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The Nuclear Thermal Propulsion Stage (NTPS): A Key Space Asset for Human Exploration and Commercial Missions to the Moon

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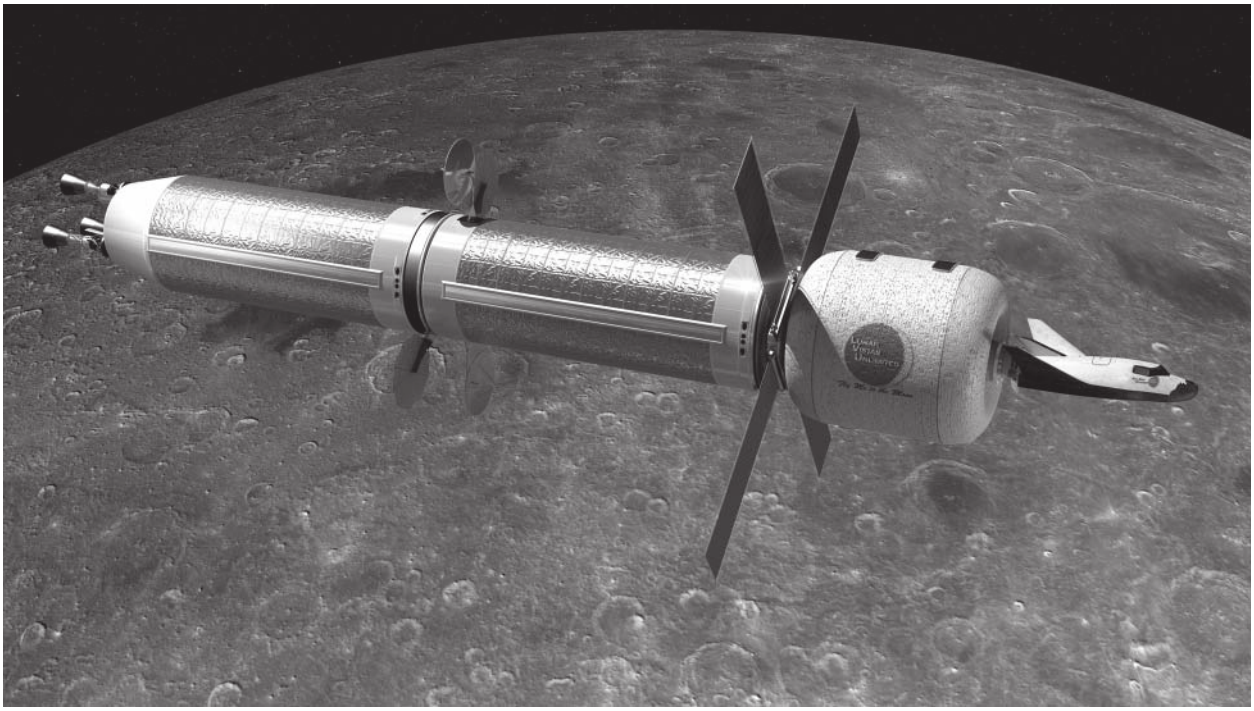

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Abstract

The nuclear thermal rocket (NTR) has frequently been discussed as a key space asset that can bridge the gap between a sustained human presence on the Moon and the eventual human exploration of Mars. Recently, a human mission to a near Earth asteroid (NEA) has also been included as a "deep space precursor" to an orbital mission of Mars before a landing is attempted. In his "post-Apollo" Integrated Space Program Plan (1970 to 1990), Wernher von Braun, proposed a reusable Nuclear Thermal Propulsion Stage (NTPS) to deliver cargo and crew to the Moon to establish a lunar base initially before sending human missions to Mars. The NTR was selected because it was a proven technology capable of generating both high thrust and high specific impulse (I_{sp} ~900 s)—twice that of today's best chemical rockets. During the Rover and NERVA programs, 20 rocket reactors were designed, built and successfully ground tested. These tests demonstrated the (1) thrust levels; (2) high fuel temperatures; (3) sustained operation; (4) accumulated lifetime; and (5) restart capability needed for an affordable in-space transportation system. In NASA's Mars Design Reference Architecture (DRA) 5.0 study, the "Copernicus" crewed NTR Mars transfer vehicle used three 25 klb_f "Pewee" engines—the smallest and highest performing engine tested in the Rover program. Smaller lunar transfer vehicles—consisting of a NTPS with three ~16.7 klb_f "SNRE-class" engines, an in-line propellant tank, plus the payload—can be delivered to LEO using a 70 t to LEO upgraded SLS, and can support reusable cargo delivery and crewed lunar landing missions. The NTPS can play an important role in returning humans to the Moon to stay by providing an affordable in-space transportation system that can allow initial lunar outposts to evolve into settlements capable of supporting commercial activities. Over the next decade collaborative efforts between NASA and private industry could open up new exploration and commercial opportunities for both organizations. With efficient NTP, commercial habitation and crew delivery systems, a "mobile cislunar research station" can transport crews to small NEAs delivered to the E-ML2 point. Also possible are week-long "lunar tourism" missions that can carry passengers into lunar orbit for sightseeing (and plenty of picture taking), then return them to Earth orbit where they would re-enter and land using a small reusable lifting body based on NASA's HL-20 design. Mission descriptions, key vehicle features and operational characteristics are described and presented.

Nomenclature

E-ML2	Earth-Moon L2 Lagrange point
K	temperature (degrees Kelvin)
klb_f	thrust (1000's of pounds force)

LEO	Low Earth Orbit (= 407 km circular)
LOX/LH_2	Liquid Oxygen/Liquid Hydrogen propellant
NERVA	Nuclear Engine for Rocket Vehicle Applications
SLS/HLV	Space Launch System/Heavy Lift Vehicle
SNRE	Small Nuclear Rocket Engine
t	metric ton (1 t = 1000 kg)
ΔV	velocity change increment (km/s)

1.0 Introduction and Background

Less than a month after the successful landing of Apollo 11 on the Moon, Wernher von Braun, then director of the Marshall Space Flight Center (MSFC), outlined NASA's Integrated Space Program Plan (1970 to 1990) to both the President's Space Task Group (Ref. 1) and the Senate Committee on Aeronautics and Space Science (Ref. 2). The plan envisioned the development of a space shuttle and orbiting space station, along with a reusable NTR propulsion stage that would function as a "workhorse" space asset delivering cargo and crew to the Moon for construction of a lunar base, and then for a human landing on Mars in 1982. The utilization of NTP for lunar mission applications was evident in the fact that the operating characteristics and requirements for the NERVA flight engine were to be based on a non-optimum, eight-burn, crewed mission to lunar polar orbit (LPO) and return (Ref. 3). Also considered was a four-burn, reusable cargo delivery mission as well.

Despite the successes of the Rover/NERVA programs and the technological triumph of Apollo, the public's interest in space waned and Apollo flights 18, 19, and 20 were cancelled, along with NASA's post-Apollo plans for a lunar base and a human mission to Mars. After the final Apollo 17 mission to Taurus-Littrow in December 1972 and cancellation of the Rover/NERVA programs in January 1973, short of flight demonstration, interest in human Moon/Mars missions and NTP development remained relatively dormant for more than a decade.

On July 20, 1989, the 20th anniversary of Apollo 11, President Bush proposed a Space Exploration Initiative (SEI) for the United States, which called for a return to the Moon "to stay", followed by a journey to Mars (Ref. 4). From 1989 to 1993, NASA conducted and funded both in-house and industry studies (Refs. 5 to 7) that outlined a campaign of human exploration that included the establishment of a transportation node in LEO, a permanent base on the Moon, then human missions to Mars. NASA's baseline lunar transportation system (LTS) used LOX/LH_2 engines for both the lunar transfer vehicle (LTV) and the single stage lunar descent/ascent vehicle (LDAV). The LTV core stage utilized two sets of propellant drop tanks—the first jettisoned after trans-lunar injection (TLI) and the second after lunar orbit insertion (LOI). The LDAV was expended in lunar orbit and the LTV utilized aeroassist for LEO capture (Ref. 5).

During this same time period, Glenn Research Center (GRC) re-introduced NTP as a viable LTS option and quantified its benefits for a variety of lunar mission applications (Ref. 8). With its high thrust and high specific impulse capability, NTP enabled a fully reusable LTS with both the NTR-powered LTV and the LDAV returned to LEO for refueling, refurbishment and reuse (Fig. 1(a)). For a comparable initial mass in low Earth orbit (IMLEO), the fully reusable NTP system had a "return payload" mass fraction of ~23 percent—twice that of the partially reusable aeroassisted chemical system. Another important consideration was the "g-loading" on the crew during Earth return. For the aeroassisted chemical LTS, the g-loading was ~5 to 7 g_E versus 0.5 to 0.7 g_E for the NTP system at the beginning and end of the Earth orbit capture (EOC) burn—an order of magnitude reduction (Ref. 8).

In NASA's First Lunar Outpost (FLO) study conducted in 1992, an expendable NTP TLI stage powered by three 25 klb_f "Pewee-class" engines (Fig. 1(b)) was compared against a chemical injection stage for sending a large (~96 t) integrated lander and ascent stage to the Moon (Ref. 9). The chemical injection stage had a total mass of ~155 t compared to ~105 t for the NTP system—a savings of ~50 t for this single TLI

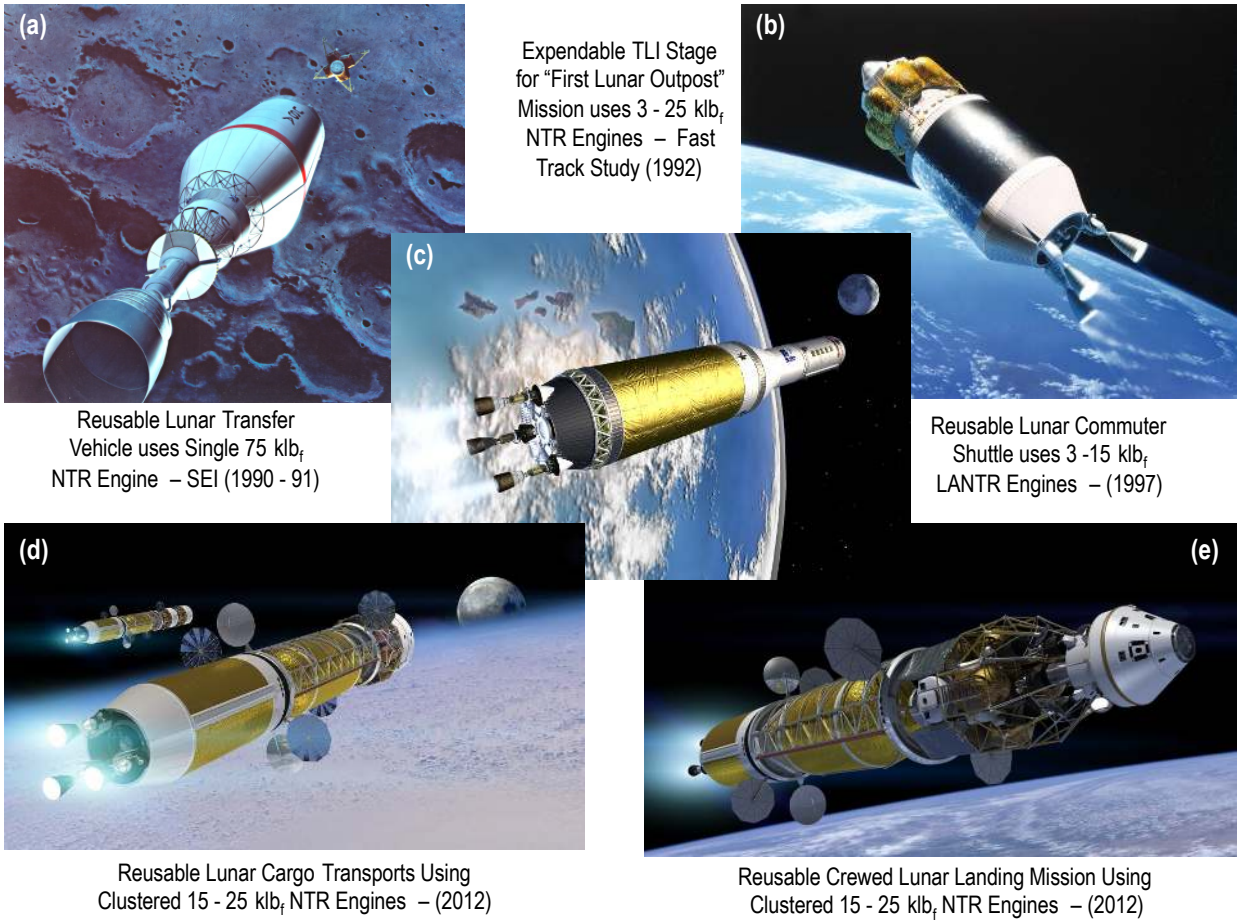

Figure 1.—Sampling of crewed and cargo lunar transfer vehicles designed by GRC over the past two decades show a transition away from single large to multiple smaller engines.

maneuver. The FLO study also marked the first use of smaller clustered NTR engines to help improve packaging and overall mission reliability.

Over the next 5 years, with its industry partner Aerojet, GRC quantified the operational characteristics and performance potential of an enhanced NTR—known as the LOX-Augmented NTR (LANTR)—in an evolutionary LTS architecture (Ref. 10). The LANTR concept adds an oxygen (O_2) "afterburner" nozzle and feed system to the basic NTR allowing O_2 injection and supersonic combustion in the engine's hot H_2 exhaust downstream of the nozzle throat. By controlling the O_2-to-H_2 mixture ratio, the LANTR engine can operate over a wide range of thrust and I_{sp} levels while its reactor core power level remains relatively constant. Also, by refueling in low lunar orbit (LLO) with LOX and LH_2 produced from lunar regolith (ilmenite or iron-rich volcanic glass) or polar ice deposits, a reusable bipropellant LANTR LTS can deliver significant payload on each round trip and ultimately enable a rapid "commuter" shuttle (Fig. 1(c)) capable of 24 hr "one-way" flights to and from the Moon (Ref. 11).

In 2004, NASA's Constellation program began and by 2005 the Exploration Systems Architecture Study (ESAS) had outlined the basic building blocks needed to land a four-person crew on the Moon by December 2019 (Ref. 12). ESAS examined four different lunar mission options with various size cargo HLVs. Included were: (1) a 2-Launch lunar orbit rendezvous (LOR); (2) a 2-Launch Earth orbit rendezvous (EOR)-LOR; (3) a 2-Launch EOR-Direct Return approach similar to NASA's earlier FLO study; and (4) a 1.5-Launch EOR-LOR option which NASA eventually selected for use in its Constellation program. The basic transportation elements are shown in Figure 2. A cargo HLV delivered a dual use upper stage, called the Earth departure stage (EDS), plus an expendable 2-stage LDAV called

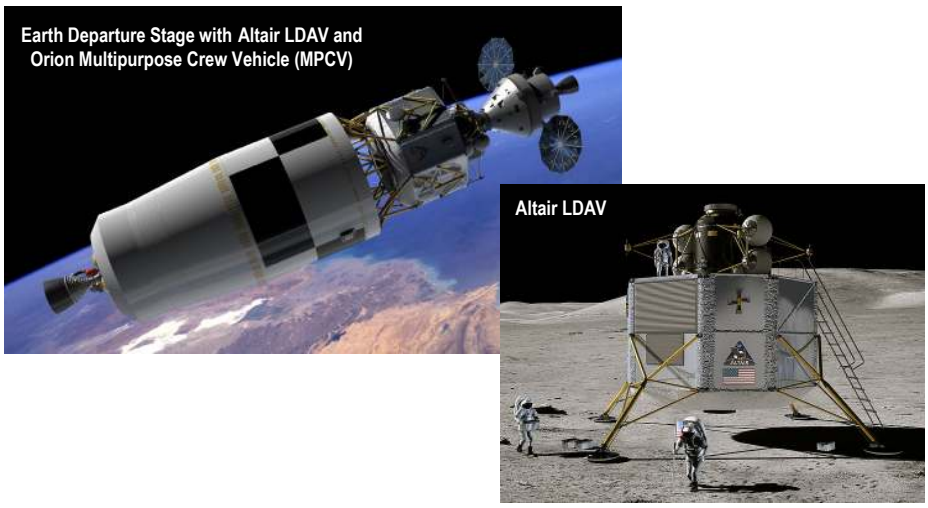

Figure 2.—Lunar Space Transportation System elements for the Constellation "1.5 launch" architecture.

Altair to LEO. A much smaller launch vehicle then delivered the Orion capsule, service module and crew to LEO for rendezvous and docking with Altair.

The EDS then performed the TLI burn to send the combined stack on its way to the Moon in much the same way as the Saturn V's S-IVB upper stage did during Apollo. However, compared to the Apollo Command and Service Module, the Orion's service module was less capable carrying only enough propellant to return itself and its crew to Earth. As a result the job of LOI for the combined Orion-Altair stack was assigned to Altair's LOX/LH_2 descent stage already tasked with landing on the lunar surface with a storable ascent stage and a crew of four—twice that carried by the Apollo lunar module (LM). As a result, the mass of Altair mushroomed to ~46 t—three times the mass of the LM. The design features of the Altair LDAV, expendable with a storable ascent stage, also seemed somewhat inconsistent with landing and locating an outpost near one of the Moon's poles where deposits of lunar polar ice have been detected and could be processed to supply LOX/LH_2 propellants for a reusable LDAV. Unfortunately, after a 5 year effort, the Constellation program was cancelled by the Obama administration in favor of pursuing technologies needed for a crewed mission to a near Earth asteroid (NEA) in the late 2020's followed by an orbital mission to Mars by the mid-2030's (Ref. 13).

Despite this apparent setback to lunar exploration, interest in the Moon continues. In its Global Exploration Roadmap (GER) (Ref. 14), the International Space Exploration Coordination Group, with participants from NASA and 13 other space agencies, identified two possible pathways for future human missions after ISS utilization. These pathways have been designated the *"Moon Next"* and *"Asteroid Next"* scenarios. Both approaches utilize a stepwise development and demonstration of capabilities that are required for the eventual human exploration of Mars.

The *"Moon Next"* pathway has a strong appeal to many who would like to see humans again walk on its surface and to whom the Apollo program has become a distant memory. Located just 3 days from Earth, the Moon is an entire world awaiting exploration, future settlement and potential commercialization. It is also an ideal location to test and demonstrate key technologies and systems (e.g., surface habitation, long-range pressurized rovers, surface power and resource extraction systems) that will allow people to explore, work, and live self-sufficiently on another planetary surface. Crewed NEA missions would follow and demonstrate the additional in-space capabilities needed to reach Mars such as advanced propulsion. Efficient propulsion and an affordable in-space transportation system with reuse capability will also be essential if initial lunar outposts are to evolve into eventual settlements capable of supporting commercial activities.

In FY'12, GRC quantified the benefits of using NTP for human missions to two candidate NEAs—2000 SG344 and Apophis (Refs. 15 and 16) using scaled-down versions of the "Copernicus" crewed Mars transfer vehicle (MTV) design developed during NASA's Mars DRA 5.0 study (Refs. 17 and 18). These smaller Asteroid Survey Vehicles (ASVs) had a lower IMLEO than their chemical and SEP-chemical counterparts and were also reusable. The same two key components used in the Copernicus MTV and the smaller ASVs—the "core" nuclear thermal propulsion stage (NTPS) and the integrated "saddle truss" and LH_2 propellant drop tank assembly connecting the NTPS to the payload element—were also configured for reusable lunar cargo delivery (Fig. 1(d)), and crewed lunar landing missions (Fig. 1(e)) (Ref. 16) as envisioned by von Braun.

Recently, industry has stepped up its efforts to develop and demonstrate technologies and systems that can support potential near term and future commercial space ventures. Examples include SpaceX, Sierra Nevada Corporation (SNC) and Boeing's involvement in commercial cargo and crew delivery to the ISS, development of inflatable space habitats by Bigelow Aerospace, as well as, plans for propellant depots by United Launch Alliance (ULA), asteroid mining by Planetary Resources Inc. and Deep Space Industries, even commercial human flights to the surface of the Moon by the Golden Spike Company. In addition to its significant Commercial Crew and Cargo Program (Ref. 19), NASA's Advanced Exploration Systems (AES) program will also test out inflatable space habitat technology aboard the ISS using the Bigelow Expandable Activity Module (BEAM) (Ref. 20) scheduled for launch in 2015.

NASA and Bigelow Aerospace have also partnered, under a Space Act Agreement signed in March, to study potential public-private collaborations in space (Ref. 21). Following discussions with 20 companies and international space agencies, Bigelow presented the first of two reports to NASA (Ref. 22) that focused on near-term opportunities in LEO, in lunar orbit and on the Moon, and indicated a significant private sector interest in lunar activities (Ref. 22). Even NASA's plans for a crewed mission to a NEA by 2025 are being reexamined in favor of a less ambitious mission that would capture a small asteroid and return it to E-ML2 (Ref. 23). The SLS and Orion MPCV would then launch and transport two astronauts there to collect samples and study the asteroid up close.

Over the past 4 years, NASA's Human Architecture Team has been pursuing a strategy, referred to as a Capability Driven Framework (CDF), which assumes the development and utilization of evolving technologies and systems to perform a series of ever more challenging missions first to a NEA, then the Moon and finally Mars. With flat or reduced budgets for NASA expected in the future, a CDF may be short-sighted and jeopardize the Agency's ability to orbit Mars by 2035 by diverting scarce resources away from proven technologies like NTP towards less capable systems that are large, operationally complex to use and unlikely to support fast transit missions to Mars.

This paper proposes a multi-prong approach to human exploration that involves collaboration between NASA and private industry and can support either the *"Moon Next"* or *"Asteroid Next"* pathways outlined in the GER. It assumes a "Technology Driven Framework" with NASA and other space agencies working together to develop the high-leverage technologies and systems needed for Mars (like a heavy lift version of SLS, NTP and reverse turbo-Brayton refrigeration for zero-boiloff LH_2 storage) albeit with scaled-down systems to start with. Also, by exploiting the technology synergies that exist between NASA's SLS (e.g., large aluminum/lithium (Al/Li) LH_2 tanks) and existing flight-tested chemical rocket hardware (e.g., LH_2 turbopumps, regenerative- and radiation-cooled nozzles and skirt extensions) substantial savings in the time and cost to develop a NTPS are to be expected.

Industry would develop, mature then provide the commercial services—including crew delivery, space habitats, propellant depots and lunar landers—necessary to sustain an affordable in-space transportation system. Forty years after Apollo 17, as we look to the future, NASA, industry and the country must consider the following pressing question: Can we afford to continue human space exploration while operating systems in a throwaway mode? With a reusable "workhorse" NTPS, valuable in-space assets can be returned to Earth orbit for refurbishment and reuse, thereby reducing the cost of space travel not only for NASA but for future private sector endeavors as well.

This paper examines the use of NTP for a variety of reusable lunar mission applications of potential interest to both NASA and industry. The missions include exploration lunar cargo delivery and crewed lunar landing missions to both equatorial and lunar polar orbits, a crewed survey mission to a small asteroid returned to E-ML2, and a week-long, round trip "lunar tourism" mission. Individual vehicle components are limited to 70 t and it is assumed that an "upgraded" SLS, with a capable upper stage, is available to deliver them to LEO. The paper covers the following topic areas. First, the operational principles and performance characteristics of the baseline ~16.7 klb_f SNRE used in this analysis are presented followed by a brief discussion of NASA's current NTP development activities funded under its AES program. Mission and transportation system ground rules and assumptions used in the analysis are then presented. The paper's focus then turns to a discussion of the candidate lunar missions and includes a description of various mission scenarios, key vehicle features and engine operational requirements. The paper ends with a summary of our findings and some concluding remarks.

2.0 NTR System Description, Performance Characteristics and Development Status

The NTR uses a compact fission reactor core containing 93 percent "enriched" Uranium (U)-235 fuel to generate 100's of megawatts of thermal power (MW_t) required to heat the LH_2 propellant to high exhaust temperatures for rocket thrust. In an "expander cycle" Rover/NERVA-type engine (Fig. 3), high pressure LH_2 flowing from either a single or twin turbopump assembly (TPA) is split into two paths with the first cooling the engine's nozzle, pressure vessel, neutron reflector, and control drums, and the second path cooling the engine's tie-tube assemblies. The flows are then merged and the heated H_2 gas is used to drive the turbine. The hydrogen turbine exhaust is then routed back into the reactor pressure vessel and through the internal radiation shield and core support structure before entering the coolant channels in the reactor core's fuel elements. Here it absorbs energy produced from the fission of U-235 atoms, is superheated to high exhaust temperatures (T_{ex} ~2550 to 2950 K depending on fuel type and uranium loading), then expanded out a high area ratio nozzle (ε ~300:1) for thrust generation.

Controlling the NTR during its various operational phases (startup, full thrust and shutdown) is accomplished by matching the TPA-supplied LH_2 flow to the reactor power level. Multiple control drums, located in the reflector region surrounding the reactor core, regulate the neutron population and reactor power level over the NTR's operational lifetime. The internal neutron and gamma radiation shield, located within the engine's pressure vessel, contains its own interior coolant channels. It is placed between the reactor core and key engine components to prevent excessive radiation heating and material damage.

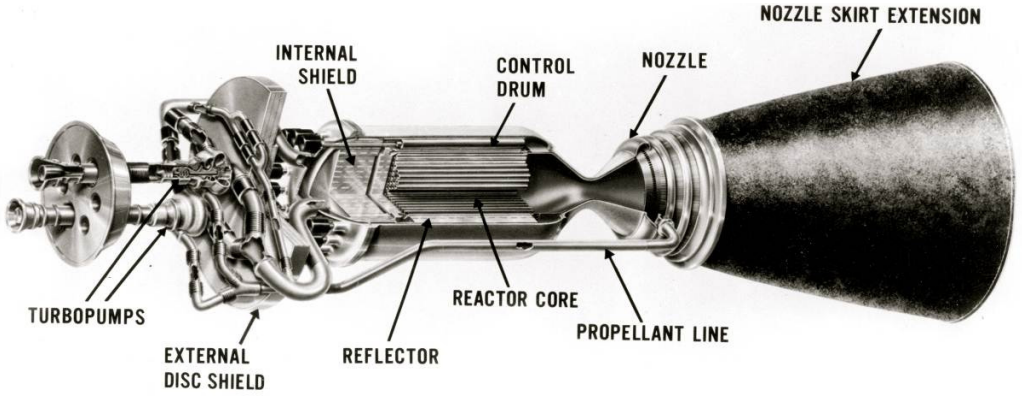

Figure 3.—Schematic of "expander cycle" NTR engine with dual LH_2 turbopumps.

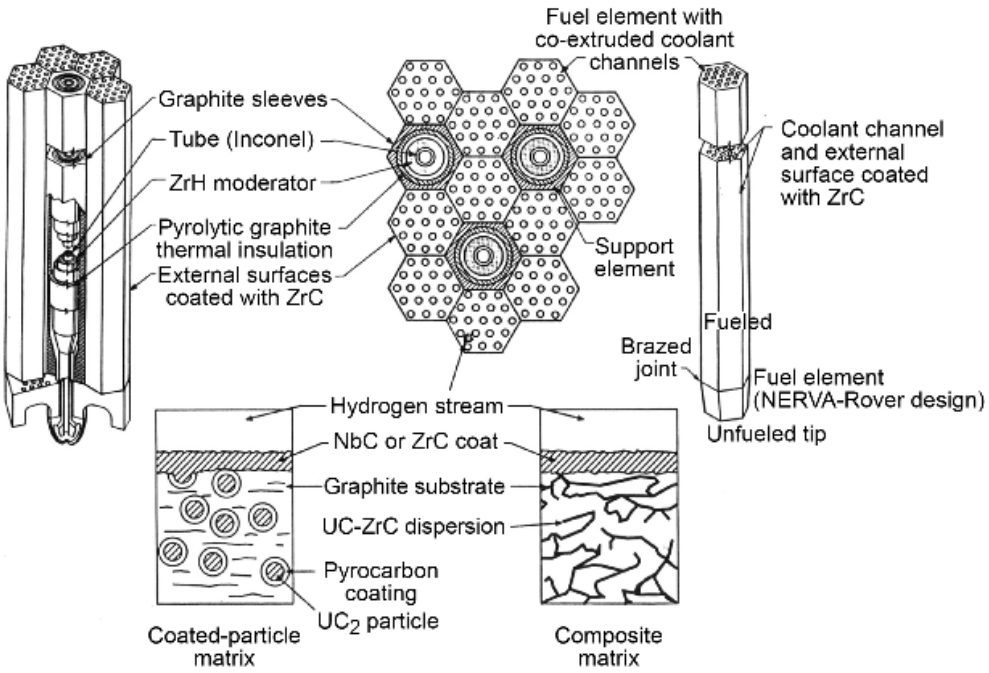

Figure 4.—Coated particle and composite SNRE fuel element and tie tube arrangement.

The fuel elements (FE) tested in the Rover/NERVA program (Ref. 24) consisted of a "graphite matrix" material that contained the U-235 fuel in the form of either coated particles of uranium carbide (UC_2) or as a dispersion of uranium and zirconium carbide (UC-ZrC) referred to as "composite" fuel. Each FE (see Fig. 4) had a hexagonal cross section (~0.75 in. across the flats) and 19 axial coolant channels that were coated with niobium carbide (NbC) initially, then with zirconium carbide (ZrC) using a chemical vapor deposition (CVD) process. This protective coating, applied to the exterior FE surfaces as well, helped reduce hydrogen erosion of the graphite. Individual elements were 52 in. in length and produced ~1 MW_t.

This basic FE shape was introduced in the KIWI-B4E reactor and became the standard used in the 75 klb_f Phoebus-1B, 250 klb_f Phoebus-2A, 25 klb_f Pewee and the 55 klb_f NERVA NRX series of engines (Ref. 24). Also included in the engine's reactor core were cooled coaxial tie tube (TT) elements that provided structural support for the FEs, as well as a source of energy for turbine drive power. The TTs also included a sleeve of zirconium hydride (ZrH) moderator material to help raise neutron reactivity (shown in Fig. 4). In the larger size engines tested in Rover/NERVA, a "sparse" FE—TT arrangement was used with each FE having two adjacent TTs and four adjacent FEs comprising its six surrounding elements (Ref. 25). In this sparse pattern, the FE to TT ratio is ~3 to 1.

A Small Nuclear Rocket Engine (SNRE) design producing ~16.4 klb_f of thrust was analyzed by Los Alamos National Laboratory near the end of the Rover/NERVA program (Ref. 26). The FE had the same hexagonal cross section and coolant channel number, but was 35 in. long, used composite fuel, and produced ~0.65 MW_t. To help increase core reactivity, the "SNRE" FE—TT pattern increases the number of TTs with each FE having three adjacent TTs and three adjacent FEs that surround it (shown in Fig. 4). With the SNRE pattern, the FE to TT ratio is ~2 to 1. An important feature common to both the sparse and SNRE FE—TT patterns is that each tie tube is surrounded by and provides mechanical support for six fuel elements. Also, the same hexagonal cross-section for the FE and TT elements can be maintained across a range of different thrust levels although shorter length elements are likely for lower thrust engines. Additional analysis by Schnitzler (Refs. 25, 27, and 28) has shown that the SNRE design can be scaled down to even smaller thrust levels (~7.5 klb_f) or up to the 25 klb_f Pewee-class engine used in Mars DRA 5.0.

The rationale for considering the NTR for lunar missions is simple—it is a proven, high thrust (10's of klb_f) propulsion technology with a specific impulse that is 100 percent higher than today's best chemical rockets. During the Rover/NERVA programs (1955 to 1972), a technology readiness level (TRL ~5 to 6) was achieved (Ref. 24). Twenty rocket reactors were designed, built and ground tested in integrated reactor/engine tests that demonstrated: (1) a wide range of thrust levels (~25, 50, 75, and 250 klb_f); (2) high temperature carbide-based nuclear fuels that provided hydrogen exhaust temperatures up to 2550 K (*achieved in the Pewee engine*); (3) sustained engine operation (*over 62 min for a single burn on the NRX-A6*); as well as; (4) accumulated lifetime at full-power; and (5) restart capability (*>2 hr with 28 startup and shutdown cycles on the NRX-XE experimental engine*)—all the requirements needed for a viable lunar space transportation system, also for human NEA and Mars exploration missions. Lastly, it is important to note that NTP requires no large scale-ups in size or performance that are needed with other non-chemical propulsion options. In fact, the smallest and highest performance engine tested during the Rover/NERVA programs—the 25 klb_f "Pewee" engine (Ref. 24) is sufficient for a human mission to Mars when used in a clustered engine arrangement. Even smaller, lower thrust engines are sufficient for lunar mission applications.

The NTR engine baselined in this paper is an ~16.675 klb_f "SNRE-class" expander cycle engine with the following performance parameters: T_{ex} ~2726 K, chamber pressure ~450 psia, ε ~300:1, and I_{sp}~900 s. The LH_2 flow rate is ~8.40 kg/s and the engine thrust-to-weight ratio is ~3.06. The overall engine length is ~6.1 m including the radiation-cooled nozzle skirt extension, and the nozzle exit diameter is ~2.31 m. The engine's reactor core contains 564 FEs and 241 TTs each ~0.89 m (35 in.) long. The core power level and fuel matrix power density are ~367 and ~3.44 MW_t/liter, respectively. The U-235 fuel loading is ~0.60 g/cm^3 and the inventory of 93 percent enriched U-235 in the core is just under 60 kg.

High temperature ZrC-coated UC-ZrC in graphite "composite" fuel was selected as the primary fuel form in this analysis. Composite FEs were first tested in the "Nuclear Furnace" element test reactor (Ref. 24) and withstood peak power densities of ~4500 to 5000 MW_t/m^3. They also demonstrated better corrosion resistance than the standard coated particle graphite matrix fuel element used in the previous Rover/NERVA reactor tests. Composite fuel's improved corrosion resistance is attributed to its higher coefficient of thermal expansion that more closely matches that of the protective ZrC coating, thereby helping to reduce coating cracking.

Electrical-heated composite fuel elements were also tested by Westinghouse in hot hydrogen at 2700 K for ~600 min—equivalent to ten 1-hr cycles. At the end of Rover/NERVA, composite fuel performance projections (Ref. 29) were estimated at ~2 to 6 hr at full power for hydrogen exhaust temperatures of ~2500 to 2800 K and fuel loadings in the range of ~0.60 to 0.45 g/cm^3. A ceramic-metal or "cermet" fuel consisting of uranium dioxide (UO_2) in a tungsten (W) metal matrix was developed in the General Electric (GE)-710 and Argonne National Laboratory (ANL) nuclear rocket programs (Refs. 30 and 31) as a backup to the Rover/NERVA fuel. While no integrated reactor/engine tests were conducted, a large number of fuel specimens were produced and exposed to non-nuclear hot H_2 and irradiation testing with promising results. Both fuel options are currently under development.

A NTP technology development effort was started by NASA in FY'11 under the Advanced In-Space Propulsion (AISP) component of its Exploration Technology Development and Demonstration (ETDD) program. The effort included two key tracks: "Foundational Technology Development" followed by "Technology Demonstration" projects. The Foundational Technology Development component continues today under NASA's AES program and the Nuclear Cryogenic Propulsion Stage (NCPS) project (Ref. 32) which began in FY'12. This 3-year project is a collaboration between NASA and DOE and includes five key tasks and objectives:

Task 1. Mission Analysis, Engine/Stage System Characterization and Requirements Definition is aimed at establishing performance goals for fuel development, testing and concept designs for both small, scalable demonstration engines and higher thrust-class engines needed for future human Moon, NEA and Mars missions;

Task 2. NTP Fuel Development and Assessment is focused on recapturing fabrication techniques, testing and maturing fuel, coating and cladding materials, then selecting between the two primary fuel forms previously identified by the DOE and NASA—NERVA composite and UO_2 in tungsten cermet fuel (Ref. 33). Partial, then full-length fuel elements, based on "heritage" designs, will be fabricated and tested in the NTR Element Environmental Simulator (NTREES) (Ref. 34) at the MSFC using up to ~1.2 MW of RF heating to simulate the NTP thermal environment including exposure to hot H_2. Fuel element performance at required temperature, duration, and with cycling to mimic engine restart, will be evaluated before final fuel selections are made and irradiation testing begins;

Task 3. Engine Design, Analysis and Modeling is aimed at developing conceptual designs for small (~7.5 klb_f) demonstration engines and higher thrust-class (~25 klb_f) engines utilizing the candidate fuels discussed above. State-of-the-art numerical models are being used to determine reactor core criticality, detailed energy deposition and control rod worth within the reactor subsystem (Refs. 25, 27, and 35), provide thermal, fluid and stress analysis of reactor fuel elements and core components (Refs. 36 and 37), and predict engine operating characteristics and overall mass (Refs. 38 and 39);

Task 4. Demonstration of Affordable Ground Testing is focused on maturing equipment requirements and cost estimates for a "proof-of-concept" validation test of the Subsurface Active Filtration of Exhaust (SAFE) (Refs. 40 and 41) concept (also known as the "bore-hole" option) at the Nevada Test Site (NTS). Non-nuclear, subscale hot gas injection tests, some with a radioactive tracer gas, would be conducted in a vertical bore-hole to obtain test data on the effectiveness of the porous rock (alluvium) to capture, holdup and filter the engine exhaust. The data would also help calibrate design codes needed by DOE to design the SAFE test facility and support infrastructure needed for the small engine ground technology demonstration tests and larger thrust class engine tests to follow; and

Task 5. Formulation of an Affordable and Sustainable NTP Development Strategy is aimed at outlining the content of an affordable development plan that utilizes separate effects tests (e.g., NTREES and irradiation tests), existing assets and innovative SAFE testing at the NTS, and small scalable engines for ground and flight technology demonstrations. The above tasks, successfully carried out by the end of FY'14, would provide the basis for a NCPS *Phase II* effort that could culminate with ground technology demonstration tests at the NTS in the early 2020's, followed by a flight technology demonstration mission in 2025 (Ref. 42).

3.0 Mission, Payload and Transportation System Ground Rules and Assumptions

Specific mission and payload ground rules and assumptions used in this paper are summarized in Table 1. It provides information about the different lunar mission scenarios, and the assumed parking orbits at Earth, the Moon and at the Earth-Moon L_2 Lagrange point. Specific trajectory details and ΔV budgets are provided within the appropriate sections of the paper. In addition to the large ΔV requirements for the primary propulsion maneuvers, like trans-lunar injection (TLI), smaller ΔV maneuvers are needed for rendezvous and docking (R&D) of vehicle components during the LEO assembly phase, vehicle mid-course correction (MCC) maneuvers, and for spacecraft attitude control during in-space transit.

Cargo delivery and crewed lunar landing missions are considered first in this paper. On cargo flights, an integrated habitat lander with surface mobility (shown in Fig. 5(a)) is delivered to lunar orbit by a reusable NTR transport in a manner reminiscent of von Braun's reusable lunar NTR shuttle. On the crewed landing missions, a forward mounted saddle truss connects the payload elements to the transfer vehicle's in-line tank. The truss is open on its underside and its forward adaptor ring provides a docking interface between the Orion MPCV and a single stage LOX/LH_2 LDAV (shown in Fig. 5(b)). The LDAV is a "heritage" design (Ref. 7) analyzed in considerable detail during SEI. It carries a crew of four plus 5 t of surface payload stored in two "swing-down" containers mounted on each side of the crew cab. The LDAV mass breakdown with propellant loadings for a range of landed payload is shown in Table 1.

TABLE 1.—MISSION AND PAYLOAD GROUND RULES AND ASSUMPTIONS

Mission Options / Profiles: • Cargo delivery (Round trip time: 7 days with 1 day in lunar orbit) • Crewed lunar landing (Round trip time: 3 day transits to and from the Moon with 3 – 14 days on surface) • Crewed survey of small asteroid at Earth-Moon L_2 Lagrange point (E-ML_2) (Round trip time: ~33 days) • Commercial orbital tourism (Round trip time: 7 days with 1 day in lunar orbit) • Reusable mission scenarios assume refueling and outfitting in Earth orbit before next mission • Envision IOC starting in mid-to-late 2020 timeframe	• Cargo transport delivers integrated Habitat lander to lunar orbit then returns to Earth orbit • Crewed landing mission has surface stay times up to 2 weeks or longer with pre-deployed Habitat landers; Reusable LTV carries MPCV and a lunar lander all returned to Earth orbit • Crewed asteroid survey vehicle carries TransHab and MMSEV all returned to Earth orbit • Fully reusable orbital tourism vehicle carries a passenger habitat module and "HL-20-type" lifting body all returned to Earth orbit • Orion capsule used for crew recovery at mission end • HL-20 lifting body returns passengers to KSC at mission end
Missions depart from low Earth orbit (LEO) and return to a 4-hr to 24-hr elliptical Earth orbit (EEO); capture and depart from either an equatorial low lunar orbit (LLO), lunar polar orbit (LPO) or E-ML_2	• LEO: 407 km circular • 4-hr EEO: 500 km x 12,330 km • 24-hr EEO: 500 km x 71,136 km • LLO: 300 km circular; LPO: 100 km circular (NERVA DRM) • E-ML_2: Located ~60,000 km beyond the lunar far side
Lunar Mission ΔV Budgets:	• ΔV budgets & other mission details provided in appropriate sections
Additional ΔV Requirements: Advanced Material Bipropellant Rocket (AMBR) RCS thrusters used to perform non-primary propulsion maneuvers	• LEO R&D between orbital elements: ~50 m/s • Coast attitude control and mid – course correction: ~15 m/s and ~20 m/s, respectively • Lunar orbit maintenance plus R&D: ~20 m/s
Cargo / Crewed Landing Mission Payload Masses: Reusable cargo transports deliver Habitat landers to LLO; on crewed landing missions, reusable NTR LTV delivers Orion / MPCV and single stage LOX LH_2 Lunar Descent / Ascent Vehicle (LDAV) to LLO; LDAV carries 4 crew and up to 5 t of payload to lunar surface; LTV with Orion / MPCV, LDAV and surface samples returned to a 24-hr EEO	• Habitat lander: 67.4 t • LDAV crew cab: 2.5 t • Crew (4) & EVA suits: 0.8 t • LDAV dry mass: 6.1 t • LDAV propellant load: 18.6 t – 20.9 t • LDAV surface payload: 1.25 t – 5.0 t • Orion / MPCV: 13.5 t • Returned Samples: 0.1 t
E-ML_2 Asteroid Sampling & Orbital Tourism Payload Masses: Varies with crew size and mission duration; consumables based on a consumption rate of ~2.45 kg/person/day; payload elements include a Habitat module, and either an Orion/MPCV or 7-passenger HL-20; for asteroid mission a short saddle truss (SST) & transfer tunnel (TT) connect a "2-person" MMSEV (used for sample collection) to the Habitat module	• Habitat Module: 18.4 t – 31.6 t (minus consumables) • SST / TT: 2.89 t / 0.6 t • Crew (4 – 7): 0.8 t – 1.4 t • Total Consumables: 0.12 t – 0.32 t • MMSEV: 6.7 t • Orion / MPCV: 13.5 t • HL-20 Re-entry vehicle: 11.657 t • Returned Samples: 0.1 t (from small asteroid)

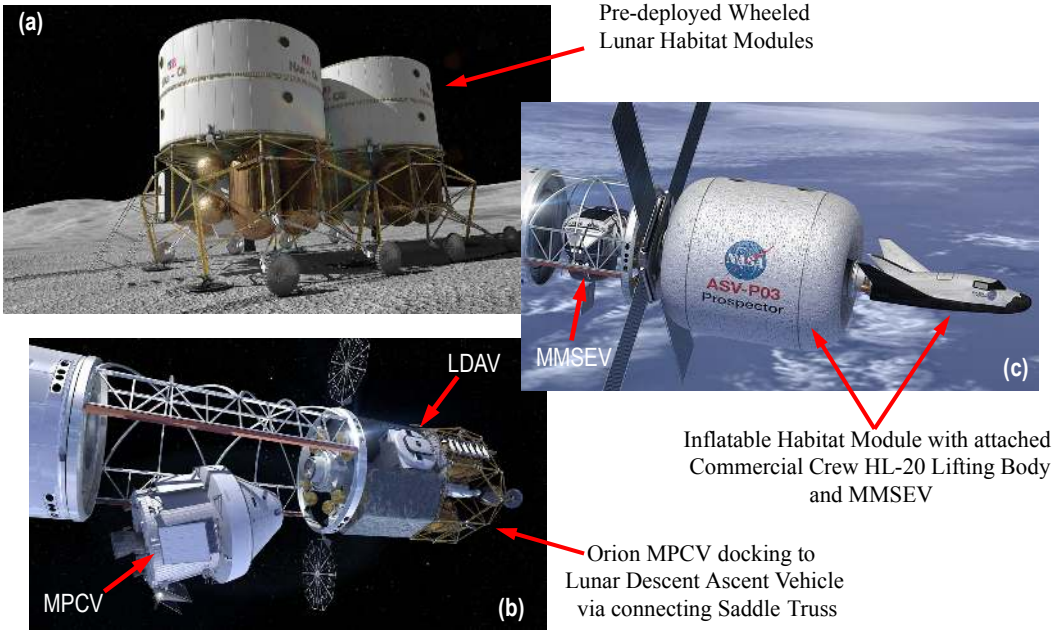

Figure 5.—Payload elements carried by NTP cargo and crewed lunar transfer vehicles.

For crewed science missions to small NEA(s) delivered to E-ML_2, or commercial orbital tourist flights around the Moon, an inflatable habitation module, like TransHab or Bigelow Aerospace's BA-330 module, can be carried to accommodate larger crew/passenger sizes along with the extra life support, consumables and accommodations needed to sustain them. A seven-passenger "mini-Shuttle" based on NASA's HL-20 lifting body concept is another option for commercial crew delivery that is being developed by Sierra Nevada Corporation (Ref. 43). A small auxiliary multi-mission space excursion vehicle (MMSEV) can also be carried on NEA science missions. The MMSEV provides a livable volume for a crew of two for up to two weeks (Ref. 44) and would be attached to the back end of the TransHab module. The above elements are shown in Figure 5(c). The MMSEV provides ~200 to 300 m/s of translational ΔV, suitports for EVA sorties, and remote manipulation capability for sample collection. For the lunar landing and small NEA science missions analyzed here, it is assumed that the crews collect and return ~100 kg of samples.

Table 2 lists the key ground rules and assumptions used in the NTP lunar transportation system consisting of the core NTPS plus an in-line LH_2 propellant tank (shown in Fig. 6). The NTPS uses a three-engine cluster of ~16.7 klb_f SNRE-class engines discussed previously in Section 2.0. The engines use composite fuel with a U-235 fuel loading of 0.6 g/cm^3. With a hydrogen exhaust temperature (T_{ex}) of ~2726 K, chamber pressure of ~450 psia, and a nozzle area expansion ratio of ~300:1, the I_{sp} is ~900 s. The total mission LH_2 propellant loading consists of the usable propellant plus performance reserve, post-burn engine cooldown, and tank-trapped residuals. For the smaller auxiliary maneuvers, a storable bipropellant RCS system is used. All transfer vehicle configurations utilize a split RCS with approximately half the AMBR thrusters and bipropellant mass located on the rear NTPS and the other half located at the front end of the in-line tank or saddle truss adaptor section just behind the mission-specific payload.

TABLE 2.—NTR TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

NTR System Characteristics	• Engine / Fuel Type: NERVA-derived / UC-ZrC "Composite" • Propellant: LH_2 • Thrust Level: 16.675 klb_f "SNRE-class" engine is baseline (3 engine cluster on "Core" NTPS) • Fuel Element Length: 0.89 m (SNRE baseline) • Exhaust Temp: T_{ex} ~2726 K (with 2860 K peak temperature) • Chamber Pressure: p_{ch} ~450 psi • Nozzle Area Ratio: ε~300:1 • I_{sp} Range: 900 s (based on 0.6 g/cm^3 U-235 loading)
Propellant Margins	• Cooldown: 3% of usable LH2 propellant • Performance reserve: 1% on ΔV • Tank trapped residuals: 2% of total tank capacity
Reaction Control System (LEO R&D, Settling, Attitude Coast Control, and Mid-course Correction Burns)	• Propulsion Type: AMBR 200 lb_f thrusters • Propellant: NTO / N_2H_2 • Nominal I_{sp}: 335 seconds
LH_2 Cryogenic Tanks and Passive Thermal Protection System (TPS)	• Material: Aluminum-Lithium (Al/Li) • Tank OD: 7.6 m • Tank L: ~15.7 m ("core" propulsion stage) ~15.7 m – 18.7 m ("in-line" drop tank) • Geometry: cylindrical with root 2/2 ellipsoidal domes • Insulation: 1" SOFI (~0.78 kg/m^2) + 60 layers of MLI (~0.90 kg/m^2)
Active Cryo-Fluid Management / Zero Boil-Off (ZBO) LH_2 Propellant System	• Reverse turbo-Brayton ZBO cryocooler system powered by PVAs • ZBO system mass and power requirements driven by core stage size; ~760 kg and ~5.26 kW_e (7.6 m D)
Photovoltaic Array (PVA) Primary Power System	• Circular PVA sized for ~7 kW_e at 1 A.U, two arrays provide power for ZBO cryocoolers on core stage and in-line tank if needed, PVA mass is ~455 kg and array area is ~25 m^2 • "Keep-alive" power supplied by lithium-ion battery system
Dry Weight Contingency Factors	• 30% on NTR system and composite structures (e.g., saddle truss) • 15% on established propulsion, propellant tanks, spacecraft systems
SLS / SLS Upgrade Launch Requirements: – Usable Payload Delivered to LEO – Cylindrical Payload (PL) Envelope	• ~70 t to LEO (=407 km circular) • 7.6 m D x ~26.8 m L

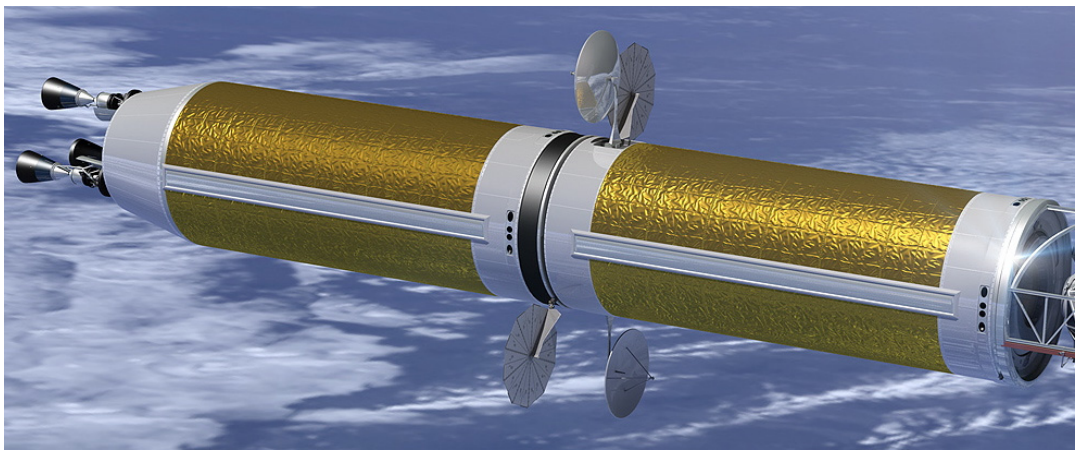

Figure 6.—Key NTP lunar transfer system elements—the NTPS and in-line LH_2 tank.

The LH_2 propellant carried in the NTPS and its in-line tank is stored in the same "state-of-the-art" Al/Li LH_2 propellant tank being developed for the SLS/HLV that will support future human exploration missions. For this analysis, tank sizing assumes a 30 psi ullage pressure, 5 g_E axial/2.5 g_E lateral launch loads, and a safety factor of 1.5. A 3 percent ullage factor is also assumed. All tanks use a combination foam/multilayer insulation (MLI) system for passive thermal protection. A zero boil-off (ZBO) "reverse turbo-Brayton" cryocooler system is used on the NTPS to eliminate boil-off during LEO assembly and over the course of the mission. It is not used on the in-line LH_2 tank since it is drained during the TLI maneuver. The propellant tank heat load is largest in LEO and sizes the ZBO cryocooler system. Solar photovoltaic arrays are baselined for supplying the primary electrical power needed for all key transfer vehicle subsystems.

Table 2 also provides the assumed "dry weight contingency" (DWC) factors, along with the requirements for delivered mass to LEO and the shroud cylindrical payload envelope for the upgraded SLS/HLV. A 30 percent DWC is used on the NTR system and advanced composite structures (e.g., stage adaptors, trusses) and 15 percent on heritage systems (e.g., Al/Li tanks, RCS, etc.). The NTPS determines the upgraded SLS lift capability (~70 t) and the usable PL volume within the shroud (~7.6 m OD and ~26.8 m in length). The combined saddle truss (~13.7 m) and LDAV (~9.6 m) with its attached cargo containers used on the crewed landing mission (Fig. 5(b)) has this same approximate length. For crewed NEA science missions to E-ML_2, the PL includes a "packaged" TransHab module with PVA power system, a short saddle truss and a MMSEV (Fig. 5(c)). The overall length of this element is ~22.8 m. Options for crew delivery include NASA's Orion MPCV, SpaceX's *Dragon* and Boeing's *CST-100* capsules, and Sierra Nevada Corporation's "*Dream Chaser*" lifting body. The commercial crew delivery systems would utilize man-rated versions of ULA's Atlas V or SpaceX's Falcon 9 launch vehicles.

4.0 NTP Space Transportation System for Lunar Cargo and Crewed Landing Missions

As discussed in the Introduction, NTP can play an important role in returning humans to the Moon by providing an affordable in-space lunar transportation system with reuse capability that could allow initial lunar outposts to evolve into eventual settlements capable of supporting commercial activities. Utilization of efficient NTP for lunar cargo delivery and crewed lunar landing missions is also consistent with the *"Asteroid Next"* pathway that includes human missions to the Moon to test out key surface systems (e.g., habitats, power systems, and long-range pressurized rovers) needed for an eventual human landing on Mars.

The NTPS is the "workhorse" element of the LTS. It uses a three-engine cluster of 16.675 klb_f composite fuel SNRE-class engines and also carries external radiation shield mass for crew protection. The NTPS uses an Al/Li LH_2 tank which has a diameter (D) and length (L) of 7.6 m D×15.7 m L. The tank's LH_2 propellant capacity is ~39.7 t. The NTPS also carries avionics, RCS, auxiliary battery and PVA power, docking and a reverse turbo-Brayton ZBO refrigeration systems located in the forward cylindrical adaptor section. To remove ~42 W of heat penetrating the 60 layer MLI system in LEO (where the highest tank heat flux occurs), the 2-stage cryocooler system requires ~5.3 kW_e for operation. Twin circular PVAs provide the electrical power needs for the NTPS.

The second major element is an "in-line" Al/Li propellant tank that connects the NTPS to the forward PL element. It has the same 7.6 m D and supplies the LH_2 propellant needed for the "2-perigee burn" TLI maneuver. Depending on the particular mission and the PL carried, the tank length can vary from ~15.7 m (same length as in the NTPS) to ~18.7 m and capable of holding ~49.0 t LH_2 propellant. The in-line tank element also includes forward and aft cylindrical adaptor sections that house quick connect/disconnect propellant feed lines, electrical connections, a RCS along with docking and payload adaptors. The total length of the in-line element varies from ~20.7 to 23.7 m.

For the reusable cargo delivery mission, three upgraded SLS launches are used to deliver the vehicle and payload elements. Here they are assembled via autonomous rendezvous and docking (AR&D). The NTP cargo transport then departs from LEO (C_3 ~ –1.678 km^2/s^2, ΔV_{TLI} ~3.214 km/s including a g-loss of ~117 m/s) and captures into a 300 km circular LLO (arrival V_{inf} ~1.151 km^2/s^2 and ΔV_{LOC} ~906 m/s including g-loss) approximately 72 hr later. Key phases of the cargo delivery mission are illustrated in Figure 7. Once in orbit, the habitat lander separates from the lunar NTR (LNTR) transport and descends to the surface, landing autonomously at a predetermined location on the Moon. It is assumed that the habitat landers use LOX/LH_2 chemical engines and are also equipped with either deployable wheels (shown in Fig. 5(a)) or articulated landing gear allowing movement in both the vertical and horizontal directions so that the landers can either "drive or walk" short distances from the landing site. Connecting several "functionally different" lander modules together (for habitation, science, equipment servicing) would form a large contiguous pressurized volume for the crew and also provide a "building block" approach to establishing an initial lunar base.

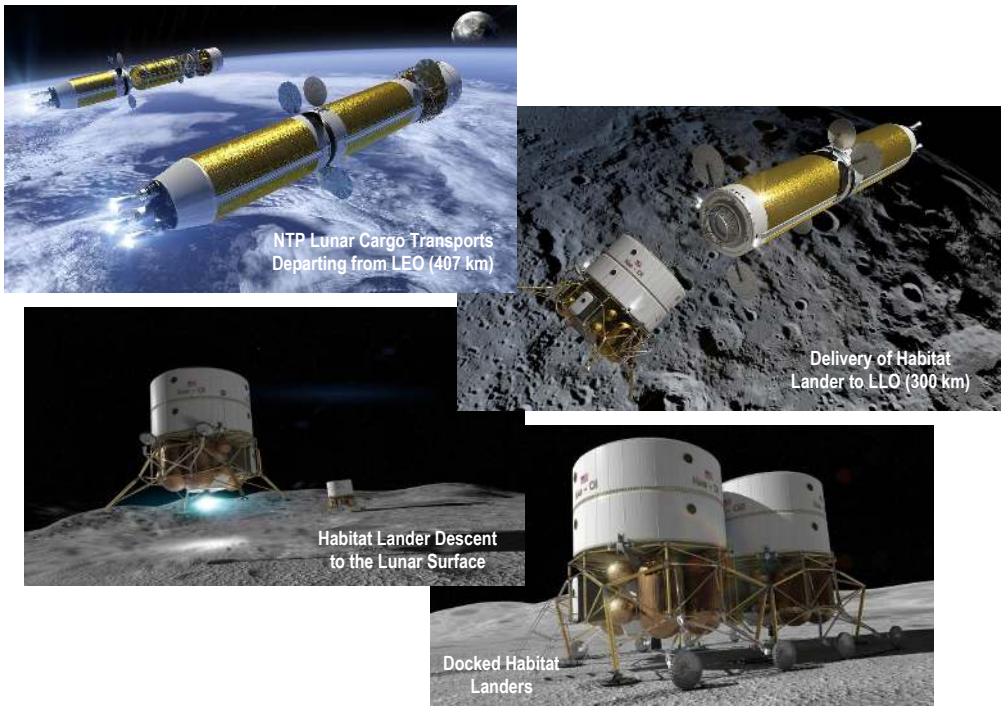

Figure 7.—Reusable NTP lunar cargo delivery mission phases.

After payload separation and a day in LLO, the LNTR cargo transport performs a trans-Earth injection (TEI) burn (C_3 ~ 0.945 km^2/s^2, ΔV_{TEI} ~857 m/s including g-loss) and returns to Earth 72 hr later. On final approach, it performs a braking burn (arrival V_{inf} ~ –1.755 km^2/s^2, and ΔV_{EOC} ~366 m/s) and captures into a 24-hr EEO. Post burn engine cool-down thrust is then used to assist in orbit lowering. An auxiliary tanker vehicle, operating from a LEO servicing node/propellant depot, supplies the additional LH_2 needed by the cargo transport for final orbit lowering and rendezvous with the LEO transportation node where it is refurbished and resupplied before its next mission.

The key phases of the crewed NTR landing mission are illustrated in Figure 8. Again, as with the cargo mission, three upgraded SLS launches are used to deliver the two NTR vehicle elements and the payload element—consisting of an integrating saddle truss assembly (STA) and a LDAV with its surface cargo containers—to a 407 km orbital altitude where they are assembled via AR&D. In addition to a front and rear docking capability, the STA's forward adaptor ring also carries twin PVAs and a RCS. Once assembled, the Orion MPCV and crew are launched and rendezvous with the LNTR vehicle positioning itself inside the STA and docking with the LDAV using a docking port and transfer tunnel mounted to the STA's forward adaptor ring (shown in Figs. 5(b) and (8)).

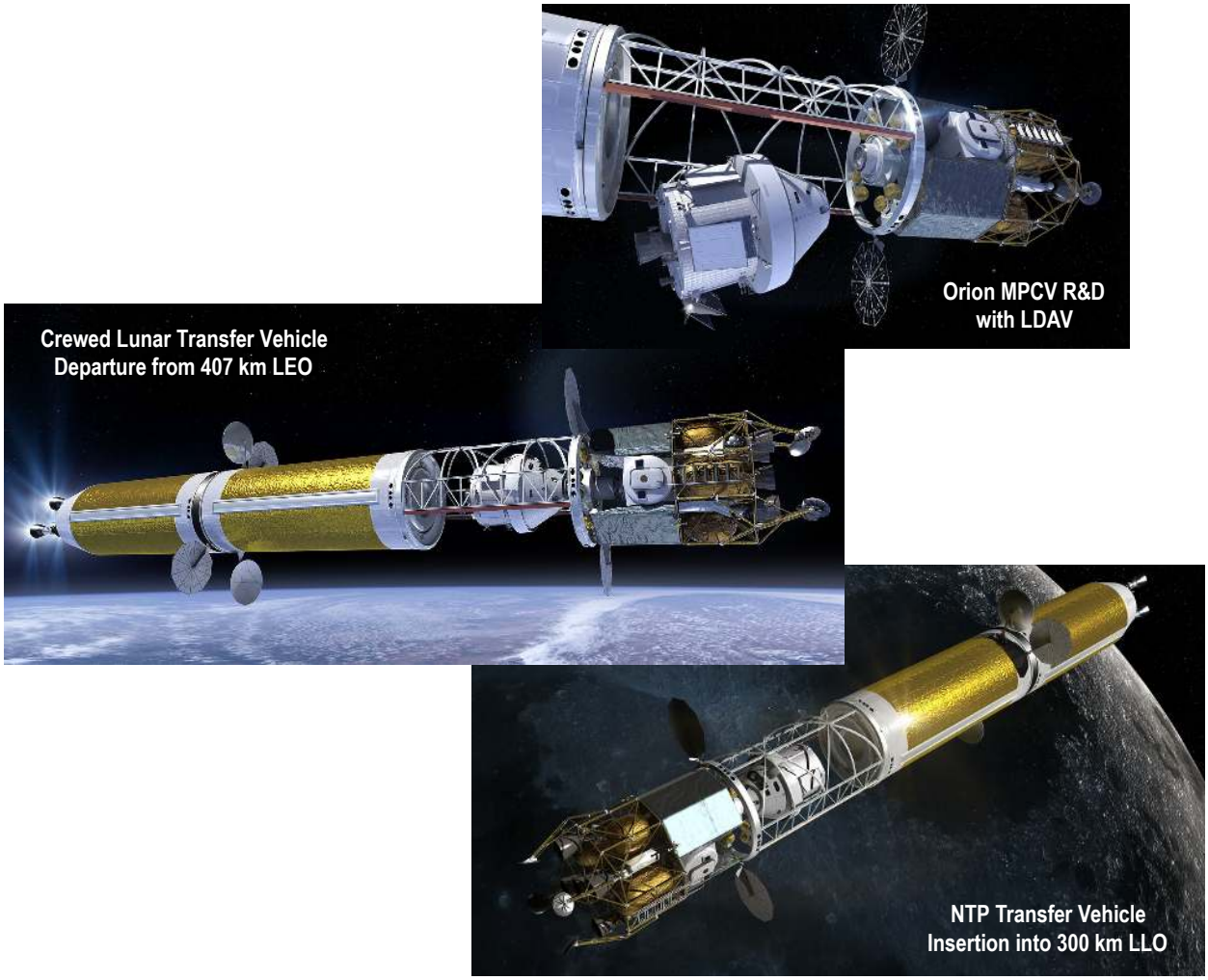

Figure 8.—Reusable NTP crewed lunar landing mission—outbound mission leg.

After the "2-perigee burn" TLI maneuver (C_3 ~ –1.516 km^2/s^2, ΔV_{TLI} ~3.214 km/s including a g-loss of ~110 m/s), the crew begins its 3-day coast to the Moon. Because the crewed LNTR transport carries a significant amount of payload mass (the STA, MPCV, and LDAV) back from the Moon, it uses a longer (~18.7 m) in-line tank to supply the required amount of LH_2 propellant needed for this reusable mission. After its 72-hr transit, the LNTR vehicle performs the LOC burn (arrival V_{inf} ~1.217 km^2/s^2 and ΔV_{LOC} ~913 m/s including g-loss) inserting itself and its payload into LLO.

Once in LLO, the crew then enters the LDAV, separates from the LNTR transport and prepares to land (shown in Fig. 9). The LDAV has a "wet" mass of ~35.3 t (Table 1) that includes the crew cab (~2.5 t), the descent/ascent stage (~6.1 t) and its LOX/LH_2 propellant (~20.9 t), surface payload (~5 t), plus the four crew and their suits (~0.8 t). After separating from the LNTR, the LDAV's two payload containers are rotated 180° and lowered into their landing position in preparation for descent to the lunar surface. The ΔV budget for the LDAV includes the following (Ref. 7): ΔV_{des} ~2.115 km/s and ΔV_{asc} ~1.985 km/s. The LDAV uses five RL 10A-4 engines that operate with a I_{sp} ~450 s consistent with the Martin Marietta design (Ref. 7). It expends ~13.4 t of LOX/LH_2 propellant during the descent to the surface (shown in Fig. 9). After lunar touchdown, the crew can operate out of the LDAV for ~3 to 14 days using its surface landed payload or longer (~180 days) using the pre-deployed habitat landers.

As the "exploration and surface systems testing" phase of the mission nears its completion, the crew prepares the LDAV for departure. At liftoff, the LDAV mass is ~15.1 and ~5.5 t of propellant is used during the ascent to LLO. The LDAV, with 100 kg of lunar samples, then rendezvous with the LNTR vehicle and preparations for the TEI maneuver begin. After completing the departure burn (C_3 ~ 0.949 km^2/s^2, ΔV_{TEI} ~856 m/s with g-loss), the crew spends the next 3 days in transit readying the LNTR for the final phase of the mission—capture into a 24-hr EEO with the MPCV and LDAV payload (depicted in Fig. 9) followed by MPCV separation and capsule re-entry of the crew.

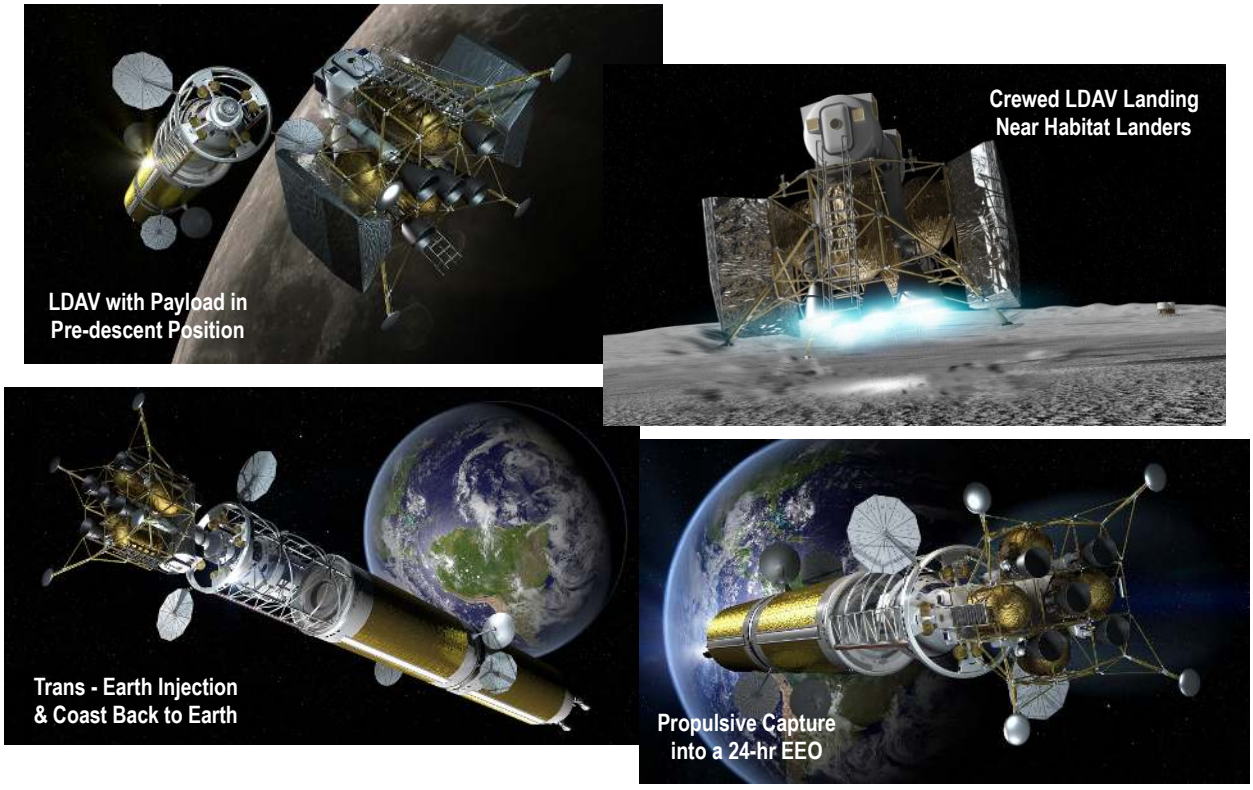

Figure 9.—Reusable NTP crewed lunar landing mission—landing and return mission leg.

4.1 Features and Characteristics of LNTR Cargo Delivery and Crewed Landing Vehicles

The key features, component lengths, and launch mass requirements for the lunar cargo and crewed landing missions are shown in Figure 10. Also shown is a reusable Asteroid Survey Vehicle (ASV) for a crewed mission to NEA 2000 SG344 in 2028 (Ref. 16) for comparison. The ASV uses the same NTPS used for the various lunar transfer vehicles discussed in this paper. It has an IMLEO of ~179.6 t that includes the NTPS (~69.5 t), a saddle truss and drop tank assembly (~54.8 t) and the crew PL section (~55.3 t). The overall vehicle length is ~78.3 m including the 8.9 m long Orion MPCV. The LH_2 tank lengths for the NTPS and the drop tank are identical at ~15.7 m with each tank carrying ~38.9 t of LH_2 propellant (~98 percent of tank's maximum capacity of ~39.7 t). Using the saddle truss/drop tank assembly has advantages for higher ΔV NEA and Mars missions because it allows the drained LH_2 drop tank to be jettisoned after the Earth departure burn thereby reducing propellant consumption on subsequent mission maneuvers. Though made of composite material, the saddle truss still has considerable mass that must be injected from LEO along with the drop tank. For the fully reusable lunar missions considered here, use of an in-line tank is the preferred approach allowing a higher delivered payload for a lower total launch mass.

The LNTR cargo transport shown in Figures 7 and 10 has an IMLEO of ~186.7 t consisting of the NTPS (~70 t), the in-line tank element (~52.6 t), and the habitat lander (~61.1 t) with its connecting structure (~3.0 t). The overall vehicle length is ~60.4 m. Like the ASV, the cargo transport also uses ~15.7 m long tanks in the NTPS and in-line element with each tank carrying ~39.7 t of LH_2 propellant. By focusing on smaller size engines and maximizing the use of common hardware elements (e.g., same size NTPS, propellant tanks) for a variety of mission applications it should be possible to reduce vehicle development and recurring costs while also improving overall affordability.

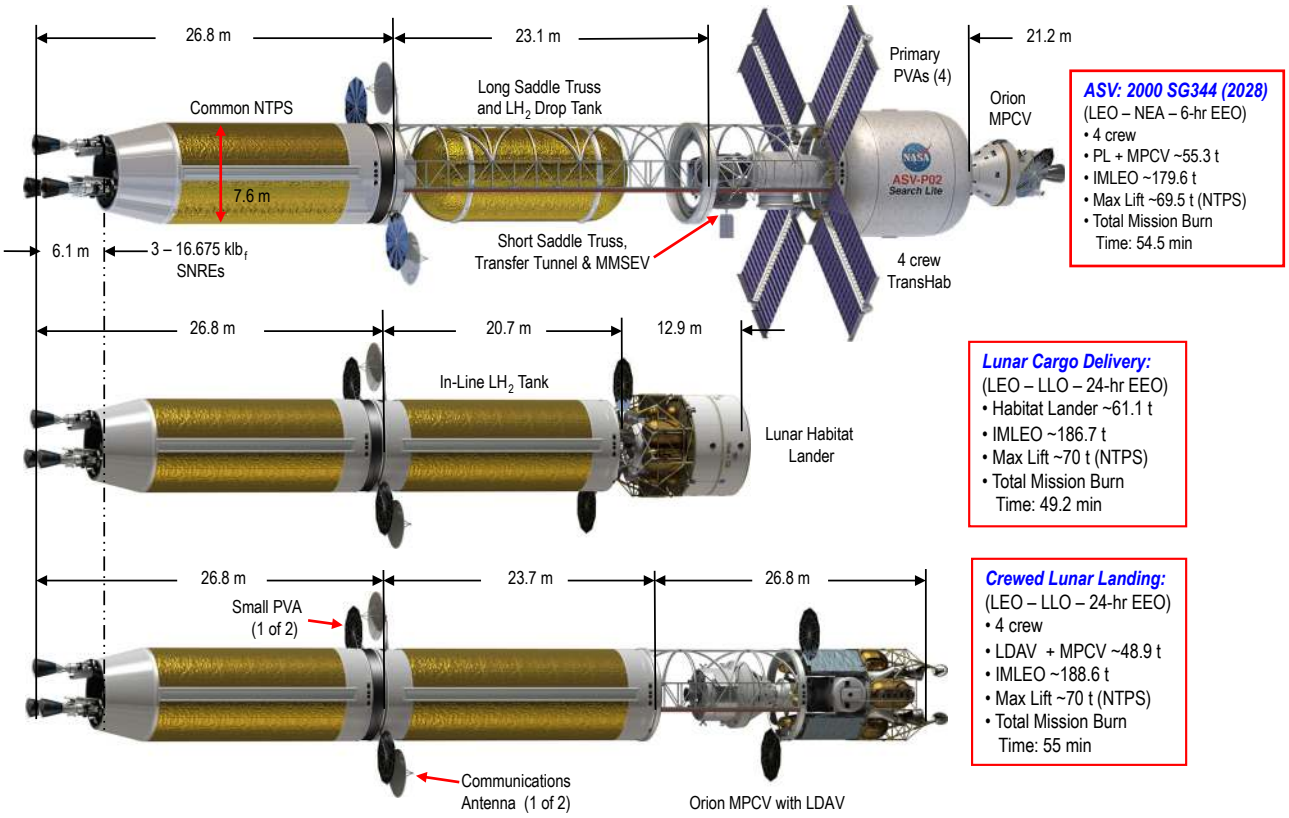

Figure 10.—Reusable NTP vehicles for NEA, lunar cargo and crewed landing missions.

For the reusable cargo delivery mission, the five primary engine burns use ~74.5 t of LH_2 propellant. With 50 klb_f of total thrust and I_{sp} ~900 s, the total engine burn time is ~49.2 min. The first of the two TLI perigee burns is the longest at ~21.4 min. The duration of the remaining burns are as follows: second perigee burn (~15.5 min), LOC (~8.0 min), TEI (~3.1 min) and EEO capture (~1.2 min). These performance requirements are well below those demonstrated in the NERVA program that included a 62 min maximum single burn demonstrated by the NRX-A6, and ~2 hr of accumulated burn time with 27 restarts demonstrated by the NRX-XE (Ref. 24). Furthermore, given projected full power operational lifetimes of ~6 to 10 hr for NERVA-derived engines using composite fuel (Ref. 29), cargo transport vehicles with multi-mission capability appear viable.

The cargo transport's delivery capability to LPO has also been analyzed for a "8-burn" Earth-to-LPO round trip mission reminiscent of that considered previously in establishing the operational characteristics and requirements for the NERVA flight engine (Ref. 3). The cargo vehicle again uses a 2-perigee burn departure from LEO and after a 3-day transit captures initially into an elliptical lunar orbit with a perilune of ~100 km and apolune of ~27,700 km. Two subsequent burns provide the plane change and circularization maneuvers that put the cargo transport into a 100 km circular LPO. Following a similar departure sequence for TEI and a 3-day return to Earth, the cargo vehicle again captures into a 24-hr EEO. Despite the higher total ΔV requirements for LOC and TEI, the cargo transport still delivers ~51.2 t to LPO. The IMLEO is ~177.0 t and the total engine burn time is ~48.9 min.

The crewed lunar landing mission has an IMLEO of ~188.6 t that includes the NTPS (~70.0 t), the in-line tank assembly (~63.3 t), the STA (~6.4 t), the wet LDAV (~29.5 t) with its surface payload (~5 t), the Orion MPCV (~13.5 t), consumables (~0.1 t), and four crewmembers (~0.8 t includes lunar EVA suits). The overall vehicle length is ~77.3 m. For the crewed mission, the LH_2 propellant loads in the NTPS and in-line tank are at their maximum capacity of ~39.7 and ~49.0 t for their specified tank lengths of ~15.7 and ~18.7 m, respectively.

The crewed landing mission also requires five primary burns. With 50 klb_f of total thrust, I_{sp} ~900 s, and ~83.2 t of LH_2 propellant used during the mission, the total engine burn time is ~55 min, again well under the capabilities demonstrated in the NERVA program. The first perigee burn is the longest at ~20.9 min and the remaining maneuvers having the following burn durations: second perigee burn (~16.2 min), LOC (~8.2 min), TEI (~6.9 min), and EOC (~2.8 min).

5.0 Crewed NTP Science Mission to Small Asteroid Returned to E-ML2 Lagrange Point

As mentioned in the Introduction, NASA's plans for a crewed mission to a NEA in the 2025 to 2030 timeframe are being reexamined in favor of a less ambitious robotic mission that would use a xenon-fueled, 40 kW_e solar electric propulsion (SEP) system to capture a small (~7 m diameter and ~500 t) NEA and return it to the E-ML2 point (Ref. 23). The SLS and Orion MPCV would then launch and transport the crew there to collect samples and study the asteroid up close. A year earlier, in 2012, NASA considered proposing the establishment of a modest, crew-tended outpost at E-ML2, referred to as the "*Waypoint Station*". Orion crews would visit the outpost periodically conducting telerobotic science on the lunar far side, as well as radio astronomy and scientific observations of the Sun and Earth in the quiet zone behind the Moon. Returning a small asteroid to the E-ML2 point would provide an additional target of opportunity for future scientific and commercial activities in translunar space.

A reusable ASV using efficient NTP could function as a versatile "mobile research station" that can transport crew and support scientific activities at multiple locations including E-M Lagrange points, equatorial and lunar polar orbits, and select NEAs like 2000 SG344. The crewed "*Prospector*" ASV (shown below in Fig. 11) can support a month-long E-ML_2 small asteroid science mission as well as a reusable 327-day round trip mission to 2000 SG344 in 2028 carrying a crew of four. Operated in an expendable mode, the round trip time can be reduced to 178 days.

Use of the *Prospector* ASV for a small asteroid science mission at E-ML_2 is depicted in Figure 11. The ASV carries a crew of four and the mission duration is ~33 days which includes an ~9.8 day outbound transit, an ~5.8 day stay at E-ML_2, and an ~17.4 day inbound transit. Shorter round trip times of ~2 to 3 weeks are also possible. The ASV departs from LEO and captures into a 4-hr EEO at the end of the mission. The total mission ΔV is ~5.15 km/s and includes gravity losses plus lunar flyby impulsive burns performed during the outbound and return mission legs.

Rather than having tethered astronauts operating out of the close confines of the Orion capsule, the *Prospector* ASV carries an inflatable habitation module to accommodate larger crew sizes (possibly with combined NASA and industry personnel), along with the extra life support, consumables and scientific equipment needed to analyze retrieved samples on site. A 2-person MMSEV, attached to the rear of the habitation module (shown in Fig. 11), is also part of the payload allowing close-up inspection and sample gathering from the asteroid during the mission.

Like the cargo transport, *Prospector* (shown in Fig. 12) uses common ~15.7 m long tanks in both the NTPS and in-line element with each tank carrying ~39.7 t of LH_2 propellant. It has an IMLEO of ~170.8 t consisting of the NTPS (~68.3 t), the in-line tank element (~52.3 t), and the crewed payload (~50.2 t). The PL element includes the habitation module (~22.7 t), a short saddle truss with RCS and PVAs (~8.03 t), the MMSEV (~6.7 t), the *Far Side Voyager* lifting body (~11.65 t), the crew and their suits (~0.8 t) plus consumables (~0.32 t). The overall vehicle length is ~79.3 m which includes the ~9 m long *Far Side Voyager*.

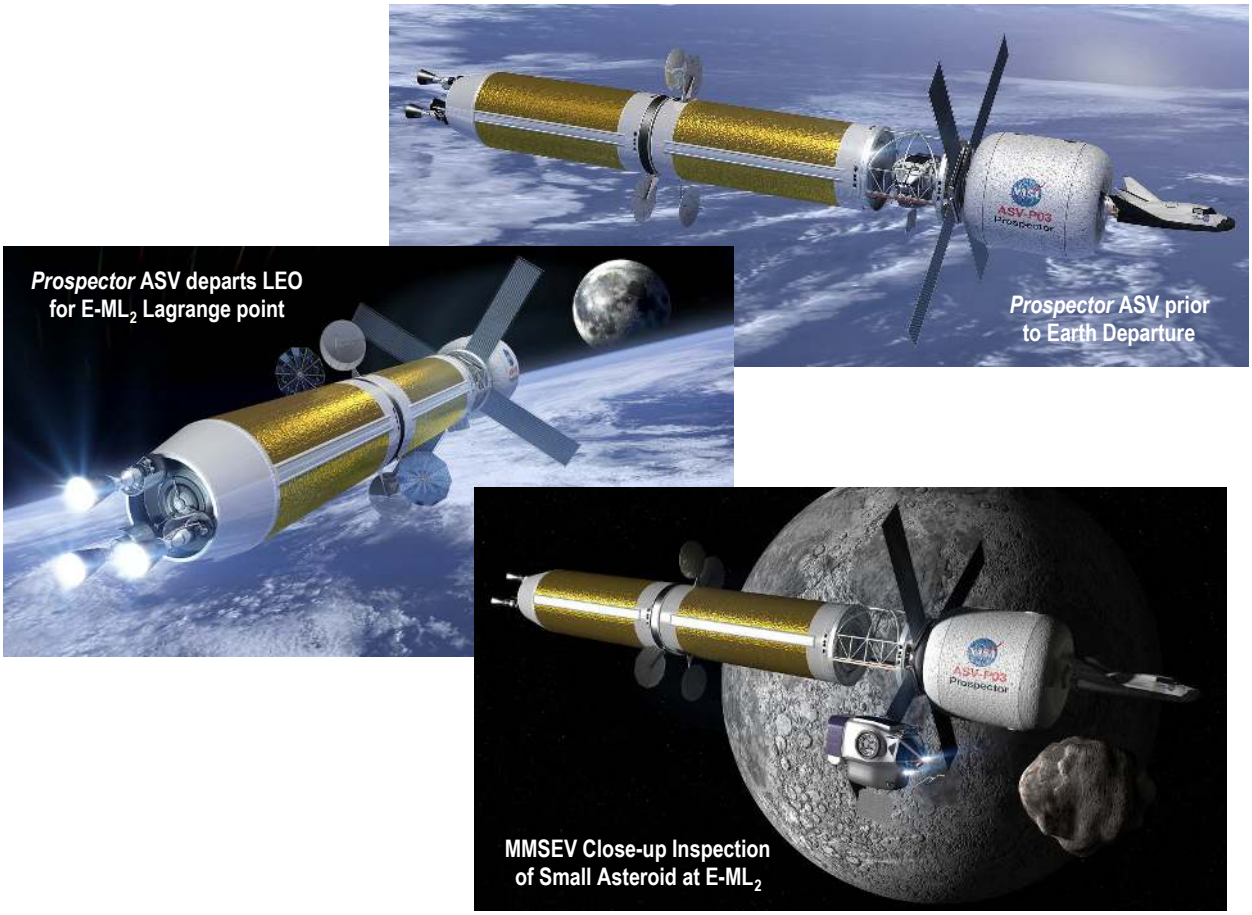

Figure 11.—Reusable NTP crewed science mission to small NEA at E-ML_2 Lagrange point.

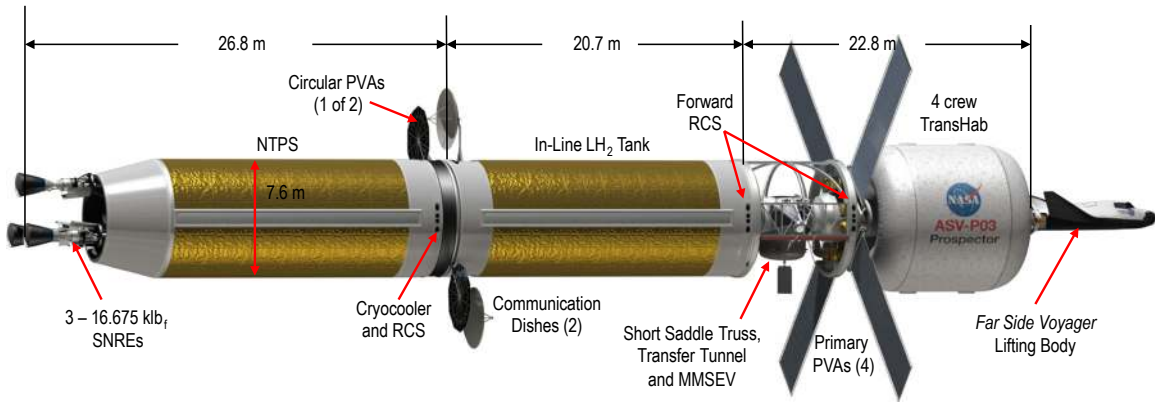

Figure 12.—Key ASV features and dimensions for crewed science mission to small NEA at E-ML_2.

The small asteroid science mission requires six primary burns and uses ~73 t of LH_2 propellant. With 50 klb_f of total thrust and I_{sp} ~900 s, the total engine burn time is ~48.3 min. The first perigee burn is the longest at ~19.8 min. The remaining maneuvers having the following burn durations: second perigee burn (~14.4 min), outbound lunar flyby burn (~1.4 min), L_2 insertion/departure burns (~0.4 min), inbound lunar flyby burn (~1.6 min), and EOC (~10.7 min).

6.0 Commercial Orbital "Tourism" Missions to the Moon Using NTP

The lunar missions discussed above are expected to be of interest primarily to NASA although there could be participation with industry in cargo delivery and possible small asteroid science missions to E-ML_2 in the future. Within a decade, it is conceivable that an orbital "lunar tourism" industry could develop providing a commercial opportunity for an industry consortium to operate. Interest in private spaceflight does exist, albeit only for the wealthy at present. Virgin Galactic (Ref. 45) has reportedly booked over 625 paying passengers (at $200,000 per person including a $20,000 deposit) for suborbital flights on its new *SpaceShip 2* spacecraft. Each flight is expected to carry six passengers and two pilots, last ~2.5 hr and provide ~6 min of weightlessness. Bigelow Aerospace (Refs. 46 and 47) is planning on launching and operating its "*Alpha Station*" in LEO for a wide range of commercial activities and with stay times lasting anywhere from 10 to 60 days. Single, per seat rates will be either $26.25 or $36.75 million depending on the transportation provider selected by the client. With these activities progressing forward, how long will it be before tourists in LEO point to the Moon and say, "I'd like to go there, can you take me?"

Many people are familiar with some of the prominent surface features and places on the Moon's Near Side, like the great rayed-craters, Tycho and Copernicus, and the Apollo 11 landing site in the "Sea of Tranquility", but only 27 humans on the 9 Apollo lunar flights have seen some of the Moon's Far Side features (shown in Fig. 13) up close and personal. With an efficient, reusable LNTR transportation system, using proven NTR technology, week-long tourism missions to the Moon can carry passengers into lunar orbit for close-up examination (and plenty of picture taking) then return them to Earth orbit where they would re-enter and land using a reusable mini-Shuttle like SNC's *Dream Chaser* or the *Far Side Voyager* (*FSV*) depicted in this paper.

Key phases of the outbound portion of the orbital lunar tourism mission are illustrated in Figure 14. The mission begins with the launch of seven passengers and crew in the *FSV* aboard a human-rated version of a commercial launch vehicle like ULA's Atlas V. Once in LEO, the *FSV* rendezvous with *Lunar Vistas Unlimited's* (*LVU's*) commercial passenger transport (CPT) after which the CPT initiates a "2 perigee burn" departure maneuver (C_3 ~ –1.678 km^2/s^2, ΔV_{TLI} ~3.206 km/s including a g-loss of ~109 m/s). The CPT carries with it a spacious habitation and observation module plus the *FSV* to the Moon. During the 3-day transit to the Moon, the passengers aboard the CPT will be able to experience the

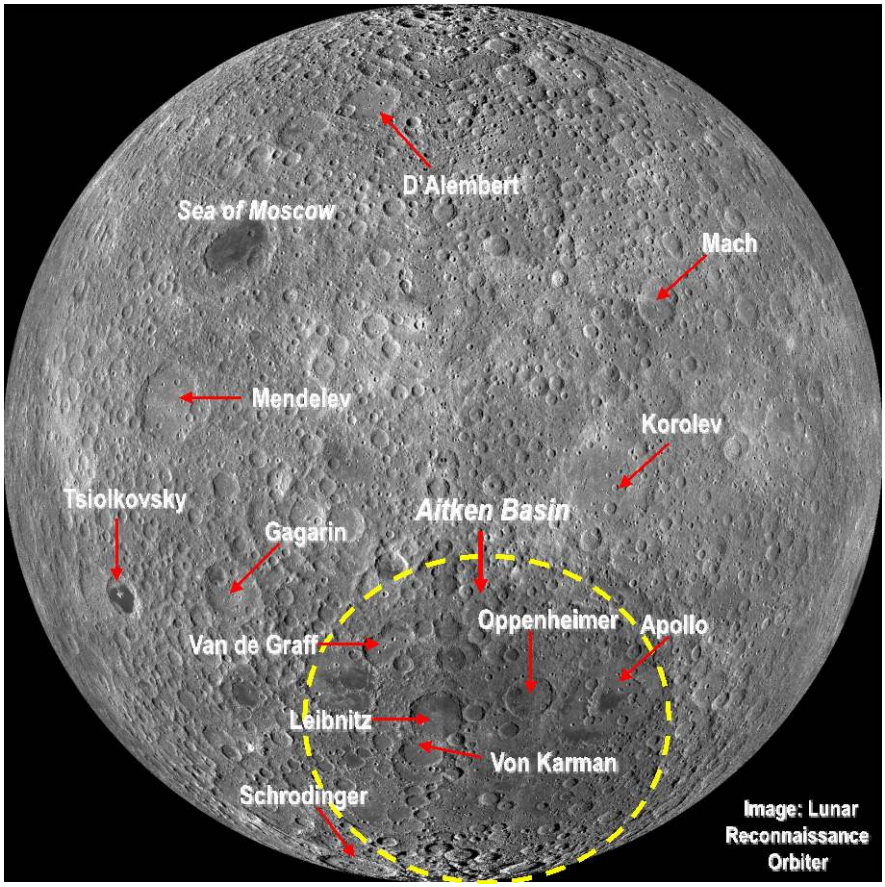

Figure 13.—Sampling of noted surface features on the far side of the Moon.

Figure 14.—Commercial orbital mission to the Moon—launch and Earth departure phases.

0-g_E environment of space as they view a shrinking Earth and expanding Moon from the four large viewing ports on the habitation/observation module as the CPT gradually rotates about its longitudinal axis oriented perpendicular to its flight path.

On the final lunar approach, the passengers return to their seats in the *FSV* and the CPT performs the orbit insertion burn (arrival V_{inf} ~1.151 km^2/s^2 and ΔV_{LOC} ~911 m/s including a 1 percent g-loss) and captures into a 300 km circular LLO (shown in Fig. 15). Over the next 24 hr, the passengers on the CPT will orbit the Moon ~10.5 times experiencing both the Moon's Sunlit Far Side and Earthlit darkened Near Side, and viewing surface features few people on Earth will ever see. After a memorable day of sight seeing in lunar orbit, the CPT performs the TEI burn (C_3 ~ 0.945 km^2/s^2, ΔV_{TEI} ~865 m/s including a 1 percent g-loss) and begins the 3-day voyage back to Earth. On final approach, the CPT performs a braking burn (arrival V_{inf} ~ –1.755 km^2/s^2, ΔV_{EOC} ~370 m/s including a 1 percent g-loss) and captures into a 24-hr EEO. On either the first or second perigee pass, the passengers and crew return to the *FSV*, detach from the CPT and perform a small de-orbit burn, landing back at the Kennedy Space Center (KSC) or other commercial landing site (shown in Fig. 15). The CPT's post burn engine cool-down thrust is used to lower its orbit until it can rendezvous with the tanker vehicle that will supply it with the LH_2 propellant needed for final orbit lowering and return to the LEO transportation node. Here it will be refurbished and resupplied in preparation for its next lunar mission.

Like the cargo transport and *Prospector* ASV, the CPT (shown in Fig. 16) uses the same common ~15.7 m long tank in both the NTPS and in-line element. It has an IMLEO of ~169.5 t consisting of the NTPS (~70 t), the in-line element (~53.4 t), and the crewed payload element (~46.1 t). This last element includes the habitation/observation module with its PVAs (~32.9 t), the seven passengers and crew with their suits (~1.4 t), consumables (~0.15 t), plus the *FSV* mini-Shuttle (~11.65 t). The overall vehicle length is ~71.3 m including the *FSV*.

Figure 15.—Commercial orbital mission to the Moon—insertion, Lunar observation and Earth return.

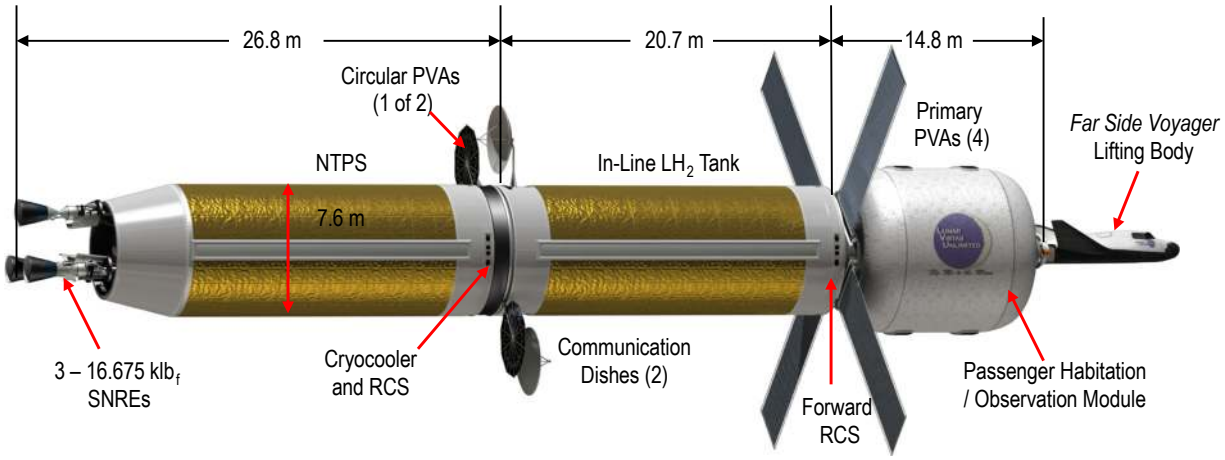

Figure 16.—Key features and dimensions for the commercial lunar passenger transport.

The CPT mission requires five primary burns. With 50 klb_f of total thrust, I_{sp} ~900 s, and ~74.7 t of LH_2 propellant used during the round trip mission, the total engine burn time is ~49.4 min. The first of the two TLI perigee burns is again the longest at ~18.8 min. The duration of the remaining burns are as follows: second perigee burn (~14.5 min), LOC (~7.3 min), TEI (~6.3 min), and 24-hr EEO capture (~2.5 min).

With a fixed NTPS and in-line tank mass, and total propellant loading, it is also possible to return the CPT deeper into Earth's gravity well (e.g., into a 6-hr rather than 24-hr EEO) at the end of the mission in order to reduce the amount of propellant that the tanker needs to deliver to the CPT for final orbit lowering. Doing so increases the capture ΔV requirements at Earth by ~300 percent (arrival V_{inf} ~ –1.755 km^2/s^2, ΔV_{EOC} ~1097 m/s including a 1 percent g-loss) and the propellant needed for capture from ~3.8 to ~9.8 t, thereby decreasing the mass of the "outfitted" habitat/observation module that can be transported to the Moon and back.

For this particular case, the CPT's IMLEO decreases from ~169.5 to ~156.0 t with the following mass breakdown: NTPS (~69.9 t), the in-line tank (~53.3 t), the habitation/observation module with its PVAs (~19.6 t), the seven passengers and crew with suits (~1.4 t), consumables (~0.15 t), plus the *FSV* (~11.65 t). The total engine operating time for the mission remains roughly the same at ~49.7 min with the individual burn durations as follows: first perigee burn (~17.3 min), second perigee burn (~13.4 min), LOC (~6.7 min), TEI (~5.8 min), and 6-hr EEO capture (~6.5 min). For the round trip mission, the burn-up of U-235 fuel in each engine is ~15.3 g (assuming ~1.2 g consumed per megawatt-day of operation) or ~0.025 percent of the total amount of U-235 contained in each SNRE. It is therefore quite apparent that fuel burn-up in the engines of the CPT is not an issue and that significant reuse capability exists with these systems.

With its high performance NTPS, the CPT can also fly an 8-burn LEO-LPO-24-hr EEO round trip trajectory carrying an ~24 t habitat/observation module with its seven passenger and crew and the *FSV*. The CPT uses a 2-perigee burn departure from LEO and after a 3-day transit captures into an elliptical lunar orbit with a perilune of ~100 km and apolune of ~27,700 km. Two subsequent burns provide the plane change and circularization maneuvers that place the CPT into a 100 km circular LPO (depicted in Fig. 17). Following a similar departure sequence for TEI and a 3-day return to Earth, the CPT again captures into a 24-hr EEO. The IMLEO is ~162.7 t, the total engine burn time is ~49.1 min, and the U-235 fuel burn-up is ~15 g (~0.025 percent of the total amount of U-235 contained in each engine).

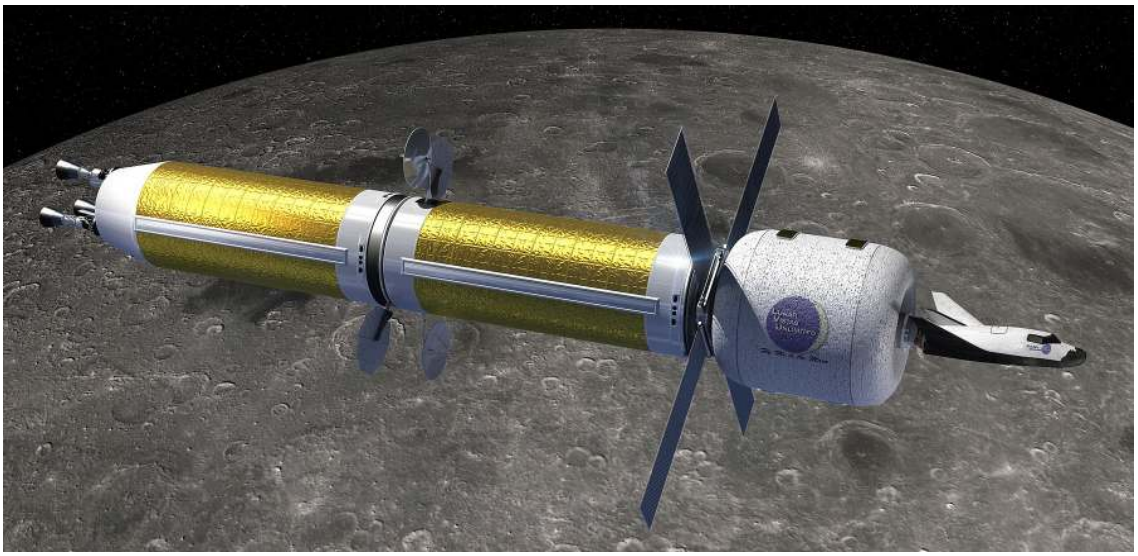

Figure 17.—Commercial passenger transport in polar orbit over the Moon's southern hemisphere.

7.0 Summary and Conclusions

The NTR has frequently been discussed as a key space asset that can bridge the gap between a sustained human presence on the Moon and the eventual human exploration of Mars. Wernher von Braun himself envisioned a reusable "workhorse" NTPS delivering cargo and crew to the Moon for construction of a lunar base, then being outfitted with additional propellant tanks for human missions to Mars. The NERVA program also utilized a non-optimum 8-burn crewed mission to lunar polar orbit and back as its DRM for determining the operating characteristics and requirements for the NERVA flight engine.

The superiority of NTP over conventional chemical propulsion was well documented in analyses conducted during NASA's SEI. Its use enabled a fully reusable LTS architecture that included the ability to also return the LDAV to LEO for refurbishment, resupply and reuse. The addition of an oxygen afterburner nozzle to the NTR also offers the potential for bipropellant operation and refueling in LPO with LOX and LH_2 propellants produced from lunar polar ice in the future. Yet despite NTP's performance advantages and growth potential, it is often overlooked as a viable propulsion option by NASA mission planers. Their frequent response to the question, "Why don't we consider NTP for the Moon?" is that it's overkill or simply not needed since we did the Apollo program with chemical propulsion. It is true that chemical propulsion got us to the Moon but each mission started with an ~3000 t Saturn V on the launch pad at KSC and ended with the return of a charred capsule, the crew and ~63.5 kg of lunar samples (average of six landing missions). If humans are to return to the Moon and establish a permanent presence there, affordability, maintainability and reusability will be essential. Throwing away $100's of millions of dollars of expensive hardware during each mission may not be a sustainable or acceptable mode of operation in the future.

Despite cancellation of the Constellation program, interest in lunar exploration continues. The Global Exploration Roadmap continues to show the *"Moon Next"* pathway as one of its two possible options for future human exploration with the second option being the *"Asteroid Next"* path. Private industry (e.g., SpaceX, SNC and Bigelow Aerospace) has also stepped up its pursuit of commercial space business and the private sector has indicated a significant interest in lunar activities as evidenced by Golden Spike's proposed plans to offer commercial human landing missions on the Moon by the early 2020's.

With its high thrust and specific impulse (100 percent higher than today's best chemical rockets), proven NTP technology can provide the affordable *"access through space"* needed to support future exploration and commercial development activities on the Moon. It is also the only advanced propulsion system successfully ground tested over the full range of performance parameters required for tomorrow's

human missions to the Moon, NEAs, and Mars. For the lunar missions discussed in this paper, a three-engine cluster of SNREs are used on the NTPS. This size engine is smaller than the smallest and highest performing engine tested in the Rover program—the 25 klb_f-class Pewee engine. Through the NCPS project, NASA and DOE are currently engaged in a number of key NTP task activities that include state-of-the-art engine modeling, mission design and requirements definition, fuel element fabrication and non-nuclear testing, and analysis of affordable options for nuclear ground testing and engine development. If successfully completed by the end of FY'14, a NCPS-Phase II effort would begin that could culminate in ground testing a small NTR engine at the NTS in the early 2020's, followed by a flight demonstration mission several years later.

Four different lunar mission applications—cargo delivery, crewed landing, small asteroid science at E-ML_2, and orbital tourism—are examined using a reusable NTP transportation system consisting of two key elements. Each element is limited to 70 t in LEO. The NTPS uses three composite fuel SNRE-class engines that operate at 900 s specific impulse and produce ~50 klb_f of total thrust. In one week's time, using less than 75 t of LH_2 propellant, the NTP cargo transport can deliver ~61 t of payload to LLO then return to a 24-hr EEO for tanker servicing and subsequent return to LEO for resupply before the next mission. In this same time period, the cargo transport can also deliver ~51.2 t of payload to LPO if so desired.

For the crewed landing mission, the LNTR transfer vehicle uses the same NTPS, carries out ~53.6 t of payload to LLO, then returns to the same 24-hr EEO with ~28.7 t of payload mass including collected samples and the spent LDAV. It requires a slightly longer in-line tank to provide the extra propellant needed for the mission. The total engine burn times for the cargo and crewed landing missions are ~50 and 55 min, respectively and both missions require five engine restarts, performance requirements well below those demonstrated in the NERVA program. The U-235 burn-up for the cargo and crewed landing missions is also quite small—no more 0.028 percent of the total U-235 inventory in each SNRE.

The NTP crewed science mission to a small asteroid returned to E-ML_2 using SEP is an interesting combination of technology utilization, system demonstration and mission destinations that has synergy with both the *"Asteroid Next"* and *"Moon Next"* pathways being considered in the GER. Capturing and returning a small asteroid to E-ML_2 helps to validate the technology for a 40 kW_e SEP system and brings together in translunar space two targets of opportunity that are of scientific and commercial interest to both NASA and private industry. It also provides a precursor demonstration mission for a crewed NTP spacecraft, *Prospector*, that can function as a mobile Waypoint Station initially, before being used for actual NEA missions lasting anywhere from ~6 months to a year in duration. The round trip time for the small asteroid science mission at E-ML_2 can range from ~2 weeks to a month and can utilize a combination of NASA and commercial space assets. Like the cargo transport vehicle, *Prospector* also uses the same length LH_2 tank in both the NTPS and in-line tank element in order to maximize component commonality and minimize recurring costs.

A commercial passenger transport for orbital tourism is perhaps the most interesting of the NTP lunar mission applications. It allows 7-day round trip missions including 3-day transits to and from the Moon with a day in lunar orbit for some *"out of this world"* sightseeing. With the available propellant in the NTPS and in-line tank element, the CPT can trade habitation/observation module mass against different elliptical capture orbits back at Earth. The shorter the orbital period, the lower the mass transported out to the Moon and back. With a 6-hr EEO and IMLEO of ~156 t, the CPT's NTPS and in-line elements can be delivered to LEO on two upgraded SLS launches while the habitat/observation module with its PVAs at ~20 t can potentially use a smaller commercial launch vehicle. With its high performance NTPS, the CPT can also fly an 8-burn LEO-LPO-24-hr EEO round trip trajectory carrying an ~24 t habitat/observation module, seven passengers and crew plus the *FSV* mini-Shuttle. The CPT can also carry larger modules and more passengers on each round trip if the *FSV* is left at the LEO transportation node and used only for passenger delivery and pickup at the end of the mission.

NTP is frequently identified as a propulsion option to be used primarily for Mars but it can also play an important role in future human exploration and commercial missions to the Moon by providing affordable transportation through cislunar and translunar space. With a sustained and credible funding

profile, NASA, DOE and industry could have an operational NTR engine and stage available within a decade. After that, how long will it be before the travel section of your Sunday newspaper features an advertisement for week-long orbital missions to the Moon with the caption, "Come Fly with Us…Come Spend a Day in Lunar orbit"?

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14. ABSTRACT
The nuclear thermal rocket (NTR) has frequently been discussed as a key space asset that can bridge the gap between a sustained human presence on the Moon and the eventual human exploration of Mars. Recently, a human mission to a near Earth asteroid (NEA) has also been included as a "deep space precursor" to an orbital mission of Mars before a landing is attempted. In his "post-Apollo" Integrated Space Program Plan (1970 to 1990), Wernher von Braun, proposed a reusable Nuclear Thermal Propulsion Stage (NTPS) to deliver cargo and crew to the Moon to establish a lunar base initially before sending human missions to Mars. The NTR was selected because it was a proven technology capable of generating both high thrust and high specific impulse (I_{sp} ~900 s)-twice that of today's best chemical rockets. During the Rover and NERVA programs, 20 rocket reactors were designed, built and successfully ground tested. These tests demonstrated the (1) thrust levels; (2) high fuel temperatures; (3) sustained operation; (4) accumulated lifetime; and (5) restart capability needed for an affordable in-space transportation system. In NASA's Mars Design Reference Architecture (DRA) 5.0 study, the "Copernicus" crewed NTR Mars transfer vehicle used three 25 klb_f "Pewee" engines-the smallest and highest performing engine tested in the Rover program. Smaller lunar transfer vehicles-consisting of a NTPS with three ~16.7 klb_f "SNRE-class" engines, an in-line propellant tank, plus the payload-can be delivered to LEO using a 70 t to LEO upgraded SLS, and can support reusable cargo delivery and crewed lunar landing missions. The NTPS can play an important role in returning humans to the Moon to stay by providing an affordable in-space transportation system that can allow initial lunar outposts to evolve into settlements capable of supporting commercial activities. Over the next decade collaborative efforts between NASA and private industry could open up new exploration and commercial opportunities for both organizations. With efficient NTP, commercial habitation and crew delivery systems, a "mobile cislunar research station" can transport crews to small NEAs delivered to the E-ML2 point. Also possible are week-long "lunar tourism" missions that can carry passengers into lunar orbit for sightseeing (and plenty of picture taking), then return them to Earth orbit where they would re-enter and land using a small reusable lifting body based on NASA's HL-20 design. Mission descriptions, key vehicle features and operational characteristics are described and presented.

15. SUBJECT TERMS
Nuclear thermal rocket (NTR); Spacecraft; Lunar transportation system; Lunar tourism; Human exploration

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