Concept for a Shuttle-Tended Reusable Interplanetary Transport Vehicle Using Nuclear Electric Propulsion

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Abstract. NASA has placed new emphasis on the development of advanced propulsion technologies including Nuclear Electric Propulsion (NEP). This technology would provide multiple benefits including high delta-V capability and high power for long duration spacecraft operations. One potential mission application of this technology would provide a reusable deep space transfer vehicle for multiple transfers to and from the inner planets. Such a space "truck" would make full use of the high delta-V capability available from the NEP system, while providing additional benefits to the payload. It could be used for multiple transfers from the Earth to the inner planets and back, supporting both Mars Sample Return and Venus Sample Return cargoes. Point designs are developed for such a "multi-cycle" system and then compared against a similar single cycle system based on solar electric propulsion. In order to extend the operational life and versatility of the NEP system, we propose to enable the servicing of the vehicle and payload transfer using the Space Shuttle. A baseline operational scenario is developed for such a mission that would also include the change out of the xenon propellant tanks and the ion thrusters. The Shuttle provides a number of benefits to this type of mission, such as high launch reliability, a high degree of operational flexibility, availability of contingency operations, and prior experience with launch of radioactive payload components and on-orbit servicing. The launch and rendezvous orbit will be maximized for altitude and inclination to minimize radiological exposure during spiral transits through the Van Allen radiation belts. Preliminary examination of requirements indicates that Shuttle safety concerns for launch and servicing operations can be addressed through the standard Shuttle safety review process. A break-even point exists beyond which a multi-cycle NEP system could potentially become more cost-effective than a single cycle chemical or SEP system for both Mars and Venus sample return missions. However, greater utility of the NEP system could be realized if it were used to enable cycler missions involving the transportation of payload to and return of samples from the outer planets.

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Abstract—NASA has placed new emphasis on the development of advanced propulsion technologies to overcome current power and propulsion limitations. One promising technology is Nuclear Electric Propulsioin (NEP). NEP would provide multiple benefits including high delta-V capability and high power, two of the most pressing limitations, for long duration spacecraft operations. One potential mission application of this technology would provide a reusable deep space transfer vehicle for multiple transfers to and from the inner planets. Such a space "truck," or "NEPTranS" for NEP Transportation System, would make full use of the high delta-V capability available from the NEP system, while providing additional benefits to the payload. NEPTranS could be used for multiple transfers from the Earth to the inner planets and back, supporting both Mars Sample Return and Venus Sample Return cargoes. In order to extend the operational life and versatility of the NEP system, we have studied the use of the Space Shuttle to enable the servicing of the vehicle and payload transfer. A baseline operational scenario is developed for such a mission that would also include the change out of the xenon propellant tanks and the ion thrusters. The launch and rendezvous orbit will be maximized for altitude and inclination to minimize radiological exposure during spiral transits through the Van Allen radiation belts. Preliminary examination of requirements indicates that Shuttle safety concerns for launch and servicing operations can be addressed through the standard Shuttle safety review process. A design of a "multi-cycle" mission employing NEPTranS is compared against a similar single cycle system based on solar electric propulsion. A break-even point should exist beyond which the NEPTranS vehicle could potentially become more cost-effective than a single cycle chemical or solar electric propulsion (SEP) system for both Mars and Venus sample return missions. The versatility of a system such as that designed in this study, however, has broad implications for the establishment of a long-term deep space transportation infrastructure for the next decade and beyond.

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1. INTRODUCTION

The combination of fission reactor based power systems in space and electric propulsion technology would provide multiple benefits including high delta-V capability for access to anywhere in the solar system and high power for long duration science operations. For outer planet missions where solar energy is very scarce, the use of nuclear reactors is enabling for a wide variety of science missions. For the inner planets, however, the benefits of NEP to science missions are less obvious, given the relative abundance of solar energy. One potential mission application of this technology that has the potential to be enabling for a variety of future missions is to provide a reusable deep space transfer vehicle for multiple transfers to and from the inner planets. Such a space "truck" would make full use of the high delta-V capability enabled by the NEP system, while providing additional benefits to the payload. It could be used for multiple transfers from the Earth to the inner planets or other near-earth objects (NEOs), supporting sample return or science observation cargoes. In order to extend the operational life and utility of the NEP system, it is proposed to enable the deployment and servicing of the

NEPTrans vehicle using the Space Shuttle. A baseline operational scenario is developed for such a mission that would include, refueling of the vehicle and exchange of wear-limited components (e.g., ion thrusters) by the shuttle crew between planetary missions. A configuration is developed to accommodate this versatility feature. Preliminary assessment of the trajectories, the radiation environment and shuttle safety considerations, including contingency operations in the event of major vehicle failures indicate that the baseline scenario developed for this study is feasible. The NEPTranS design for a "multi-cycle" mission is then compared against the use of single cycle systems based on solar electric propulsion. Preliminary cost analysis indicates that a break-even point should exist beyond which a multi-cycle NEP system would become more cost-effective than a single cycle SEP system for both Mars and Venus sample return missions. The versatility of a system such as that designed in this study, however, has broad implications for the establishment of a long-term deep space transportation infrastructure for the next decade and beyond.

2. MISSION CONCEPT

The NEPTranS mission concept is based on providing the ability to perform multiple robotic inner planet rendezvous missions. The key word is "multiple." NEPTranS is an unmanned spacecraft designed to make multiple trips between the Earth and Mars and/or Venus to deliver payloads and return samples collected from these planets on each trip back to Earth. The baseline vehicle design comprises an NEP system carrier with a fully integrated (and shielded) complement of flight hardware subsystems to support multiple round trip missions to inner planet target bodies. This has driven a design that incorporates the capability for autonomous rendezvous and capture of a sample return capsule in Mars or Venus orbit inserted by a corresponding ascent vehicle. The design must also be compatible with rendezvous and capture by the Space Shuttle in low Earth orbit. This capability allows the potential for a variety of payloads (e.g., multiple landers/rovers, science instruments, etc.) to be delivered to Mars or Venus on subsequent trips from Earth, and at the same time, exchange of consumables and other limited-life items such as ion thruster assemblies and allows for delivery of the sample return capsule in a controlled manner as opposed to a direct entry and descent. In addition, the high sustained power levels available from the NEPTranS nuclear power system enables application of the basic vehicle to other uses such as high gain/high bandwidth radio and optical communications relay, microwave or optical power transmission, as well as the ability to support a host of high-power science instruments (radar, magneto-sounding, laser ablation, etc.) In essence, NEPTranS is more than just a simple space truck – it is a highly versatile space utility vehicle.

Key Features

NEPTranS is designed to take advantage of the following key features:

- High sustained power, unaffected by solar range
- High Isp electric thrusters
- Long duration operation: >10 years
- Higher payload mass deliveries and/or shorter travel times than a solar electric propulsion vehicle
- No need for sun-tracking of photo-voltaic arrays
- Avoids degradation of photo-voltaic panels
- Economy of scale leads to long term cost effectiveness
- Basic design is not limited to inner planet missions. With simple fuel tank replacement the same vehicle may be used for missions to outer planets or a variety of alternative missions.

Key Challenges

NEPTranS will need to overcome the following challenges:

- Technology development, testing and verification of low mass NEP system and high Isp ion engines (alpha <50 kg/kW, high throughput, long duration operation, etc.)
- Technology development, testing and verification of power conversion system (Brayton, Stirling, thermoelectric, thermionic)
- System reliability in harsh radiation environment (from Van Allen belts during spirals as well as reactor dose)
- Safety and launch approval issues (Shuttle safety, launch safety, disposal)
- Cost (mainly development, testing and verification)

Key Assumptions

The current study is constrained by the following assumptions.

- NEPTranS is an unmanned spacecraft and therefore does not need to be man-rated
- NEPTranS is designed to be serviced by the Space Shuttle
- NEPTranS will be operational roughly within the timeframe of the current Mars exploration mission plans that include the Mars Smart Lander and other Mars Exploration Program (MEP) missions (i.e., 2007-2020 and beyond).
- A single NEPTranS carrier operational lifetime is 10-15 years
- Launch vehicle capabilities evaluated are limited to performance of Delta IV heavy, Atlas V and Space Shuttle

Key Trades

Table 1. shows the key architectural design trades by which we examined possible alternatives to a number of key design parameters associated with the NEPTranS. The most significant of these trades was that of between-mission servicing using the Space Shuttle. The Shuttle provides a number of benefits to this type of mission, such as high launch reliability, a high degree of operational flexibility, availability of contingency operations, and prior experience with launch of radioactive payload components and on-orbit servicing.

Table 1. Key Mission Trades

Mission Trade	Baseline	Alternatives	Reason
Launch	Space shuttle	ELV	Reliability, versatility, contingency operations
Main propulsion system	Xenon ion engines	MPD, VaSIMR, etc.	Minimal technology development required
Reactor power levels	100kWe	20kWe, 200kWe, 1000kWe	100 kWe offers reasonable trip times, matches current NSI baseline
Transfer to Mars (Venus)	Escape spiral trajectory High inclination orbit (60° spiral trajectory)	Ballistic trajectory Low inclination	Necessary for reuse Minimizes Van Allen radiation exposure
Capture at Mars (Venus)	Capture spiral trajectory	Aerocapture, fly-by of Mars (Venus)	Design hard to optimize for aerocapture
Transfer to Earth	Escape spiral trajectory	None	
Capture at Earth	Capture spiral trajectory	Fly-by	Allows controlled return to altitude for shuttle servicing and pickup of new payload
Carrier-payload separation	Boom	Tether	Rigid structure essential for Shuttle proximity operations
Sample canister recovery	Space shuttle capture	Ballistic re-entry	Higher reliability, greater assurance of meeting planetary protection requirements
Follow-on payload deployment	Space shuttle delivery and attachment	ELV delivery, autonomous rendezvous and docking	Simpler, requires no new infrastructure
Carrier servicing (including propellant resupply and ion thruster change out)	Space shuttle tended at LEO	Robotic servicer and autonomous resupply vehicle at MEO or GEO	Requires no new infrastructure. Flexibility for contingency operations

Key Scenarios

The NEPTranS mission consists of multiple cycles of the following phases of operation.

Initial Launch and Deployment—For its initial launch the NEPTranS vehicle, with its planetary payload attached, will be delivered to a 500 km circular orbit at a 57-degree inclination by the Space Shuttle. Following establishment of the parking orbit the Shuttle payload bay doors will be opened and the NEPTranS vehicle will be deployed from the Orbiter's payload bay. The Orbiter will then perform a maneuver to separate to a minimal safe distance to allow vehicle and deployment operations to occur, while retaining the capability to return to the vehicle should contingency operations be required. The NEPTranS vehicle's major deployment operation will begin with extension of its main separation mast. Mast extension will also effect the deployment of the power system radiators, which are structurally tied to the mast assembly. Following verification of nominal mast and radiator extension, the deployment operations will continue with the extension of the solar array wings, the three thruster booms and the HGA boom. All of the non-nuclear subsystems will then be activated and verified. Upon verification of nominal subsystem operation, the Orbiter will reposition to a safe distance within the power system's shield cone and a command will be sent to initiate automatic start-up of the reactor system, monitored by ground crew and the Shuttle astronauts. After the reactor is brought to full power and all operational parameters are verified to assure nominal operation, the ion propulsion system will be activated to begin the spiral process to place the vehicle on a trajectory to its target planet. Figure 1. shows the NEPTranS vehicle being deployed out of the Shuttle payload bay prior to boom and thermal radiator panel extension.

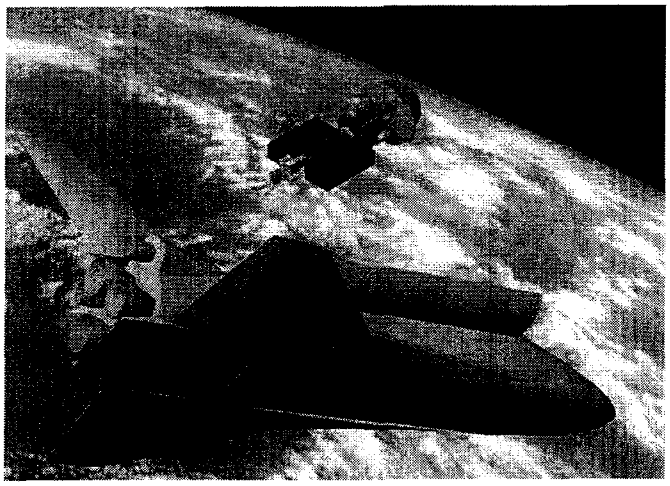


Figure 1. Deployment from Shuttle Orbiter

Planetary Target Operations—On approach to Mars (or Venus), the NEP system will provide thrust to place the spacecraft on a capture spiral trajectory. The NEP system will provide the delta-V necessary to lower the vehicle orbit to the desired altitude for deployment of the payload and/or rendezvous with the sample return canister. Following establishment of the final planetary orbit, the NEPTranS vehicle will deploy the lander payload for its descent to the landing site. The NEPTranS spacecraft will then loiter in planetary orbit with the reactor power throttled down to a low level until rendezvous and capture of the sample canister is completed. Figure 2. shows NEPTranS on approach to Mars prior to orbit insertion.

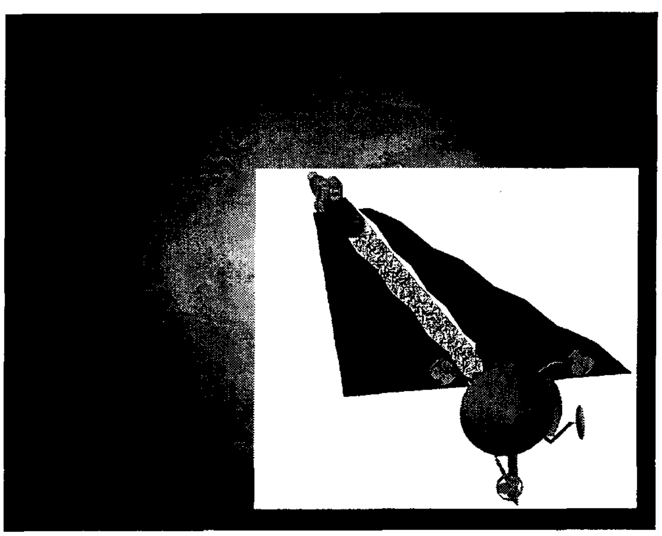


Figure 2. NEPTranS Delivering Payload to Mars.

Ascent Vehicle Rendezvous and Sample Canister Capture—The Sample Return landed system is assumed to acquire and store a sample in a return canister, which is subsequently launched back into the orbit of the NEPTranS vehicle (in the case of Venus, the baseline assumption is that a helium balloon lifts the canister and ascent vehicle to approximately 66km altitude from which point three solid propellant rocket stages lift the canister to the NEPTranS altitude). The NEPTrans vehicle will track the sample canister in orbit and initiate autonomous rendezvous and capture. Fine maneuvering during this phase will be accomplished using the NEPTrans vehicle's monopropellant hydrazine RCS system. Figure 3. shows NEPTranS in orbit around Mars in preparation for capturing of the sample return canister.

Figure 3. NEPTranS Capturing Sample Return Canister.

Mars (or Venus) to Earth Leg—Once the canister is captured by the NEPTranS vehicle the reactor will be brought back up to full power and the NEP system will provide thrust to place the return spacecraft on a spiral trajectory for escape and transit back to Earth. On Earth-approach the NEPTranS vehicle spirals down to a high-inclination circular orbit at a Shuttle-serviceable altitude of about 500 km. Upon reaching this orbit the reactor is shut down and safed in preparation for rendezvous with the Space Shuttle and all vehicle power requirements are turned over to the auxiliary solar array power system. Shuttle rendezvous is timed to take place a minimum of 30 days after reactor shut-down to provide time for daughter-product radiation to decay to manageable levels.

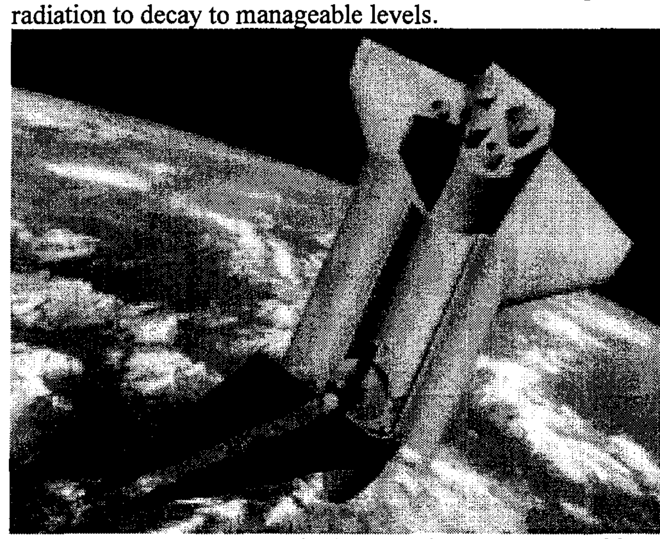


Figure 4. NEPTranS Being Serviced and Resupplied by Orbiter

At the end of this decay time the Orbiter will rendezvous with the NEPTranS vehicle and grapple it with the Shuttle

Remote Manipulator System (RMS). The Space Shuttle can then service the spacecraft, which will as a minimum consist of removing the depleted fuel tanks and attaching full ones sized for the next mission. The thrusters and certain other orbit-replaceable subsystems may also be replaced or upgraded during the servicing mission. Finally, the Orbiter crew will attach a new payload to the NEPTranS vehicle for a subsequent planetary delivery mission. Figure 4. shows NEPTranS rendezvous and docking with the Space Shuttle in preparation for propellant tank exchange and other servicing operations.

If the NEP carrier spacecraft does not require servicing for its next mission, it has the option to swing by the Earth and release the sample return canister for direct re-entry into the Earth's atmosphere. The vehicle could then return more quickly to Mars or Venus to rendezvous with another return payload, if desired.

3. Mission Design

The concept of operations as highlighted in the previous section forms the basis for the NEPTranS mission design. This design is influenced by such factors as Earth orbital operations, performance trades, orbital inclination, telecommunications system capabilities, and system safety. A top level configuration is developed for NEPTranS and basic trajectory analysis is performed to validate the mission design.

Earth-Vicinity Operations

One of the key operating parameters of NEPTrans is initial Earth orbit insertion. NEPTranS is launched by the Space Shuttle for several reasons. First, the Space Shuttle (with the exception of the Columbia Orbiter) is able to lift approximately 18,000 kg to 500 km at 28° inclination. This is more than adequate to lift preliminary estimates of a second-generation 100kWe NEP propulsion system carrier with a Mars (Venus) lander attached (approximate wet mass is 14,000 kg). For this lift capacity, the Space Shuttle is the most reliable launch vehicle available. Reliability and safety are top priorities for a nuclear payload. The nuclear reactor is essentially non-radioactive at launch and prior to extended operation at high power (Houts and Poston, 2002) so flight crewmembers will not be affected by its deployment in low Earth orbit. Shuttle-tended operations and the availability of astronaut contingency EVA operations will ensure a successful deployment of critical elements such as the thermal radiator assembly, high gain antenna system and the power system-to-payload boom. Finally, should some malfunction prevent nominal deployment or operation of the vehicle (prior to startup of the reactor), the Shuttle offers the unique opportunity to return the entire NEPTranS vehicle to Earth.

Performance Trades

The wide range of potential power system designs being considered allows several trades to be made between power level, propellant mass, payload mass, and trip times. The use of an NEP system brings considerable flexibility to mission design, allowing a single vehicle to deliver a wide range of payload masses to a choice of targets by varying the amount of propellant and the trip times. An additional basic design factor for such an NEP system is the power level of the fission reactor. Within 100 to 1000 kWe it may be possible to produce a power system without extensive changes to the reactor design. Increasing power does, however, come at a penalty in mass associated with power conversion, heat rejection, and propulsion systems, but overall higher powers will result in significant reductions in trip time or, alternatively, increased payload capability for the same trip time. One parametric comparison was made for this study between 100kWe, 200kWe and 1,000kWe nuclear fission reactor power systems. A 2,500 kg planetary payload was assumed for all cases. The results for a typical Mars round trip mission are shown in Table 1.

Table 1. Mars sample return trajectories for 100, 200 and 1000 kW electric power

Parameter	NEP System Power (kWe)		
	100	200	1000
Earth Departure Date	1/18/2015	7/29/2015	3/24/2016
Earth Return Date	4/26/2019	2/19/2019	11/25/2018
Total Round Trip Mission Time, days	1558.2	1301.7	975.6
Earth Departure Mass, kg	14019.7	17942.5	35000
Consumed Propellant, kg	5854	7742.1	16130.9

This comparison demonstrates that a doubling of power from 100 to 200 kWe reduces total mission time by about 256 days, or slightly more than 16% over the total 100 kWe mission time of 1558 days. The use of a 1000 kWe system shows a potential reduction in total mission length of 583 days, or a full 37% over the 100 kWe case. The penalty, however, is evident in the expected increase in launch mass of the higher power system. As shown in the table, it is expected that a 1000 kWe system will raise the vehicle Earth-departure mass to as much as 35,000 kg, which would likely require multiple launches and on-orbit assembly to realize.

Further parametric analysis is recommended to determine the effects of additional payload mass for a given system power level. Requirements on a planetary sample return capsule are constrained by the ascent vehicle capabilities. However, NEPTranS could enable a larger delivery mass allowing a more powerful ascent vehicle to be deployed, which provides a larger sample mass that potentially allows more varied sample characteristics.

Orbital Inclination

The departure/arrival scenario also involves trades. Once the decision to rely on Shuttle deployment and servicing has been made, the primary consideration becomes that of how to minimize transit radiation dose incurred by prolonged spiral time in the Van Allen radiation belts. Figure 5. illustrates how much time is spent spiraling out of Earth orbit using a low-thrust propulsion system such as that envisioned for NEPTranS. Sweetser, et al. (2001) has shown that an inclined circular spiral can significantly minimize radiation exposure. Indeed, modeling results from that paper show that a spiral at an inclination of 57° can cut total ionizing dose by almost a factor of two over a spiral at 28.5°. This becomes especially important for a reusable vehicle like NEPTranS, where Van Allen belt transits may be repeated many times over the life of the vehicle. Thus this study has baselined an inclination of 57° for outbound and return Earth-spiral orbits of the NEPTranS vehicle.

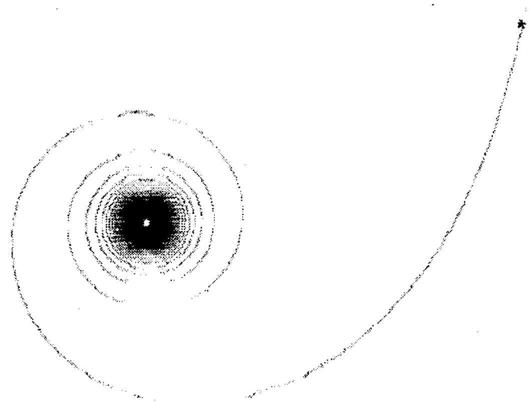


Figure 5. A typical low-thrust circular capture spiral into low Earth orbit. The point where the trajectory has zero energy is marked with a star and is about 840,000 km from the center of the Earth.

High-Rate Communications

Higher sustained power levels allow for incorporation of a communications system to enable a very high bandwidth direct-to-Earth data downlink. Optical transponders for downlink of science data could also be incorporated requiring the use of telescopes for high data rate transmissions (e.g., 100 Mbps). Though such a capability is not required in the baseline NEPTranS concept, it may be worth examining the potential use of the NEPTranS vehicle as part of a Mars telecommunications infrastructure. For the current NEPTranS concept the baseline includes a 200 W TWTA and a 1.3 m high gain antenna (HGA) operating in X band to provide a sufficient data rate through the Deep Space Network (DSN) 34 m network even at worst-case Earth-Mars distances.

System Safety

Nuclear system safety factors must be addressed in the process of developing reactor systems for space flight applications. The nuclear safety review and launch approval process is well established through our experiences with the launch of radioisotope thermal generators on numerous spacecraft launches. This includes the Galileo and Ulysses spacecrafts that were launched by the Space Shuttle. Although the reactor-powered Russian spacecraft Cosmos 954 reentered the atmosphere by accident in 1978, the subsequent UN report on Cosmos 954 in 1981 reaffirmed that nuclear power is safe in outer space if it meets basic safety requirements (Wertz and Larson, 1999).

The Space Shuttle Payload Safety Review Panel (PSRP) would nonetheless have to review all aspects of what would likely be one of the more complex payloads flown on the Shuttle. The mission operations for the rendezvous, capture, servicing, and redeployment of the spacecraft for the multiple missions envisioned for NEPTranS would be challenging, but probably no more so than a Hubble Space Telescope or International Space Station servicing mission. The standard payload safety review process for Shuttle payloads is probably sufficient to ensure Shuttle and crew safety even for a payload this complex. While many aspects of the design will likely be similar to systems already flown on the Shuttle, complex payloads frequently require additional attention without considering the added challenge of the nuclear feature. An important aspect of the payload safety review process to understand is that the nominal phased safety reviews for complex payloads are quite often supplemented by special topic technical interchange meetings (TIMs). Experience has shown that where the payload has complex or unique design features these TIMs have been of great benefit for both the payload and the Shuttle Program in establishing an acceptable safety path for the payload to follow.

While there are likely to be several aspects of the design that will be challenging from a Shuttle safety perspective, there are at least two that may require complex. In order to minimize the radiation shielding needed to protect the orbiter and crew the reactor will probably need to be kept as far above the payload bay as possible. One of the suggested design solutions is an extendable mast of the type used on the Shuttle Radar mission and the Space Station solar arrays. While this approach has been demonstrated in flight the potential dynamic structural interaction with the Shuttle attitude control system must be well understood. This approach typically has required an additional jettison interface to meet the fault tolerance requirements for Shuttle payload bay closure. The potential effects of ionizing radiation from the reactor on the Shuttle and crew for the servicing missions are an aspect of the payload that deserves early attention. It is likely that acceptable crew exposure limits will be the more difficult criteria to establish since there are not currently well-defined limits for the intentional exposure that may occur during a servicing mission.

Since these two aspects of the payload design would appear to have a potentially significant impact on the radiation shield design, alternatives to the single shield design may need to be considered. Possible solutions such as splitting the shielding, part attached to the NEPTranS and part deployed from the orbiter payload bay, use of the orbiter RMS or other robotics to perform certain aspects of servicing, or performing the servicing mission from the Space Station where several automated rendezvous and remotely controlled, (station crew) servicing scenarios are already in work.

Some thought toward contingency operations early in the design process is useful in so much as it helps guide the designers in choosing solutions that don't preclude continued operations in the event of failures. A typical contingency operation is a deploy flight retrieval in the event of a critical system failure, (reactor start, critical appendage deployment, etc.). The important aspect of these scenarios for the designer to address is that the payload must have the capability to restore the fault tolerance required for systems having potential catastrophic hazards in order to demonstrate compliance with the Shuttle safety requirements.

Definition of Flight System

The conceptual flight system configuration for the NEPTranS vehicle is illustrated in Figure 6.

The configuration of the NEPTranS vehicle is driven by the multi-use mission design and by the requirement for Shuttle maintenance and servicing. All payload attachment and serviceable units are grouped at the payload end of the vehicle, inside the 10° half-cone angle of full shielding provided by the reactor shield.

The Xenon propellant tanks are mounted on the sides of the spacecraft bus, and are designed as modular units with quick release fittings to allow them to be exchanged by the Orbiter's robot arm. The size of the tanks can be varied by mission to accommodate a range of destinations and mission designs.

The ion engines used in the design are mounted in three clusters of three engines each placed on articulated booms to allow clearance of the payload. Two engines of each cluster of three are required for nominal operations; the third in each cluster is a spare. In addition, the thruster booms are articulated such that any two booms can maintain thrust through the center of mass of the vehicle should one cluster fail. The mounting of the thrusters at the payload end facilitates their exchange between missions, should that be required. It should be noted that current ion engine designs are throughput-limited and it is expected that each round-trip mission will probably require at least the six primary thrusters to be changed out before beginning a subsequent mission. The modularity of the thruster mounting design will also allow for thruster upgrades, should technology developments result in significant thruster improvements between missions.

Spacecraft bus avionics and the reactor's Power Management and Distribution (PMAD) electronics will also be accessible from the payload end of the vehicle and may be designed as orbit-replaceable units as well. This will allow versatility

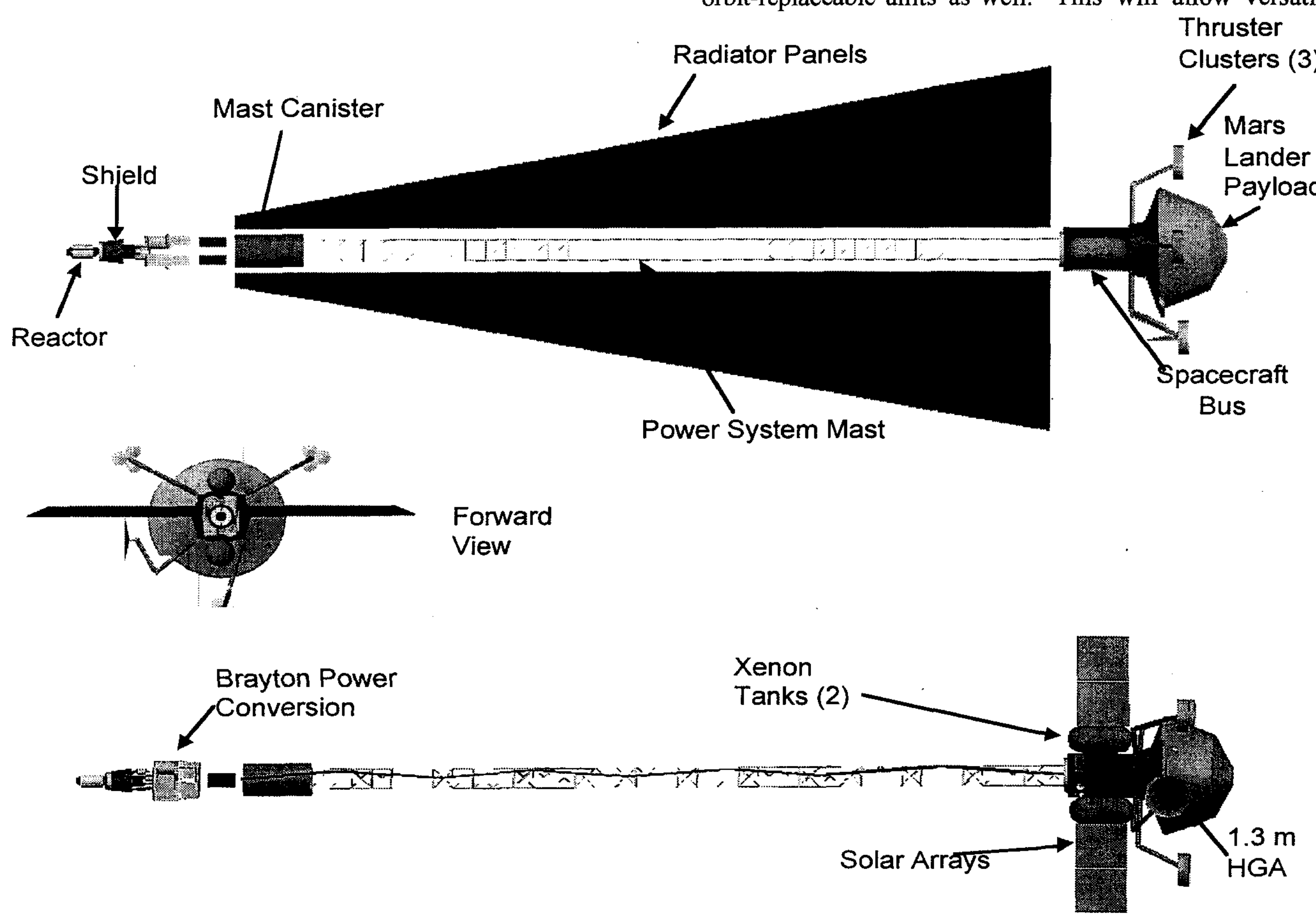


Figure 6. NEPTranS Vehicle Configuration

and a capability to upgrade vehicle avionics unmatched since the Hubble Space Telescope.

The launch configuration of the NEPTranS vehicle fits into the Shuttle payload bay as shown in Figure 7.

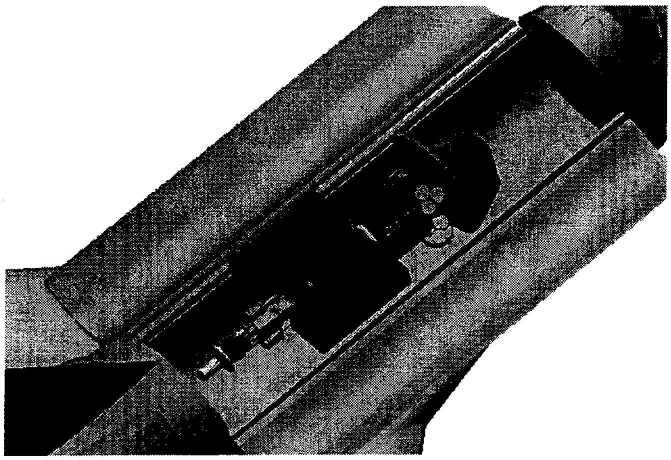


Figure 7. Launch Configuration of the NEPTranS Vehicle

Trajectory Analysis

Mission designs for both a Mars sample return and Venus sample return missions were developed for different power levels. Note that for Mars, a tenfold increase in power results in approximately 37% less days for mission duration but at more than twice the wet mass which would render single launch unfeasible.

Mass Assumptions—Limited detail design could be performed within the constraints of this study and a detailed mass breakdown was not possible. The NEPTranS vehicle design drew from other studies to estimate the mass of the vehicle. Most previous studies have been fairly consistent in estimating mass of spacecraft elements, exclusive of the NEP power and propulsion systems, on the order of 1000 kg. This study bases its nuclear power system mass on that estimated in Lipinski, et. al.,(2002) for a 100 kWe gas-cooled NEP system. That paper estimated power system mass as follows:

Table 2. 100 kWe NEP System Mass

Element	Mass (kg)
Reactor and Controls	570
Radiation Shield	567
Turbine, Compressor, Recuperator, Generators, Ducts	445
Power Conditioning and Distribution	50
Radiator and Heat Exchanger	963
Mechanical Structure (10%)	259
Other (15%)	428
Power System Total Mass (kg)	3282

Adding about 1000 kg to this for the spacecraft bus, and a further 300 or so for the boom and thrusters gives a vehicle dry mass (excluding Xenon fuel and "tankage" mass) of about 4500 kg. This is the mass estimate that was used to calculate trajectories for the 100 kWe cases presented in the following tables. Vehicle dry mass for the higher power cases were scaled from this estimate according to relationships developed in joint studies by JPL, MSFC and GRC. The dry mass for the 200 kWe case was assumed to be 6157 kg and the 1000 kWe vehicle mass was assumed to be 13,148 kg. It is important to note that all of these mass assumptions are quite optimistic when compared to recent studies looking at current state-of-the art systems. This design study is assumed to represent a second-generation system that incorporates a number of technology developments now under study that are predicted to bring power and propulsion system masses down to the levels estimated within the next decade. In addition to the vehicle dry mass, each case assumed an outward-bound payload mass of 2500 kg, which was dropped after spiraling into a 500 km orbit at the destination. Figure 8 shows two sample trajectories.

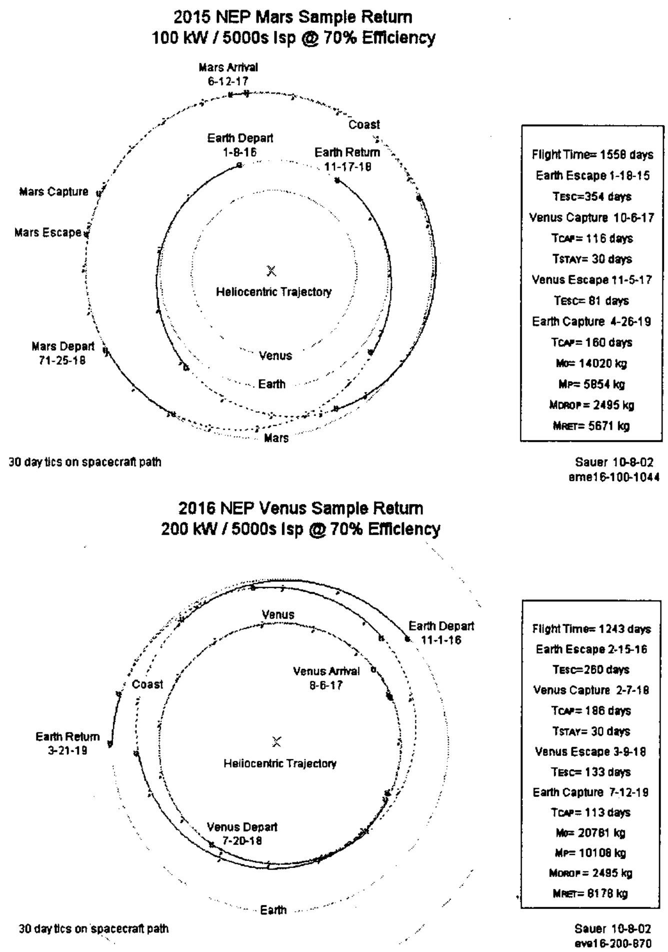


Figure 8. Mars and Venus Sample Return Trajectories for 100kWe and 200kWe NEP System, Respectively

Table 3. Mars and Venus Sample return trajectories for 100, 200 and 1000 kW electric power

Parameter	Mars			Venus		
	100kWe	200kWe	1000kWe	100kWe	200kWe	1000kWe
Earth Calendar Date at Departure	1/18/2015	7/29/2015	3/24/2016		2/15/2016	11/27/2016
Earth Calendar Date at Arrival	4/26/2019	2/19/2019	11/25/2018		7/12/2019	3/3/2019
Total Mission Time, days	1558.2	1301.7	975.6		1243.314	825.9901
Earth Escape Spiral Time, days	354.3	223.1	83.5		259.8149	108.3097
Mars Capture Spiral Time, days	116.5	71.9	25.5		185.7539	70.96191
Mars Escape Spiral Time, days	81.4	53.8	25.5		133.0167	56.49313
Earth Capture Spiral Time, days	166.3368	113.8785	50.77358		113.4987	47.68042
Thruster Specific Impulse, seconds	5000	5000	5000	5000	5000	5000
Thruster Input Power, kW	100	200	1000	100	200	1000
Earth Departure Mass, kg	14019.7	17942.5	35000		20781.42	44871.68
Consumed Propellant, kg	5854	7742.1	16130.9		10107.85	24357.23
Earth Escape Mass, kg	12237.2	15697.8	30801.5		18167.13	39422.54
Mars Arrival Mass, kg	10771.4	13629.6	25867.5		16173.45	32218.87
Mars Capture Mass, kg	10185.5	12906.5	24582.9		14304.37	28648.73
Mars Departure Mass, kg	7690.5	10411.5	22087.9		11809.37	26153.73
Mars Escape Mass, kg	7281.2	9870.4	21011.3		10470.94	23311.52
Earth Arrival Mass, kg	6475.4	8778.1	18540		9320.61	20418.28
Final Spacecraft Mass, kg	5670.8	7705.4	16374.1		8178.57	18019.45
Total Propulsion Time, days	1163.6	769.4	320.6		1004.543	484.1362
Equivalent Free Space Velocity, km/s	30.605	30.912	32		36.32727	40.26797
Minimum Sun Spacecraft Distance, AU	0.983	0.992	0.998		0.723649	0.577398

The stay time at each destination planet was assumed to be at least 30 days, and the vehicle was assumed to pick up a 5 kg sample return payload for return to Earth. Ion engine Isp was assumed to be 5000 s for all cases and the launch date was specified as 2015-2016.

Table 3 shows results of the trajectory calculations. The 100 kWe Mars case shows that the total round trip time is about 4.3 years. Unfortunately, the study was unable to converge the 100 kWe case for Venus, but it appears that the round trip time will be fairly similar, based on the relative trip times found for the higher powers for Mars. Given a 15 year operating life, the NEPTranS vehicle operating at 100 kWe should be able to perform at least three round trip missions to Mars, Venus, or any combination of the two target planets.

4. Radiation Environment and Contingency Operations

NEPTranS must protect its avionics and payload against radiation from both the fission reactor and the inner and outer belts of trapped radiation due to the Earth's magnetic field. In addition, the operational scenarios developed in this study pose unique questions regarding the potential for failure and disposal of the reactor power system in Earth orbit. In order to operate the reactor in LEO all possible failure scenarios will need to be assessed and controls or contingency operations put in place to cover all credible scenarios. It is beyond the scope of this study to perform a comprehensive operational failure analysis, but it is possible to identify some of the possible worst-case scenarios that will need to be addressed.

Radiation from fission reactor

The fission reactor radiation environment can be divided into three distinct mission phases:

1. Launch to initial on-orbit startup (essentially no significant radiation)
2. Full power flight operation
3. Decay radiation during Shuttle servicing operations

The first of these is easily addressed as the reactor is essentially non-radioactive prior to initial startup. The total dose rate including both gamma and neutron radiation for a person standing 1m from a pre-operational reactor is 1.2 μR/hr. This is equivalent to an annual background exposure over 34 years (Houts, et al., 2002).

Once the reactor is started on-orbit the radiation level quickly becomes a significant factor, both for safety of the Shuttle and crew, and survival of the spacecraft avionics. Fortunately, the design of shielding for an operating reactor in a space environment is relatively straightforward. The "straight-line" nature of both the neutron and gamma ray radiation from the reactor core allows the adoption of a "shadow shield", which can be tailored to provide a survivable total mission radiation dose in a cone with an angle specified in the vehicle design. For NEPTranS, the shield design consists of a 10° half-angle cone, providing ample room within the shadow to protect all vehicle equipment, as well as the planetary payload during reactor powered operations.

Shield design is flexible, using a variable thickness of LiH material for neutron shielding and a much smaller thickness of Tungsten or other High-Z material for mitigation of gamma ray dose. For NEPTranS the shield design is specified to result in no more than 100 krads total mission dose to the vehicle avionics and no more than 10^{11} n/cm^2 total neutron fluence over the 15 year vehicle life. These doses, when combined with the contribution from multiple traverses of the Van Allen belts, will require the use of rad-hard components, but should not impose overly restrictive requirements that extend beyond currently available or planned technology.

When the NEPTranS vehicle returns to Shuttle orbit following a planetary mission, the reactor will be commanded to shut down. Upon shutdown the neutron radiation essentially disappears, and the gamma radiation also drops considerably. However, this gamma radiation (resulting from decay of daughter products built up during the period of reactor operation) remains significant for some time, and must be seriously considered in design of the Shuttle servicing portion of the mission design. The dropoff of gamma dose rate in the days following shutdown for a 400 kWt reactor operating for 5 years is shown in Figure 9.

It is apparent from this curve that it is valuable to allow a cool-down period before the Shuttle is allowed to approach the vehicle for servicing. It is evident that the greatest reduction in gamma ray dose is achieved in the first 20 days, with a slower decay continuing beyond that.

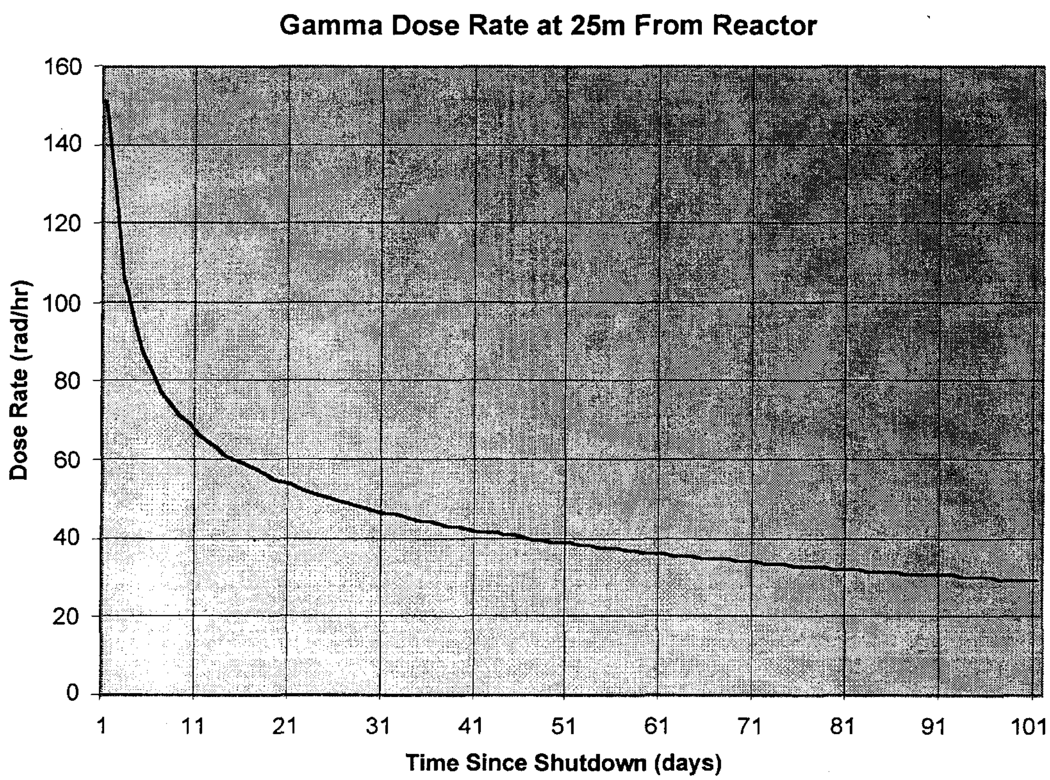


Figure 9. Gamma Dose Rate Following Shutdown at 25m from Reactor (Unshielded)

A shutdown period of 30 to 60 days appears to be adequate to bring the gamma ray dose to manageable levels to allow the Shuttle Orbiter to rendezvous with and service the NEPTranS vehicle.

It should be noted that the levels shown in Figure 9 represent unshielded dose rates. These are the radiation levels that might be seen in a worst-case condition at portions of the Orbiter that might be outside the shield cone. For servicing missions an additional gamma ray shield will be incorporated into the reactor shield design to bring the shield half-cone angle for gamma rays up to 15°. This will allow shielding of the crew compartment and work area in the payload bay to much lower levels that will protect the crew and critical equipment during servicing operations. This extent of the shadow cone during Orbiter servicing and resupply operations is illustrated in Figure 10.

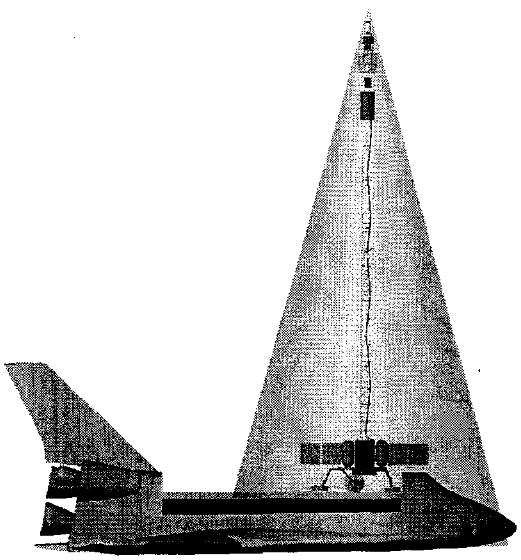
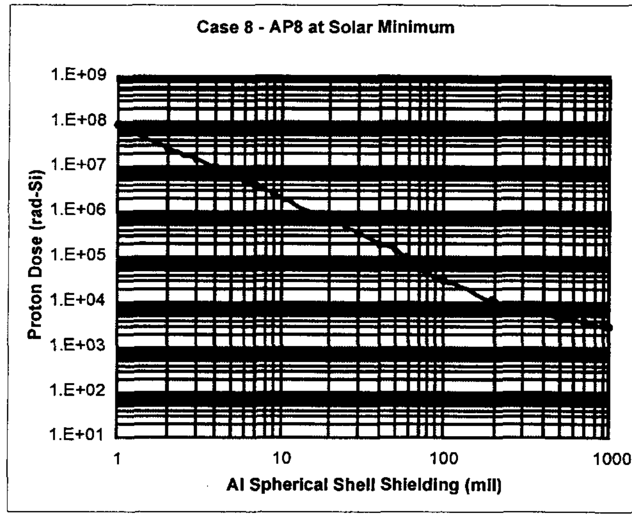


Figure 10. Illustration of 15° Shielded Area During Orbiter Servicing Operations.

Radiation from van Allen belts

Because the baseline scenario calls for Shuttle launch to 500km altitude it was decided to launch to as high an inclination as possible to minimize Van Allen radiation exposure during the Earth spiral out stage of the mission. Figure 11 below illustrate the estimated level of electron and proton flux NEPTranS can expect to encounter as a function of shielding thickness during its Earth spiral out stage for a 100kWe system following the trajectory defined in the previous section. These curves are for a 60° inclination spiral orbit, representing the limit of Shuttle capability. Shuttle performance to a 57° inclination at 500 km would be limited to a 12,000 kg payload, which is less than the 14,000 kg initial estimate for the NEPTranS Earth departure mass used for the trajectory analysis. A trade study is needed, therefore, to weigh the benefit of lower radiation levels against the need to offload the propellant tanks, for example, for on orbit attachment.



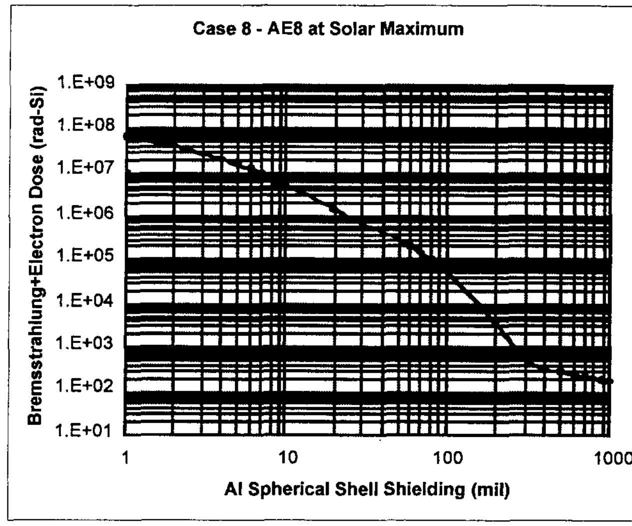


Figure 11. Proton and Electron Dose from Van Allen Radiation During Earth Spiral Out

Contingency Operations

Nuclear technology is well established with a long history of applications in terrestrial power plants and naval operation in submarines, cruisers and aircraft carriers. Both the US and Russia have space experience with nuclear reactors. Enabling technologies are all well within feasible range for the time frame being considered.

Cost risks associated with the development of the advanced ion engines and autonomous rendezvous and docking technologies are no higher than other similar scale technologies. While cost effectiveness of previous interagency cooperative programs have varied widely, there is no inherent obstacles to efficient sharing of resources among the agencies concerned.

Safety and reliability risks are manageable. While the consequences of a major failure are potentially high, the probability of occurrence of such catastrophic failures can be shown to be acceptably low. Tables 4 and 5 represent some major failures and corresponding responses.

Table 4. Contingency During Initial deployment

Failure Scenario	Contingency Operation
boom/radiator/thruster/Solar Array deployment failure	In case of a mission critical deployment or startup failure that can't be fixed on orbit, the appendages will need to be retracted and safed, and the vehicle returned to the payload bay for return to earth. An option here if landing mass is an issue is to vent the Xenon tanks before return. That will reduce vehicle mass by 6000 kg or so.
auxiliary power system (solar or battery) fails energize bus	In case of power or any subsystem failure, contingency plans should be prepared for on-orbit repair as feasible. If plans fail or are not feasible, follow procedure above for return.
reactor start up failure	Contingency ops dependent on failure mode. There may not be much recourse here but to bring the vehicle back
EP system fails to start	Provided the reactor hasn't been running very long it may be possible to shut down, safe the reactor and bring the vehicle back. However, this option quickly goes away the longer the reactor operates

Table 5. Contingency During Servicing

Failure Scenario	Contingency Operation
reactor shutdown failure	In this case, the vehicle will be commanded to boost itself back up to 2500 km
NEPTranS ACS failure (S/C is spinning/ tumbling)	If the reactor is shut down and the tumble rate is slow enough there may be something the Shuttle can do, but extensive planning will be required, since it will be difficult to keep the Shuttle in the shield cone. However, that could be helped out somewhat by giving additional time for the reactor to decay before approaching it, or perhaps an autonomous vehicle could do something to stop the tumble before the Shuttle approaches.
reactor start up failure	Provided the reactor hasn't been running very long it may be possible to shut down, safe the reactor and bring the vehicle back. However, this option quickly goes away the longer the reactor operates
propellant tank, ion thruster (or any other orbit-replaceable unit), sample return cannister/payload changeout failure	Possibly effect minor repairs or patches to radiator system if need as long as it's in an area that's either within reach of the arm or in an area that does not result in excessive dose to crew member during EVA
reactor or EP system fails to restart	In this case, we would need to attach the chemical boost stage and blast the vehicle up to 2500 km, removing tanks, payload, and whatever else can be taken off to minimize mass before the reboost

For the case of the reactor failing to shut down in LEO, the capability of Shuttle servicing will be lost. In this case a contingency operation would be to boost the vehicle up to a 2500 km disposal orbit using its NEP system. The NEPTranS vehicle Xenon fuel load will always include reserve propellant to allow such a contingency scenario.

The majority of other conceivable failure scenarios involve stranding the vehicle with a hot (but shut-down) reactor in LEO. For this case the contingency operation will involve finding an alternative to the NEP system for boosting the vehicle to the safe disposal altitude. This can be achieved by providing a suitable transfer vehicle (carried up and attached by the Shuttle) able to provide the appropriate delta-V. Table 6. shows a number of vehicles currently available or under development include that could be adapted to this task:

Table 6. Options for Contingency Boost.

Spacecraft	Launch Vehicle	Propellant Upmass
Automated Transfer Vehicle	Ariane 5	4,000 kg (for ISS reboost maneuver)
H-IIA Transfer Vehicle	H-IIA	up to 7,000 kg of pressurized cargo using standard ISS pressurized module (not currently configured to deliver propellant)
Progress M1	Soyuz	up to 1,950 kg
K-1 Orbital Vehicle	K-1	1,600 kg

The delta-V to do a Hohmann transfer from 500 km to 2500 km is 908.4 m/s. The propellant masses necessary to do this, for various Isp (chemical), are:

Isp = 325, high-performance bipropellant
Mf = 329.8 kg per 1000 kg of spacecraft mass

Isp = 310, medium-performance bipropellant
Mf = 348.3 kg per 1000 kg of spacecraft mass

Isp = 230, high-performance monopropellant
Mf = 495.9 kg per 1000 kg of spacecraft mass

Note the spacecraft mass includes the mass of the transfer vehicle. Thus if the transfer vehicle is 1000 kg and the NEPTranS vehicle with payload is 7000 kg, it would take 2790 kg of propellant using the ESA medium-performance biprop system on its ATV. It should not be difficult to run only two of the 490-Nt engines at a time, keeping the total thrust below 1000 Nt (225 lb). The boom should be designed to withstand this level of loading in longitudinal compression. The problem may be possible excitation of transverse oscillatory modes in the boom as the engines run, though if the boom is sufficiently damped, those amplitudes could be controlled within acceptable ranges.

At 980 Nt of thrust, 8000 kg of spacecraft plus transfer vehicle plus 1500 kg of propellant (an average value) accelerates at only 0.1 m/s^2. It takes about an orbit period to get 450 m/s of delta-V, so this will be a spiral-out rather than a Hohmann transfer, and thus the delta-V requirement and propellant mass requirement will increase over the Hohmann values. The four engines are rated to collectively burn the entire 4,000 kg propellant load so lifetime issues should not be a concern. Also the 1200 extra kg of propellant should be sufficient to overcome the inefficiencies of the spiral-out.

It is proposed that such a transfer vehicle be brought up by the Shuttle with each servicing mission, available for attachment should the NEPTranS vehicle fail to restart following servicing. This additional value provided by use of the Space Shuttle greatly enhances the viability of the NEPTranS mission concept.

5. COST BENEFIT ASSESSMENT

Cost estimations for NEPTranS depend significantly on whether or not the development, design, testing and verification of the nuclear power system is included as part of the overall cost. If this is the first time that an NEP system carrier is being developed, than development will likely span longer time periods than the conventional 3-9-36 week design phase template for spacecraft development projects. Unique facility and resource requirements associated with nuclear technology at the manufacturing and launch processing sites will likely add to the cost.

NEPTranS Life Cycle Cost Estimate

A baseline assumption in this study is that NEPTranS will not be the first mission for NEP. Reactor development and non-recurring infrastructure costs are assumed to have been borne by preceding missions. Thus, only the recurring cost of manufacturing the nuclear power system is considered in this analysis.

The NEPTranS study team did not have the resources to do an in-depth cost estimate for this point design, however a number of NEP studies have been performed recently in which fairly detailed cost estimates were derived by the individual centers involved with producing analogous vehicle concepts. We derived a rough order of magnitude cost estimate for NEPTranS based on these recent studies and adapting individual element costs for the particular characteristics of the NEPTranS mission, including a baseline 15-year operational life.

Breakeven Point Analysis

As part of this study it was desired to find the break-even point where the incremental cost curve of individual conventional or SEP Mars missions crosses the estimated cost curve of the NEPTranS system. For comparison, we chose 6 SEP mission designs that were developed which we felt were closest in terms of the flight system design that might be used for a Mars or Venus sample return mission.

Since none of the SEP missions have enough mass delivery capability to deliver a Mars or Venus lander and ascent vehicle with a sample return capsule, we need to add the cost of a separate launch and carrier system whose mission would be to deliver the 2,500 kg payload per the NEPTranS reference mission. When adding this cost to the average cost of the SEP missions, we find that the lifetime cost of the NEPTranS vehicle for three roundtrip sample return cycles is competitive with three separate incremental SEP missions that would be needed to achieve the same objectives. Figure 12 shows that the intersection of the two cost curves would be somewhere between the second and third roundtrip cycles.

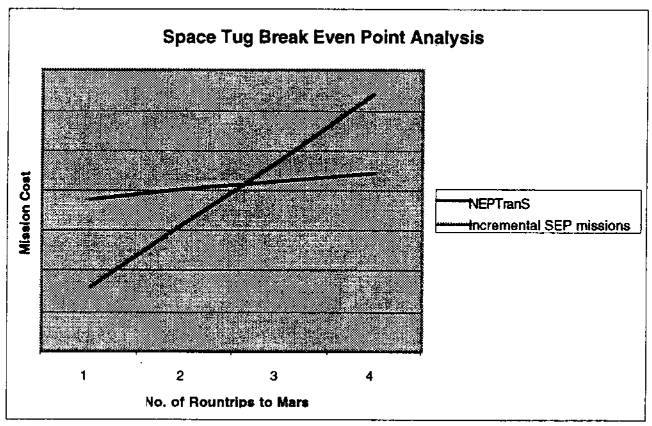


Figure 12. Breakeven Point Analysis Illustration

Another comparison is made with a Mars SEP cycler concept proposed by industry. Since this concept does not include the cost of the delivery of the lander and AV and only makes two round trips, we performed a set of extrapolations to derive another rough order of magnitude cost comparison, which provided similar results.

6. CONCLUSIONS AND RECOMMENDATIONS

The NEPTranS vehicle and operations concept could provide a major benefit to inner planet exploration in the next decade. The availability of a reusable, upgradable vehicle that can be adapted to a wide variety of diverse missions without major on-orbit modifications has broad implications for future mission planning activities. The design developed in this study will require considerable detailed analysis to verify the mass and performance that have been assumed are attainable, but the study team is confident that the basic concepts, both for vehicle and mission design, are realistic and would provide a valuable addition to any long-term interplanetary mission architecture.

To further refine the NEPTranS concept the study team recommends conducting further studies in the following areas.

- Quantify radiation effects during Earth escape and in transit
    - Consider spiraling out in Earth polar orbit
    - Consider alternative means to minimize, shield against neutrons, positrons, gamma rays, etc.
- Conduct a parametric study using payload mass as a variable
    - Consider various scenarios for delivering different amounts of mass to Mars (and Venus) and returning different amounts of mass back to Earth.
    - Consider mission designs incorporating different types of payload (e.g., micro-satellite constellation for remote sensing, communications and/or positioning on Mars (and Venus))
- Examine alternatives to ion thrusters given the potential for large amount of electrical power.
- Investigate the use of NEPTranS as a tug for outer planet missions.
- Derive detailed cost estimates.
- Analyze economies-of-scale factors in deploying a large number of NEPTranS vehicles, potentially as a backbone for an interplanetary transportation infrastructure.
- Develop alternative missions for the NEPTranS vehicle such as communications relay, microwave transmission of power, on-orbit robotic servicing and repair, spacecraft towing, etc.
- Evaluate potential need for such an interplanetary transportation infrastructure by assessing future plans by
    - International space science community
    - Space commercial operations
    - Space based Earth monitoring and protection, planetary defense, space based homeland security applications, etc.

7. ACKNOWLEDGEMENT

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