gravity assist."

The final flight profile option examined during this study is a nonoptimum, "8-Burn" piloted mission to lunar polar orbit and return (see Figure 13). It features short lunar transit times (3 days each way), and major plane change and circularization maneuvers during the transfer to and from a 60 nautical mile (~110 km) circular LPO. This type of flight profile was used by NASA in the late 1960's and early 1970's as its primary "Reference Mission" for determining functional requirements and characteristics of the NERVA engine.[15] Using the same outbound and return payloads assumed in the fully reusable NTR scenario, the 915 s composite fuel NDR can perform the "8-Burn" Reference Mission for an IMLEO of ~225.6 t. The total propellant load is 133.9 t of which ~130 t is in the main propellant tank. The fully reusable NTR vehicle shown in Figure 10 could accommodate the additional 15.6 t of LH_2 by extending the cylindrical section of its main tank an extra 3 meters for an overall length of ~29.6 m.



BURN NUMBER	1	2	3	4	5	6	7	8
VELOCITY INCREMENT, M/S	3200	445	346	546	546	346	445	3110

Fig. 13. "8-Burn" Mission Profile for NTR Lunar Shuttle (circa 1971)

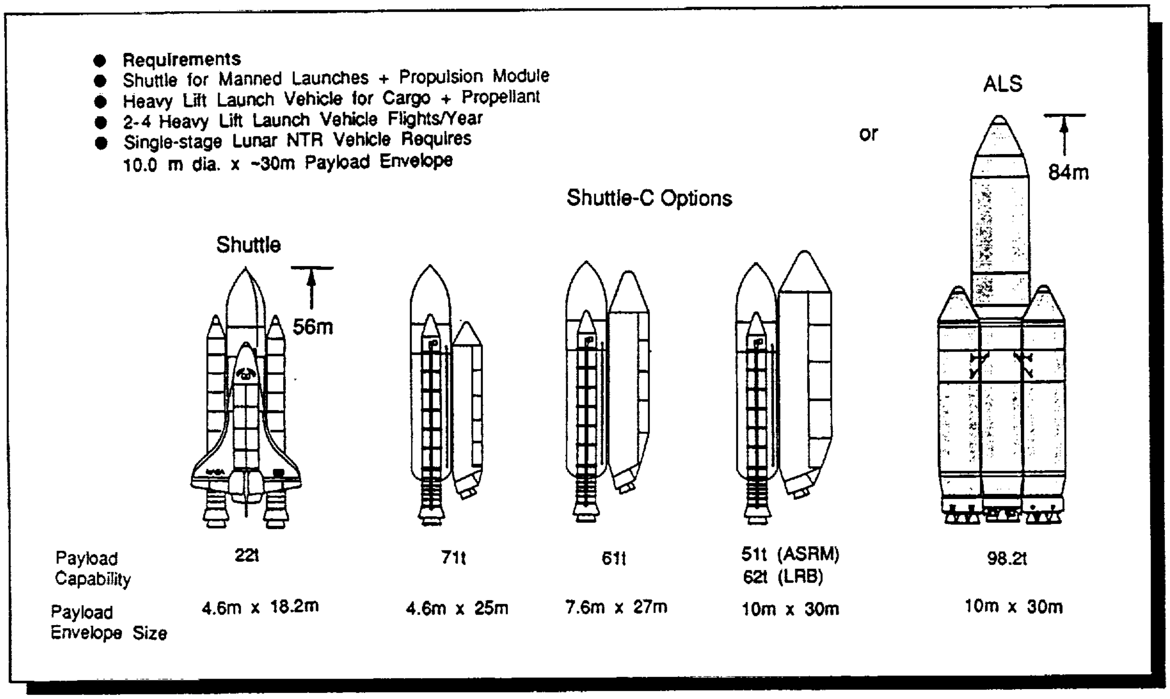


Fig. 14. Launch Vehicle Options for Lunar Missions

LAUNCH VEHICLE OPTIONS FOR LUNAR NTR MISSIONS

A variety of Heavy Lift Launch Vehicles (HLLVs) have been proposed to support SEI lunar and Mars missions. In FY'90 the two principle HLLV options being considered were
(1) Shuttle-C, an unmanned Shuttle-derived cargo vehicle in which the orbiter is replaced by a cargo carrier, and (2) the new Advanced Launch System (ALS), a joint effort by NASA and the Department of Defense. The relative size of these vehicles, together with their payload capability (to 407 km circular Earth orbit) and envelope size, is shown in Figure 14. The large 10 m x 30 m payload shroud versions of Shuttle-C or ALS could accommodate the lunar NTR vehicle's main propellant tank. Assembly of the lunar NTR vehicle would involve launching the partially filled main tank into orbit, and then "topping it off" in orbit at a propellant depot or with a propellant tanker. The propulsion module (which includes the NTR engine, external disk shield, and fueled "run tank") would be launched/deployed by the Shuttle for docking with the main propellant tank to form the NTR vehicle. It is anticipated that the "Synthesis Group" will recommend development of a HLLV with a minimum launch capability of 150 t, with designed growth to 250 t. At the 150 t range, the main propellant tank could be launched into orbit fully fueled, thereby simplifying the overall assembly process.

SUMMARY AND CONCLUSIONS

The rationale for considering the NTR for lunar missions is presented. In addition to performance benefits, the use of NTR on lunar missions can provide valuable operational experience and the technology can be "checked out" in a nearby space environment before it is used on the more demanding piloted mission to Mars.

A fully reusable, all propulsive NTR scenario and single stage vehicle design is also described. Its performance using NERVA, NDR, and PBR technology is compared to that of the reference chem/AB system and shown to be slightly better (in terms of reduced IMLEO) for low payload missions and significantly better for more demanding lunar mission profiles.

A large number of alternative NTR mission profiles have also been identified and examined. With its factor of two advantage in Isp over chemical propulsion and its high engine thrust-to-weight capability, the NTR is ideally suited to performing either piloted, cargo, or combination lunar missions. The NTR can form the basis for an efficient lunar space transportation that can be appropriately modified to also satisfy Mars transportation system needs.

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13. ABSTRACT *(Maximum 200 words)*

The solid core nuclear thermal rocket (NTR) represents the next major evolutionary step in propulsion technology. With its attractive operating characteristics, which include high specific impulse (~850–1000 s) and engine thrust-to-weight (~4–20), the NTR can form the basis for an efficient lunar space transportation system (LTS) capable of supporting both piloted and cargo missions. Studies conducted at the NASA Lewis Research Center indicate that an NTR-based LTS could transport a fully-fueled, cargo-laden, lunar excursion vehicle to the Moon, and return it to low Earth orbit (LEO) after mission completion, for less initial mass in LEO than an aerobraked chemical system of the type studied by NASA during its "90-Day Study." The all-propulsive NTR-powered LTS would also be "fully reusable" and would have a "return payload" mass fraction of ~23 percent--twice that of the "partially reusable" aerobraked chemical system. Two NTR technology options are examined--one derived from the graphite-moderated reactor concept developed by NASA and the AEC under the Rover/NERVA (Nuclear Engine for Rocket Vehicle Application) programs, and a second concept, the Particle Bed Reactor (PBR). The paper also summarizes NASA's lunar outpost scenario, compares relative performance provided by different LTS concepts, and discusses important operational issues (e.g., reusability, engine "end-of-life" disposal, etc.) associated with using this important propulsion technology.

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