NEP PROCESSING, OPERATIONS, AND DISPOSAL

FINAL REPORT AND PRESENTATION

Task Order 20

Contract NAS3-25809

by

Science Applications International Corporation

and

Martin Marietta Astronautics Group

for

NASA Lewis Research Center

Nuclear Propulsion Office

October 20, 1992

MARTIN MARIETTA

SAIC

Several recent studies by ASAO/NPO staff members at LeRC and by other organizations have highlighted the potential benefits of using Nuclear Electric Propulsion (NEP) as the primary transportation means for some of the proposed missions of the Space Exploration Initiative. These include potential to reduce initial mass in orbit and Mars transit time. Modular NEP configurations also introduce fully redundant main propulsion to Mars flight systems, adding several abort or fall-back options not otherwise available. Recent studies have also identified mission operations, such as on-orbit assembly, refurbishment, and reactor disposal, as important discriminators for propulsion system evaluation. This study is intended to identify and assess "end-to-end" operational issues associate with using NEP for transporting crews and cargo between Earth and Mars. We also include some consideration of lunar cargo transfer as well.

The study was performed by SAIC and Martin Marietta under direction of Michael Doherty of the NASA/LeRC Nuclear Propulsion Office. Mike Stancati (Study Leader) and Jim McAdams of SAIC performed the rendezvous and disposal modes analysis. Tal Sulmeisters and Dr. Robert Zubrin of Martin Marietta prepared the launch, assembly, and refurbishment sequences. The study team wishes to acknowledge the guidance and valuable comments by Mike Doherty, Jim Gilland of Sverdrup Technology, and Len Dudzinski and Jeff George of NASA/LeRC.

Study Purpose

Identify and assess operational issues associated with using Nuclear Electric Propulsion for SEI missions, including Mars cargo and piloted, and lunar cargo transfer:

- Launch and assembly
- Spiral operations and crew rendezvous
- On-Orbit Refurbishment and maintenance of a reusable NEP transfer vehicle
- NEP disposal

Ground Rules

This study concentrates on operational issues, rather than performance assessment of alternative technologies against some set of user requirements. For this reason, certain items are specified as given. The NEP system is a modular concept, which was identified and studied in several recent activities by LeRC. Changes or enhancements to this basic system are proposed only for operational reasons; beyond very basic calculations, we have not optimized specifications or sizing. Payloads are consistent with many earlier studies to support a crew of four round-trip to Mars.

Commonality of design and operations is preferred throughout. This means, for example, that a single Earth orbit will be selected for both initial assembly and refurbishment between missions. Similarly, common procedures will be used for operation of both piloted and cargo transfer vehicles.

Simplicity of in-space operation is also a ground rule. The processing sequences proposed and evaluated are selected to minimize the complexity of on-orbit operations. Infrastructure and resources are minimized, consistent with safe, effective operation.

Finally, we address reactor disposal using conservative approaches in all cases.

Ground Rules

- Specified NEP reference systems for cargo and piloted transfer vehicles, based upon propulsion module concept studied previously at LeRC
- Payload sizing generally consistent with earlier studies for a crew of 6
  - Mars transit habitat = 40 t
  - Earth Crew Capture Vehicle = 7 t, for Apollo-type reentry with $V_\infty \leq 9.4$ km/s
- Prefer common NEP vehicle configurations and processing sequences for piloted and cargo missions
- Minimize on-orbit operations and infrastructure
- Safe reactor disposal for all cases, from normal end of life to propulsion system failure
- Split mission profile
  - cargo MTV carries surface payload and MEV; crew MTV carries return propellant
  - use 2012 cargo/2014 piloted opportunity for calculations

Assumptions for NEP System Scaling

Each module includes a complete propulsion system, from energy source to thrusters, and the necessary structural support. The reactor is designed to deliver 5 MWe at full power, with an efficiency of about 20%. Design life for the reactor is two years at full power. The module mass estimate is just under 37 t, including all subsystems, so the target specific mass is 7.3 kg/kWe. Studies by LeRC and GE indicate that, while this represents an advance in state-of-the-art, it is a reasonable projection for attainable capability in the near term.

Cargo flight to the Moon or Mars would use a transfer vehicle configuration with a single propulsion module. Piloted flights to Mars would include system-level redundancy with two fully configured propulsion modules delivering a total of 10 MWe. In addition to improving nominal performance, the piloted Mars Transfer Vehicle (MTV) features several abort modes for degraded propulsion systems, including loss of an entire module. A parallel study by SAIC (Task Order 19 of this contract) reports a preliminary risk/reliability assessment of the two-module "Hydra."

Assumptions for NEP System Scaling

Each propulsion module - "relatively near-term" technology

- Complete, self-contained propulsion system with: growth SP-100 reactor, K-Rankine power conversion, PMAD, thrusters, heat rejection, and supporting truss structure
- Reactor delivers 5 MWe full power over 2 year life
- Argon ion thrusters, Isp = 5000 s, 10,000 hour life
- Module specific mass (includes all subsystems) = 7.3 kg/kWe

Transfer Vehicle Configurations

- One 5 MWe module for cargo flights
- Two 5 MWe modules for piloted flights

NEP/MCV Concept

[illegible] on-orbit assembly, a recommended [illegible] consists of [illegible] segments. The forward [illegible] a short width of [illegible] m and a large width of [illegible] side area [illegible] remaining two [illegible] [illegible] sq. m. slightly larger than [illegible] (supplied [illegible]).

The reactor is mounted on the short width end of the forward segment and can be packaged within the con[illegible] of the shroud.

The deployment sequence is automated and does NOT require on-orbit assembly. The automated extension of the boom is also possible (a design of such nature was analyzed for the Thermionic Space Nuclear Power system proposal).

The remaining key items i.e. two solar pannels (1 kw each), CTV docking port, FTS and an engine pod are launched with each vehicle. Cargo, CTV and the propellant module are launched as lift and packaging capabilities allow. Specific subsystem design concepts would be required to specifically manifest and package a given mission.

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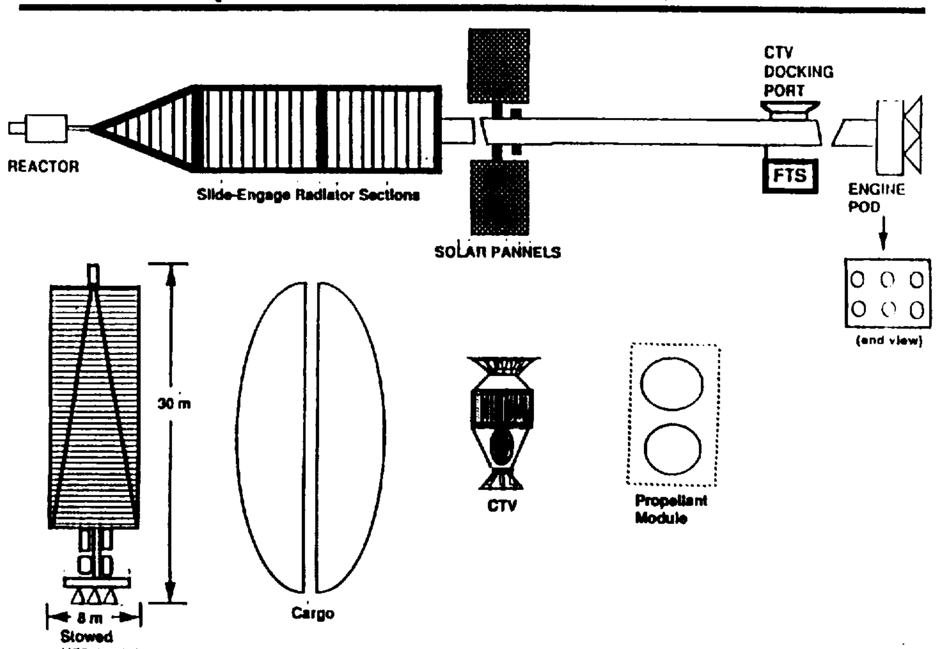
NEP Concept - MCV



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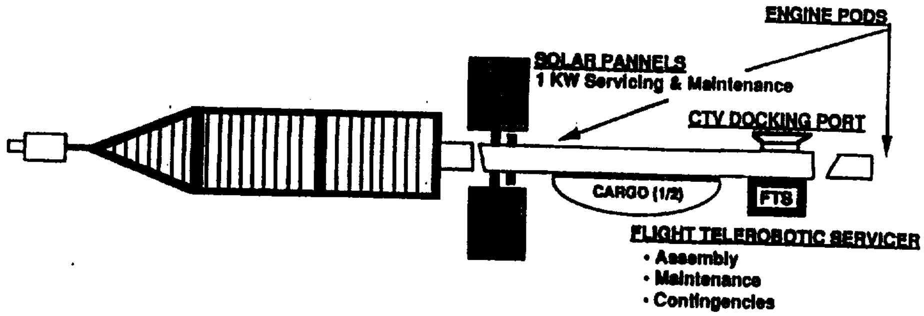
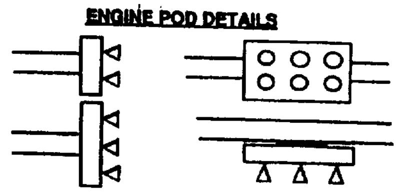
NEP Concept - Key Items



GROUND RULES
- NO Planned EVA for Assembly
- NO Planned Contingency EVA
- Docking Operations ROBOTIC/ Automated

ENGINE POD DETAILS



- Engine Sets Can be Mounted on Side or End of the Boom
- Propellant Tank Pods Can be Mounted on Side or End of the Boom

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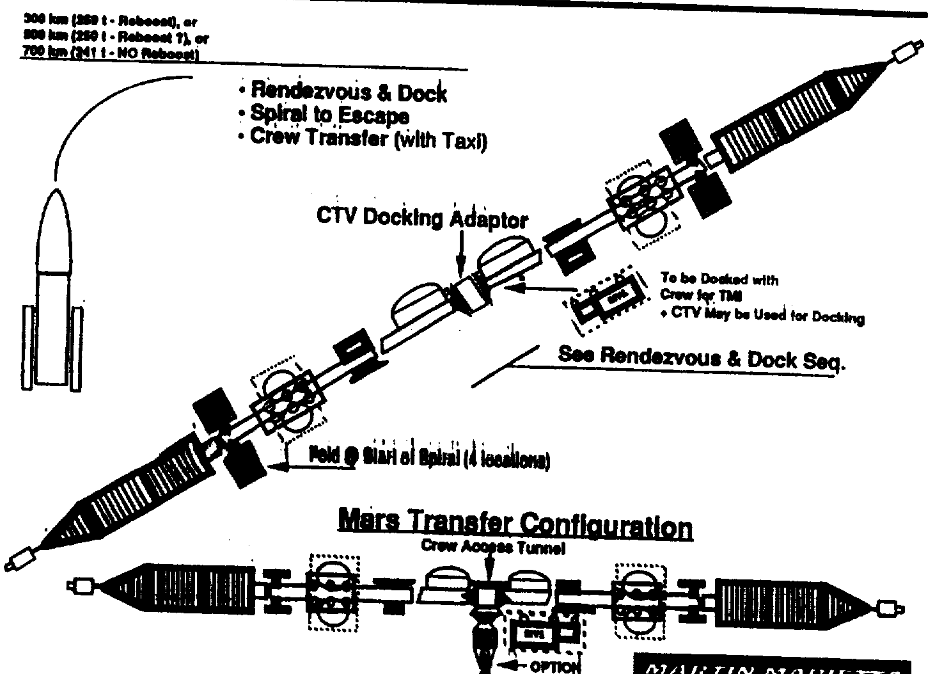
MPV Orbital Ops



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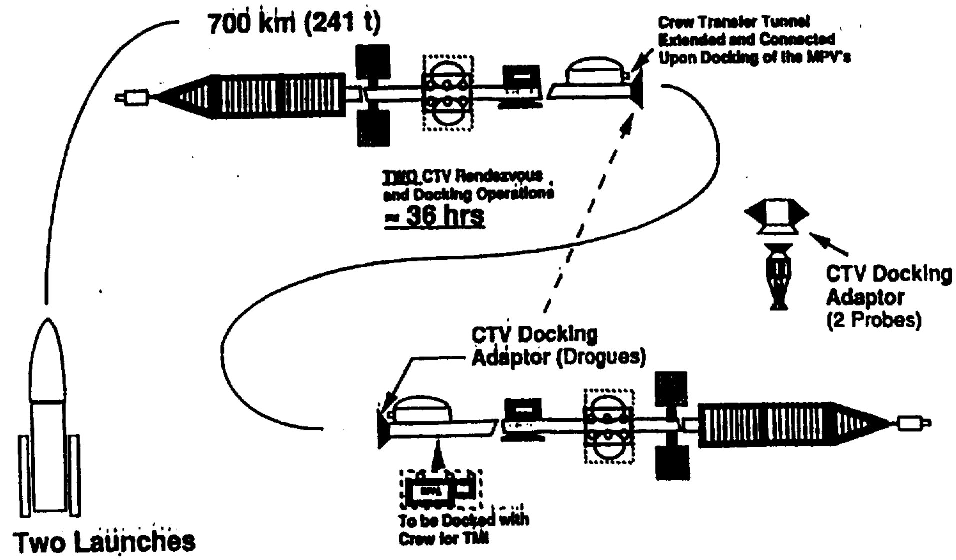
MPV Orb Ops - RENDEZVOUS & DOCK



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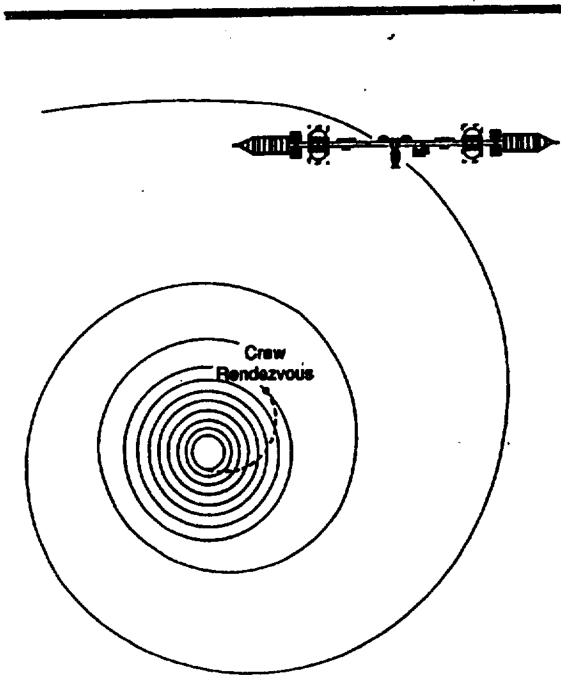
Crew Rendezvous Summary



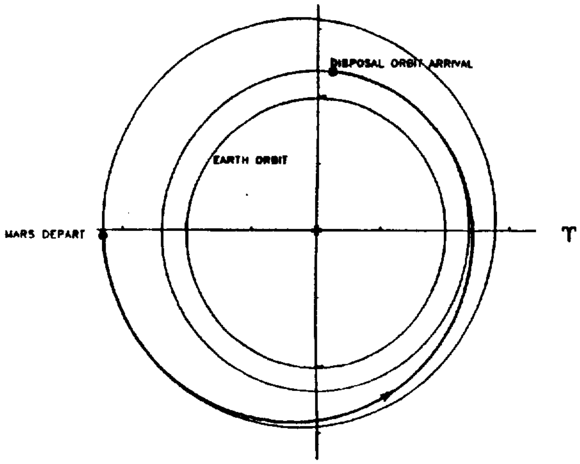
Earth Departure Spiral

- Crew rendezvous in high Earth orbit (> 20,000 km) prior to escape
- Use co-elliptic approach and terminal closing strategy of Gemini/Apollo
- Applies to all spiral thrusting programs and Earth-Mars trajectories
- Requires a Crew Taxi vehicle
- Option: co-elliptic rendezvous in lunar orbit

Mars Orbit Operations

- A sequence of co-elliptic approaches
- Piloted chase vehicle in each case
- Avoid docking 2 large structures

NEP Disposal - Summary



Vehicle and Infrastructure Implications

- Include auxiliary propulsion in 5 MWe module design for orbit raising (150 m/s)
- Separate disabled reactor from rest of module - optional capability
- OTV for assured removal from Earth orbit

- **Nominal End of Life** - use stable heliocentric orbit
  - modest propellant requirements
  - conservative risk management

- **Disabled Vehicle** - use interplanetary path
  - orbit life of ≥ 10^7 years
  - collision risk similar to asteroids
  - no ΔV

- **What About Earth Orbit?**
  - temporary storage only
  - avoid long-term storage perceived risk

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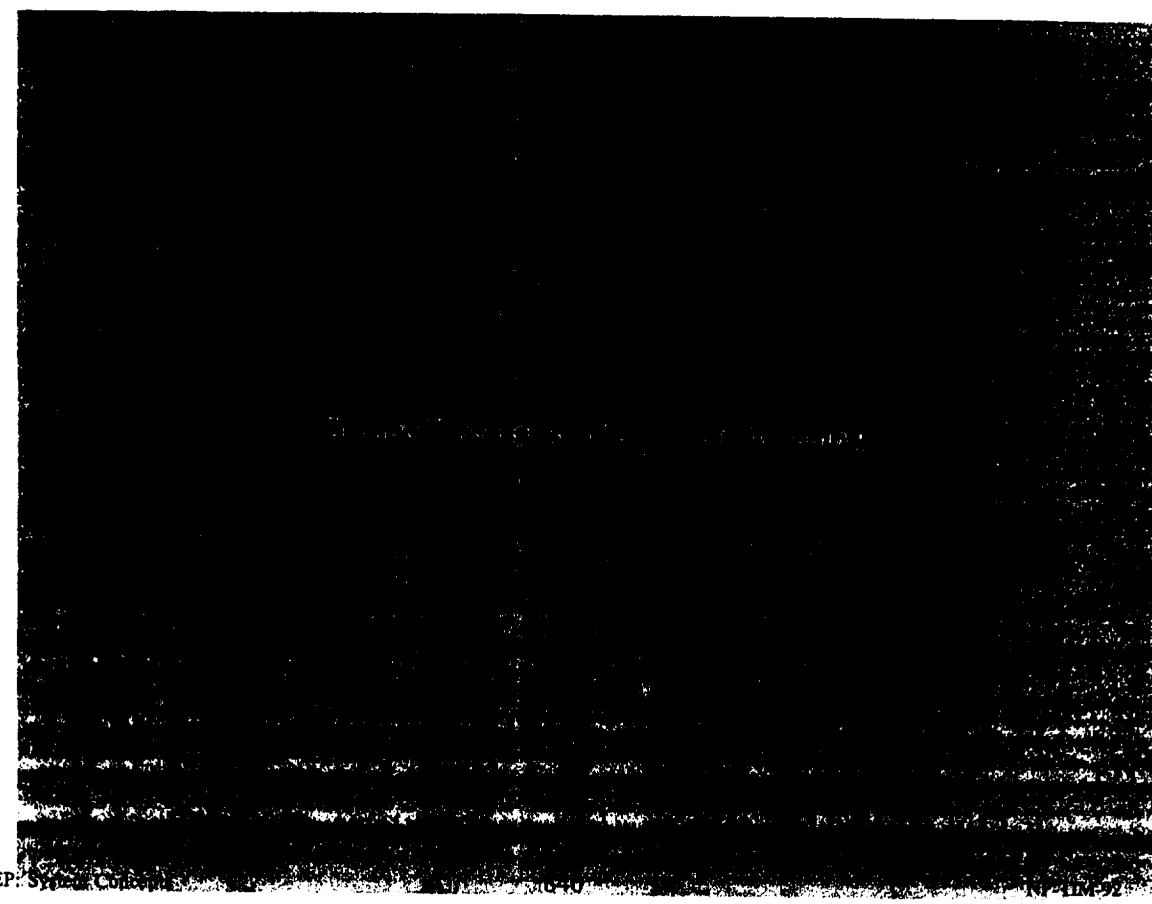

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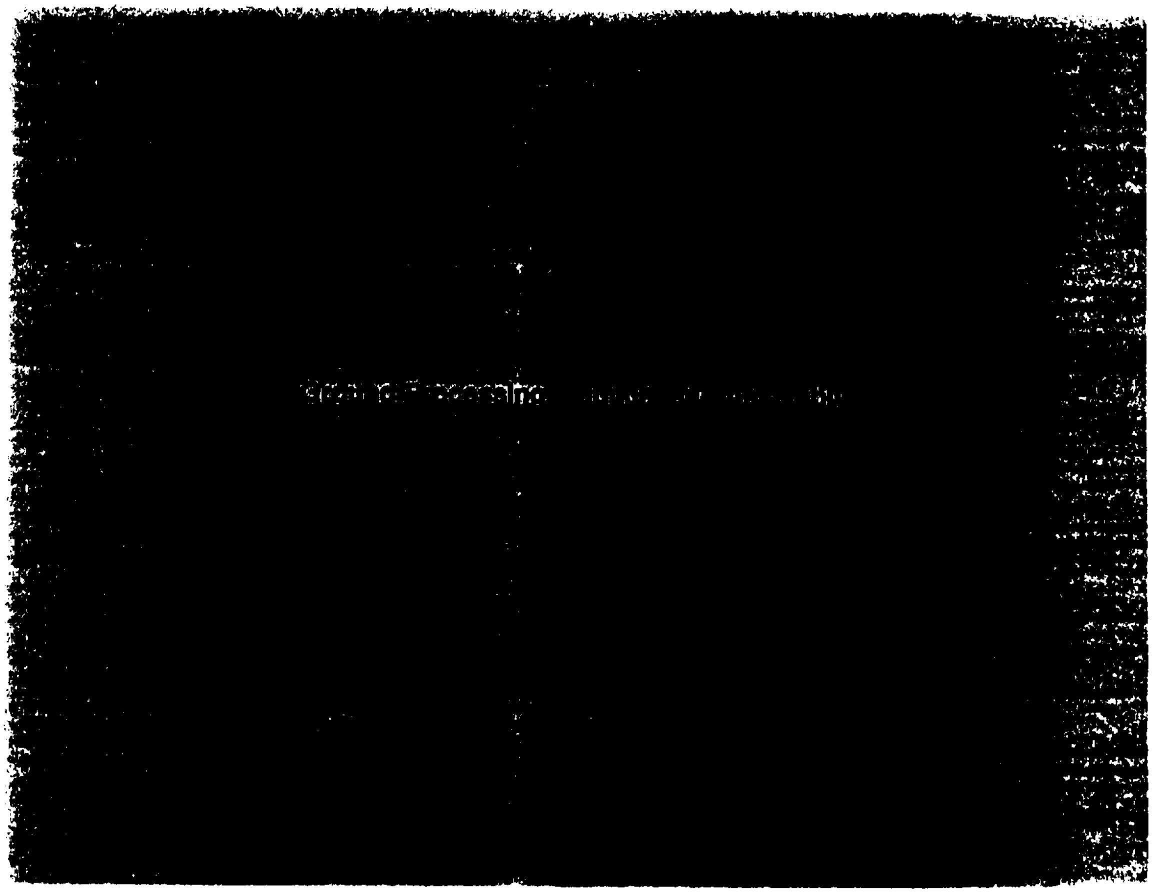

Ground Rules & Assumptions

GROUND RULES:

- NO Planned EVA's for Basic Assembly or Contingency Operations
- Docking Operations are Automated
- Robotics (i.e. FTS) Used for Maintenance and Refurbishment Ops
- 700 km Orbit is the Point of Departure for Assembly and Return Ops
- Maximize Common NEP Configurations for Cargo and Piloted Missions
- Minimize On-orbit Assembly and Required Supporting Infrastructure

ASSUMPTIONS:

- Use of a Cargo Transfer Vehicle (CTV) is Available
- Flight Telerobotic Servicer (FTS) is Available
- CTV Docking Port is Available on Each Vehicle
- ≈250 t Launch Vehicle with Supporting Facilities is Available

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Mass of NEP Vehicle Missions

The NEP vehicles addressed in this study had three missions, Lunar cargo, Mars cargo, and Mars piloted with the mass breakdown as shown on the facing page.For the manned mission, there is an additional cryogenic chemical Crew Taxi with an initial mass in LEO of 57 tonnes. It is used to transport the crew from LEO to the point of rendezvous prior to Trans Mars Injection.

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Mass of NEP Vehicle Missions

	Lunar Cargo	Mars Cargo	Mars Piloted
NEP Spacecraft	40	40	80
Habitation & ECCV	0	0	50
Propellant	48	91	177
Tanks	5	9	18
Cargo	140	160	0
Total	233	300	325

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TS-NEP-1

Saturn V Derived Orbital Delivery Capability

The performance calculations shown were based on a Saturn V derived Heavy Lift Vehicle (HLV) under consideration for use in the First Lunar Outpost (FLO) transportation system. FLYIT code (Martin Marietta proprietary launch vehicle simulation) was used. The HLV has a cryogenic 2nd stage. Since performance loss to 700 km is very modest and orbital decay from 700 km is about 30 times greater than from 400 km, this altitude was BASELINED for this study.

Examination of the launch mass requirements with the capabilities indicates the need for TWO launches to support each of the Mars missions, however, considerable excess capability exists. To improve the manifesting efficiency, it is suggested that a "banking" approach be considered where the extra capability is filled with additional propellant, spare components, etc. for use on other missions. These could be stored on orbit, possibly on a platform.

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Saturn V Derived Orbital Delivery Capability

Orbital Altitude (km)	Payload (tonnes)
300	259
500	250
700	241

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TS-NEP-2

"Gut Feel" Baseline Mission for NEP

The basic steps to accomplish a cargo or piloted mission using NEP vehicles are summarized. Individual mission sequences along with options are described in following charts. Some of the options, i.e. return to earth of a NEP cargo vehicle are also identified.

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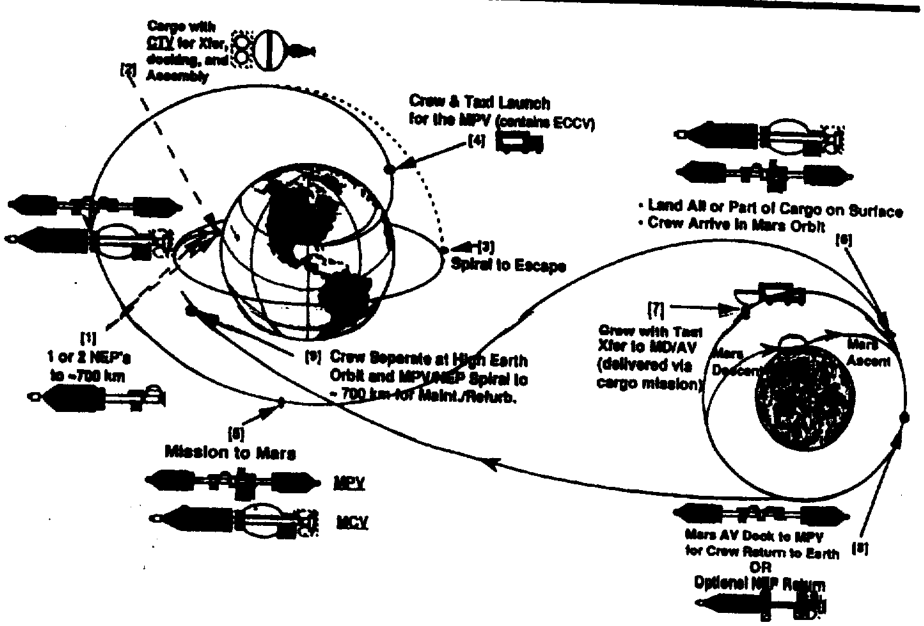
"Gut-feel" Baseline Mission for NEP



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Mission Sequence - MARS/LUNAR CARGO

The numbers indicate the sequence of functions. Some options are desirable at certain times in the mission as follows:

1. Take CTV to Mars -
2. All cargo left in Mars orbit or some landed on Mars
3. NEP from Mars/Lunar flight returned and circularized in ~ 700 km earth orbit.

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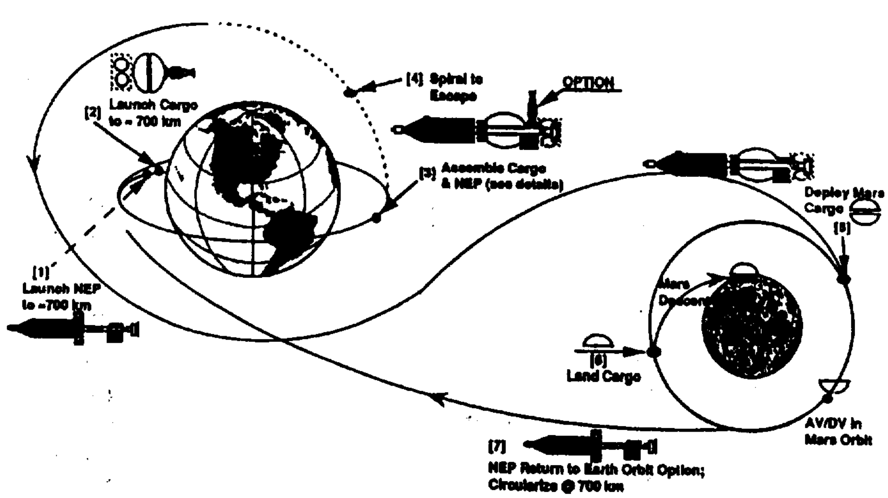
Mission Sequence - MARS/LUNAR CARGO



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Mission Sequence - MARS PILOTED, LAUNCH

Two NEP's are launched in separate launches. It may be possible to launch two NEP's with the crew habitats and one ECCV in one launch (this requires some additional conceptual work for the vehicle and habitat design definition). If the NEP's are launched separately, a CTV is used to assemble the two vehicles using a CTV adaptor. This would provide some backup since the CTV can maneuver and it would not require initial designation of each NEP as to which is the target and which is the chase vehicle. It is envisioned though that a stabilization system of some sort will be required on each NEP vehicle. Sizing of these systems and the CTV should be traded and worked in an iterative manner.

Use of the CTV and the adaptor, could provide further redundancy by implementing multiple docking probes.

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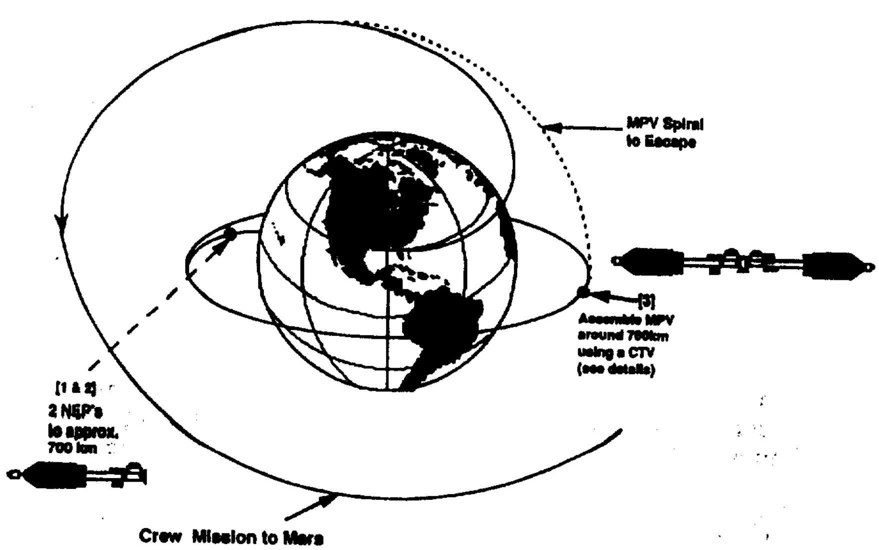
Mission Sequence - MARS PILOTED, LAUNCH



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Mission Sequence - MARS PILOTED, CONT'D

Upon MPV completion of spiraling to escape, the Mars crew is launched in a taxi that has an ECCV capability. The taxi rendezvous with the MPV assembly and continues to Mars. Once the vehicle is circularized in Mars orbit, the crew, using the taxi, transfers to the Mars Descent (MD)/Ascent Vehicle (AV), previously delivered to Mars orbit by the cargo mission. Subsequently the crew lands on Mars and after the requisite stay time, returns to the MPV for return to earth. When high earth orbit is attained, before the spiral down to 700 km, the crew separates in the ECCV for return to LEO or earth direct.

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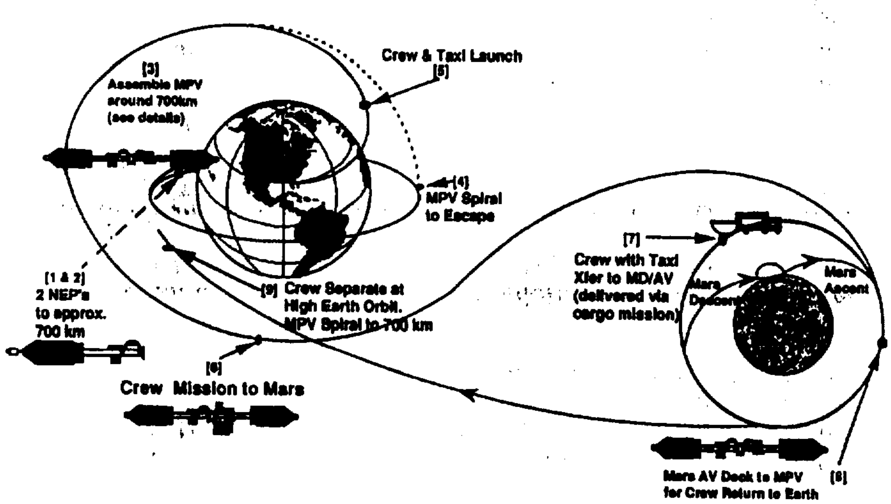
Mission Sequence - MARS PILOTED, CONT'D.



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NEP/MCV - Concept

To fit within a 10X30 m fairing, presently planned for HLV's, and to avoid on-orbit assembly, a recommended radiator design, used in this study, consists of 3 segments. The forward trapezoidal segment, 11 m long has a short width of 4.5 m and a large width of 8 m resulting in a 69 sq. m per side area. The remaining two segments are rectangular, 8X18 m resulting in an area of 144 sq.m per side. Thus the total radiator has an area of 357 sq. m, slightly larger than the baselineconfiguration of 347 sq. m (supplied design).

The reactor is mounted on the short width end of the forward segment and can be packaged within the conic region of the shroud.

The deployment sequence is automated and does NOT require on-orbit assembly. The automated extension of the boom is also possil (a design of such nature was analyzed for the Thermionic Space Nuclear Power system proposal).

The remaining key items,i.e. two solar pannels (1kw each), CTV docking port, FTS and an engine pod are launched with each vehicle. Cargo, CTV and the propellant module are launched as lift and packaging capabilities allow. Specific subsystem design concepts would be required to specifically manifest and package a given mission.

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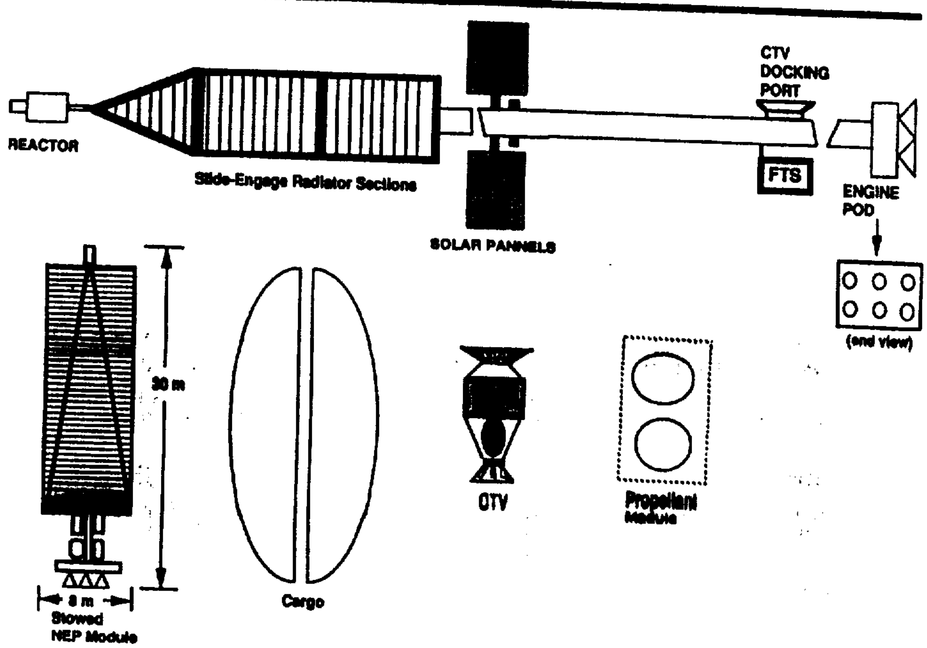
TS- NEP/MCV Conc-FP

NEP Concept - MCV



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NEP Key Items

The NEP vehicle has a reactor assembly, a boom assembly, an FTS to assist in contingency, repair and on-orbit maintenance operations, an engine pod, located at the end or along the boom, depending on the use of a given vehicle, i.e. cargo/end or piloted/side, a CTV docking port, and two solar pannels (1kw each) to provide communications, control functions (RCS subsystem may be desirable) and FTS operations.

Cargo attachments (docking ports ?) for major cargo items and onboard spares will be provided and require a conceptual design to afford timeline development for maintenance or repair operations (what parameters and to what degree of finesse they must be specified is addressed under the FTS operations part of this study).

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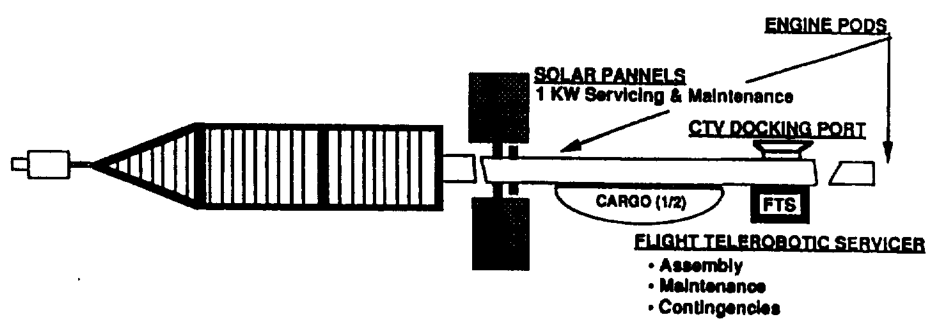
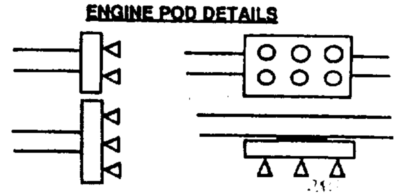
NEP Concept - Key Items



GROUND RULES
- NO Planned EVA for Assembly
- NO Planned Contingency EVA
- Docking Operations ROBOTIC/ Automated

ENGINE POD DETAILS



- Engine Sets Can be Mounted on Side or End of the Boom
- Propellant Tank Pods Can be Mounted on Side or End of the Boom

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NEP Ground Ops Flow

The NEP processing cells can handle the basic or cargo as required. Upon completion of packaging and required amount of encapsulation, the basic vehicle or the cargo set is moved to the Vertical Assembly Building for stacking with the launch vehicle.

The only on-pad operations planned would be associated with cryogenic systems and their handling.

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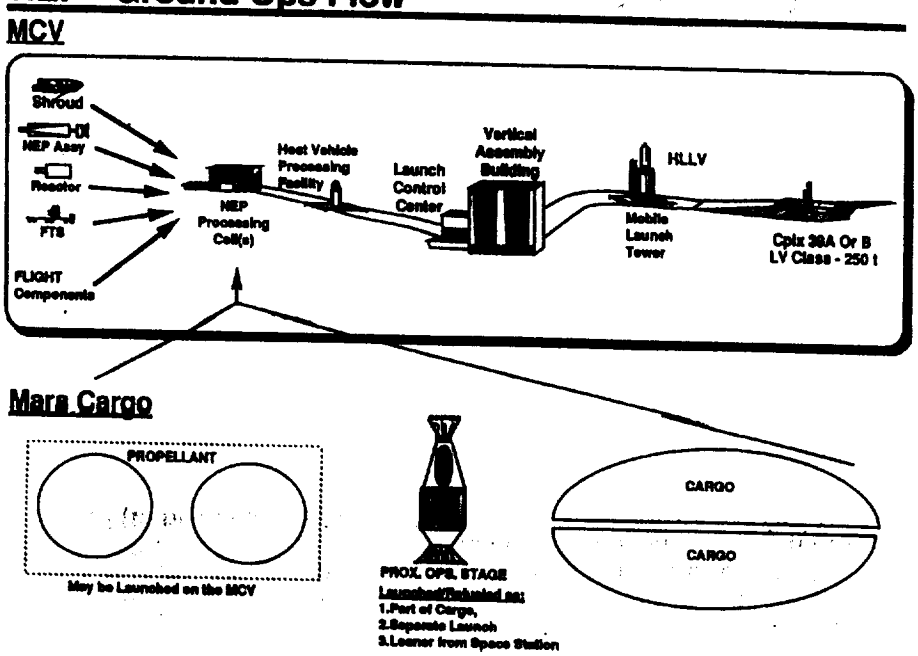
NEP - Ground Ops Flow



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NEP Processing

The items to be assembled and stowed (radiator, boom, etc.) are handled in the horizontal processing cell. The sizing of the cell should be based on a 5:1 area ratio of the stowed cargo area, plus the cargo area itself, using the shroud diameter, and adjusted for the maximum length of the unstowed (to be collapsed) items.

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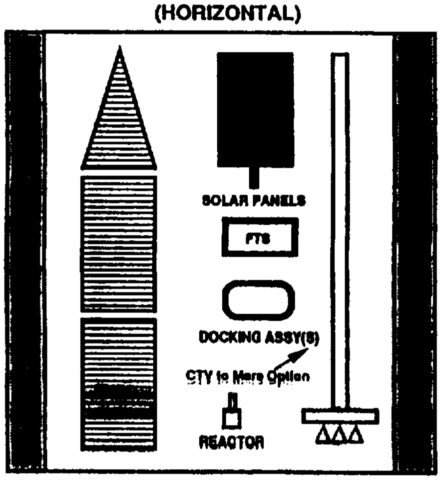
NEP Processing

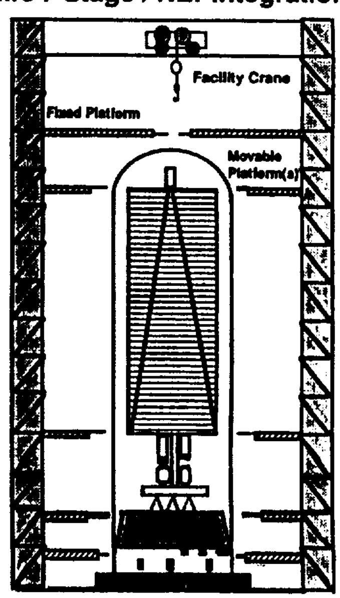
Top View

Radiator Boom and Attachments Processing

(HORIZONTAL)



MCV Stage / NEPIntegration



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Mars Cargo Processing

As shown earlier in the ground ops flow, the Mars cargo will be transported from the 700 km altitude to Mars orbit using the NEP vehicle. The cargo is planned to be launched using the same HLV and thus the same ground processing facilities are envisioned.

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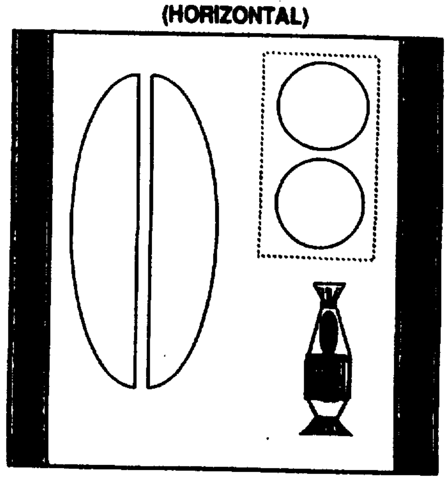
Mars Cargo Processing

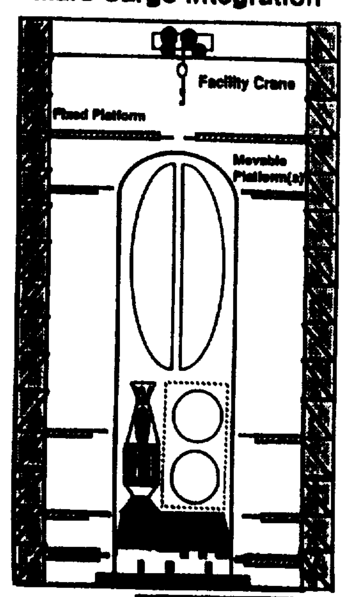
Top View

Cargo, Propellant and Cargo Transfer Vehicle

(HORIZONTAL)



Mars Cargo Integration



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NEP Orbital Ops Summary - INITIAL LAUNCH

The mission planners can select which item set (NEP or cargo) is the target and which is the chase vehicle. The two will be placed at some altitude apart. They both should be located at the same inclination, thus no mention is made of orbital plane change.

It is envisioned that after the NEP vehicle launch (probably the first launched vehicle to allow confirmation that all systems are operational before committing to launch of the cargo) the stowed systems will automatically deploy and activate the prime subsystems required to communicate with and control the vehicle. The activation and checkout sequence duration will depend on the success of the automated sequences and availability of support resources (TDRSS, etc.). The subsequent cargo launch time will depend on the pad turnaround time or GO for second launch, based on the above described timeline, if a second pad is available.

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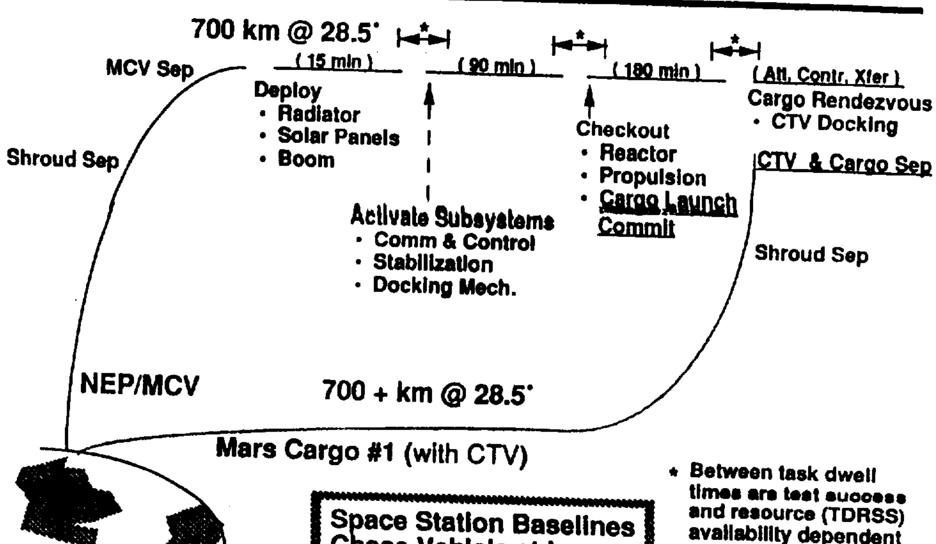
NEP Orbital Ops Summary - INITIAL LAUNCH



Space Station Baselines Chase Vehicle at Lower Altitude and Behind

* Between task dwell times are test success and resource (TDRSS) availability dependent

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NEP Orbital Ops Summary - RENDEZVOUS/DOCK

The Mars cargo is transfered from the cargo launch location to the NEP vehicle via the CTV. Upon completion of the rendezvous and docking sequence, i.e. cargo transfer, the CTV can be retained with the vehicle as a resource and eventually taken to Mars, or deployed and returned for storage somewhere in the earth orbit realm (some options are suggested in the "Deploy CTV" sequence.

As shown, the cargo transfer can take from a few hours to a few (could be many in cases of failure or available CTV propellant limitations) days depending on the separation altitude, the desired length for a launch window, available ΔV, and the phasing angle between the two vehicles. A set of parametrics over a desired range should be developed.

There are basically two options to how the cargo is transferred; the CTV *gathers* all cargo pieces at the cargo location and takes the total mass to the NEP, or it can go back and forth to pick up individual or grouped pieces. Though it appears obvious to take the first choice, a trade study is recommended once a CTV is sized (propellant, control authority, docking mechanizm, etc.)

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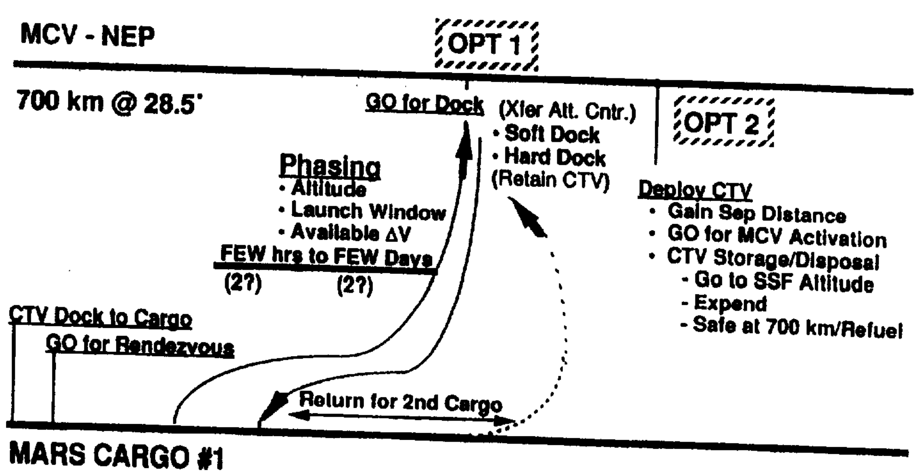
NEP Orbital Ops Summary - RENDEZVOUS/DOCK



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NEP Orbital Ops - RENDEZVOUS/DOCK Details

The choice for the 700 km orbit that was baselined (agreed upon in a joint telecon) is referenced, and as one can see, no reboost is required at the 700 km altitude. Additional consideration of radioactive decay is discussed separately.

The times shown for cargo piece capture by the CTV along with the transfer times from cargo location to the NEP vehicle are *ball park* figures estimated from similar activities calculated for specific Space Transfer Vehicle (STV) configuration studies (see referenced sources).

It is recommended that each NEP have an FTS and a CTV docking and retention capability.

One can see that using this cargo transfer approach, a minimum of 32.5 hrs, not counting validation and verification times required by the ground crews, would be required for on-orbit assembly.

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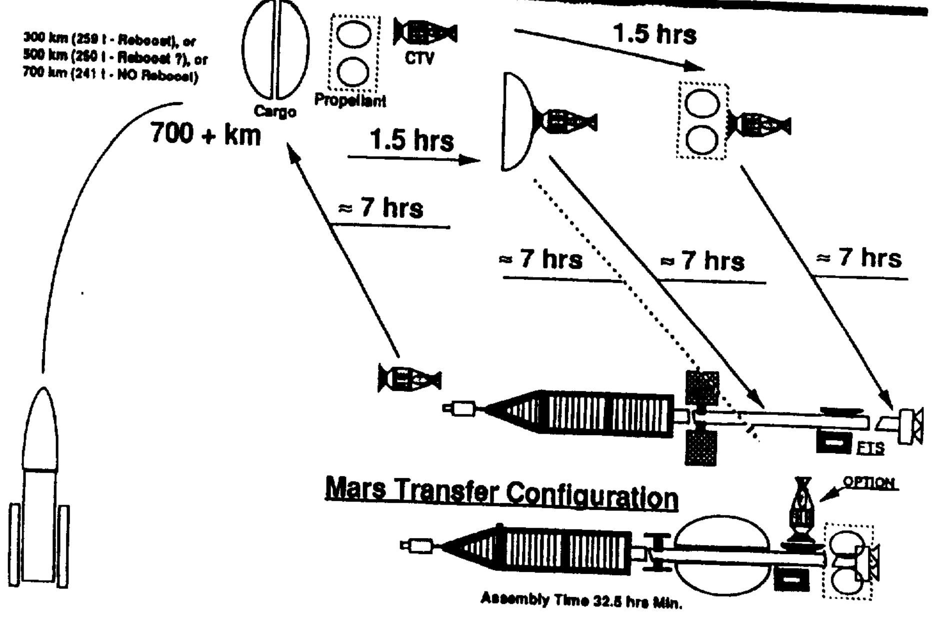
NEP Orbital Ops - RENDEZVOUS/DOCK Details



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Orbital Ops Option - 1

When the cargo pieces are assembled before transfer to the NEP and then sequentially attached to the NEP vehicle, it appears that some time and propellant can be saved; assembly time of 22 hrs. However, no validation and verification time has been allocated for the ground crew support/control operations or potential ground resource availability constraints.

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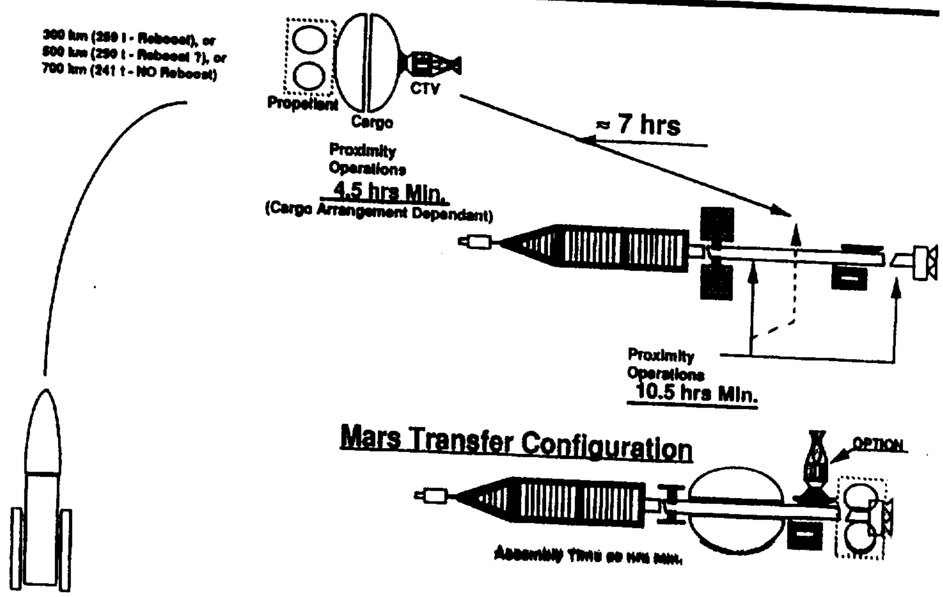
TS-803.2-FP

Orbital Ops Option - 1 (MCV)



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Orbital Ops Timeline Summary - CARGO ASSEMBLY

The times, based on the STV calculated point design for a Lunar cargo transfer vehicle study #NAS8-37856, as shown would result from the number of individual cargo pieces that must be assembled. In this study we assumed the shown three major pieces.

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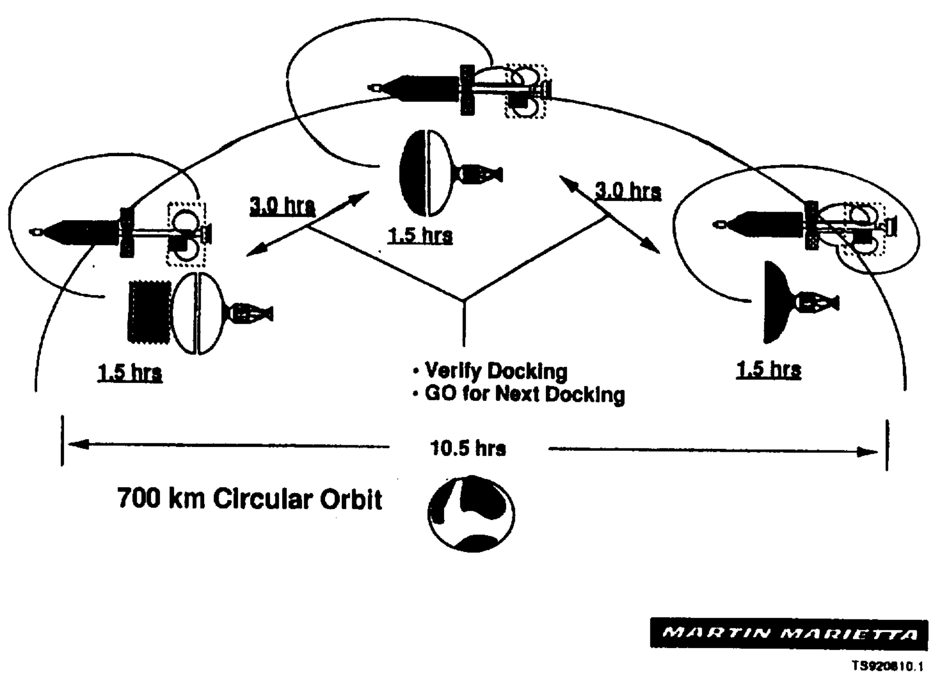
TS-810.1-FP

Orbital Ops Timeline Summary - CARGO ASSEMBLY



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TS920810.1

NEP Concept - MPV

The key differences between a NEP for Mars cargo versus the one for piloted use are:

1. The engine pod is located on the side of the boom so that adjustment for CG is possible and balanced thrust between the two assemblies during Mars transfer and return to Earth can be configured.
2. A crw habitat is provided for on each NEP to balance the CG between the two NEP modules after assembly. They are connected with a tunnel after docking. One of the habitats has an attached Earth Capture Crew Vehicle (ECCV) for contingencies. The second ECCV is carried with the taxi that is brought up as part of the crew launch.
3. A drogue assembly to interface with a CTV docking adaptor using multiple probes so that either NEP can be designated as the target vehicle and also provide backup for docking operations.

It is recommendee that each NEP for the Mars Piloted Vehicle (MPV) also be equipped with an FTS and a CTV docking port (2nd level backup).

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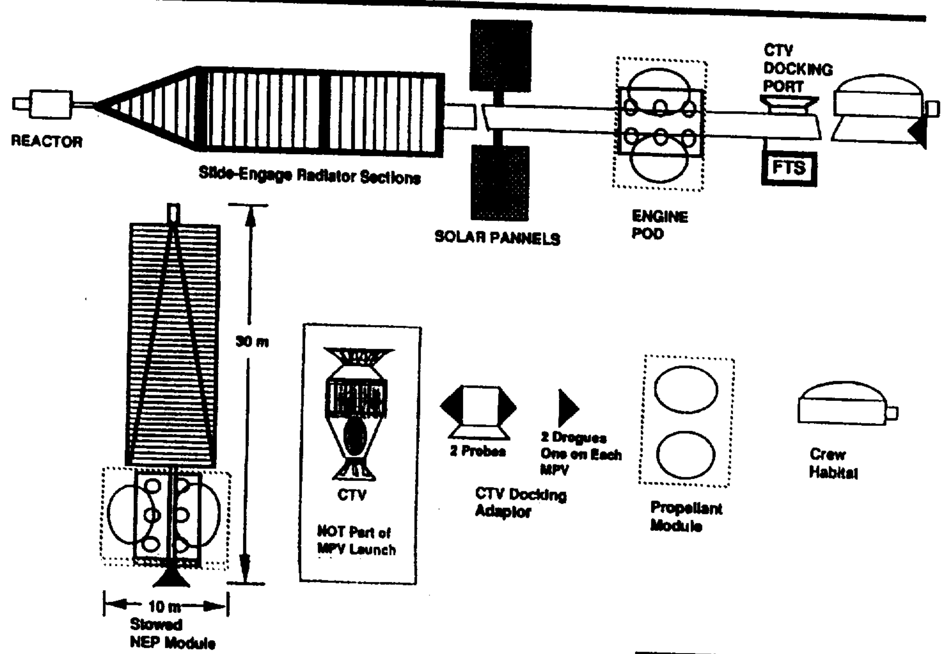
NEP Concept - MPV



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TS920814.1

MPV Ground Flow

The MPV ground flow is essentially the same as that for the NEP cargo vehicle except for the specific components involved. It takes two launches to get the two NEP vehicles in orbit. The crew with the crew taxi, which also contains an ECCV, is launched as a 3rd flight.

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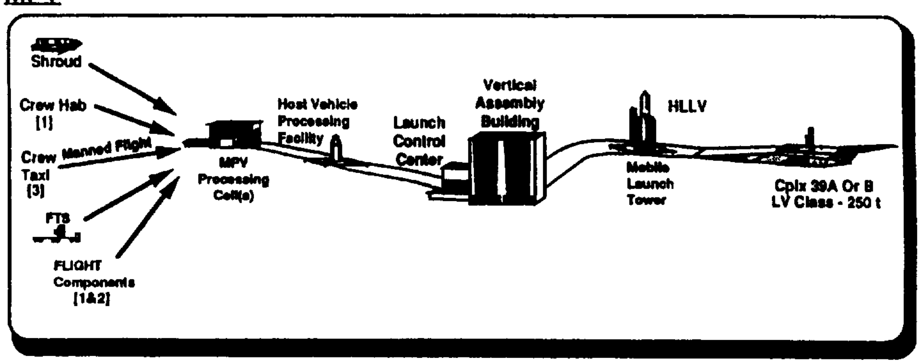
MPV Ground Flow

MPV



- TWO Launches with NEP Vehicles
  - One Crew Hab (includes ECCV)
  - Crew Taxi (includes ECCV) Launched with Manned Flight
- For GROUND Ops See NEP Processing
- CTV Assumed to be:
  - On-orbit from Cargo Launch
  - On-orbit from Space Station
  - Launched with One of the NEP's for the MPV

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TS920811.3Rev.

MPV Ground Processing

The same ground facilities, using the same sizing estimations as for the NEP cargo vehicle, are used to support the NEP's for the MPV.

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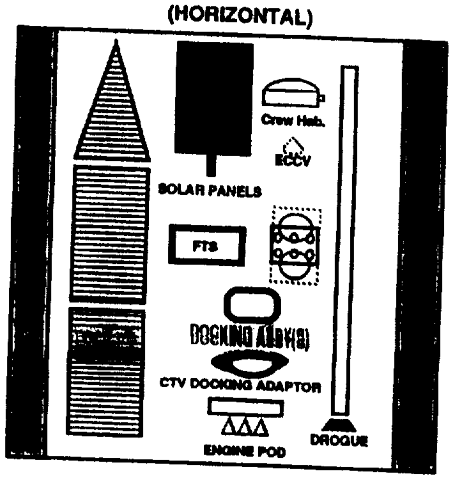
MPV Ground Processing

Top View

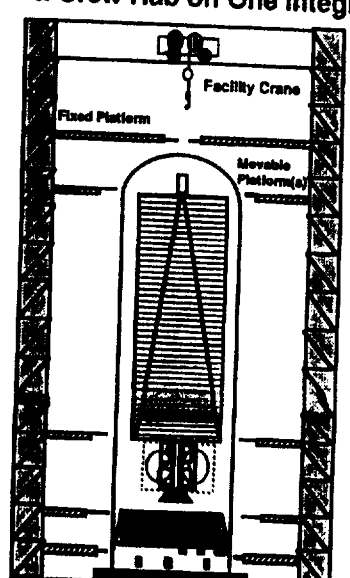
Crew Habitat & ECCV Assy.

(HORIZONTAL)



NOTE: Taxi has ECCV Capability

MPV & Crew Hab on One Integration



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MPV Orb Ops - RENDEZVOUS & DOCK

Using a CTV, after each vehicle has been checked out, it is estimated based on the earlier detailed task timelines, that the rendezvous and docking operation will require a minimum of 36 hrs.

Once docked, the crew transfer tunnel will be extended connecting both MPV/NEP modules.

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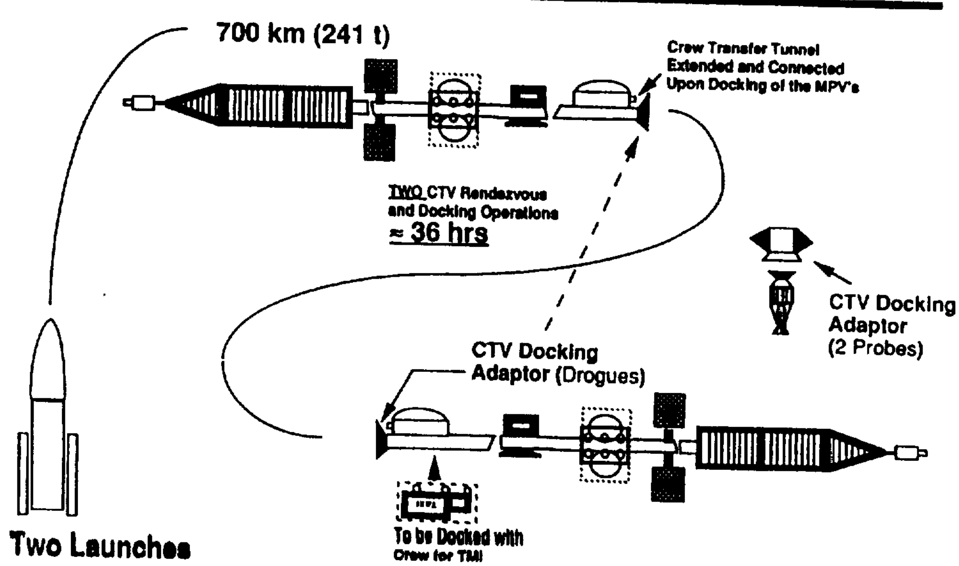
MPV Orb Ops - RENDEZVOUS & DOCK



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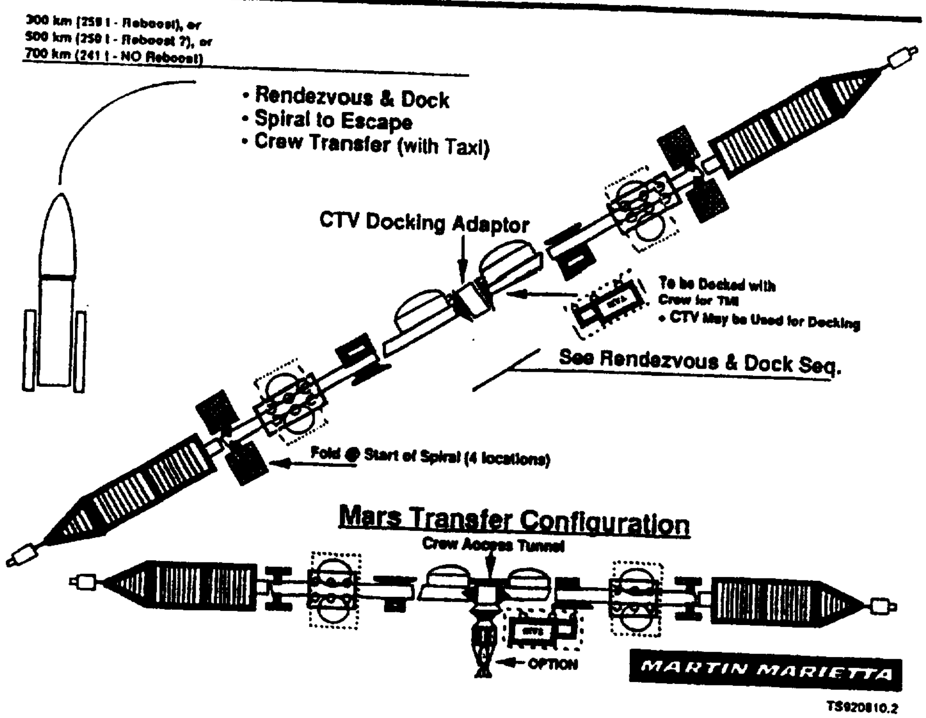
MPV Orbital Ops

For the spiral out or the final Mars transfer configuration, the CTV may be taken along or left behind. The crew taxi is brought up with the crew launch, however, the docking operation may utilize the CTV. As can be seen, sizing of the CTV in terms of control system, available propellant and ground control interfaces is desirable before more detailed task assessments are undertaken.

MPV Orbital Ops



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The Rendezvous Profile

The typical rendezvous sequence divides into [illegible] achieve a [illegible] relative positioning between [illegible] conditions of one phase [illegible] starting conditions for the next [illegible] narrow dispersion [illegible] nominal [illegible] conditions.

The approach phase results in approximate matching of the orbits of the target vehicle and the chase vehicle. [illegible] usually calls for a sequence of maneuvers by the CV [illegible] one orbit parameter at a time: inclination, line of nodes, eccentricity, and altitude. After the orbits are nearly matched [illegible] differences fall within a predetermined range, the terminal closing phase reduces the separation and closing rate to nearly zero. Final check-out, if required, is followed by the physical docking sequence.

This study examines alternate approach/terminal closing techniques for use at Earth departure and in Mars orbit [illegible]

The Rendezvous Profile

Designate a passive Target Vehicle (TV) and an active Chase Vehicle (CV)

- **Approach** Impulse sequence establishes nominal starting conditions for the terminal closing phase

  Example: CV moves to concentric circular orbit just below TV altitude (say 20 km) by adjusting one orbit parameter at a time

- **Terminal Close** Impulse sequence reduces range and range rate for final docking

  Example: CV uses line-of-sight thrusting to raise altitude and close to within a few meters of TV

- **Station-keeping** final (optional) checkout prior to docking

- **Docking** Combination of small impulses and physical grappling devices

Orbit Rendezvous Experience Base

Of the several rendezvous schemes considered for Gemini and Apollo, the circular, coplanar method was selected. First, the target vehicle's orbit was established at a selected altitude. Then, the chase vehicle launched and began the approach phase, modifying its orbit with a preplanned impulse sequence. Since these flights involved human crews, time to rendezvous was minimized at the expense of some additional propellant. Autonomous rendezvous could follow the same general procedure, using a maneuver sequence designed to minimize propellant over a longer time interval.

The chase vehicle approach phase ended in a circular, coplanar orbit at slightly lower altitude, with the chaser lagging the target by a few tens of kilometers. For Gemini, the altitude difference was 15 nautical miles, or about 28 km. The range was 30 - 40 N.Mi., since predicted visibility would give a clear line of sight to the Agena target at that range.

The Apollo rendezvous followed a similar sequence. Just after the CSM passed overhead, the LM launched from the surface to a transfer orbit of 60,000 feet by 45 N.Mi. Circularization at 45 N.Mi. gave the starting conditions for terminal closing phase. The entire sequence was completed 3.5 hours after the LM liftoff.

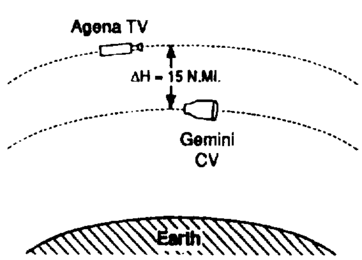
The terminal closing phase for Gemini and Apollo was flown manually, using line-of-sight thrusting by the chase vehicle. The entire approach phase design was intended to produce standard conditions (lighting, direction, range, range rate, and required ΔV) to begin the terminal closing phase. For Apollo, a faster rendezvous approach would have used direct ascent from the surface to standard terminal closing conditions; but the expected dispersion range in starting conditions would have been too large. The concentric orbit approach reduced this dispersion to acceptable values.

Note that the orbits need not be circular: the same control can be achieved with co-elliptic orbits.

Orbit Rendezvous Experience Base

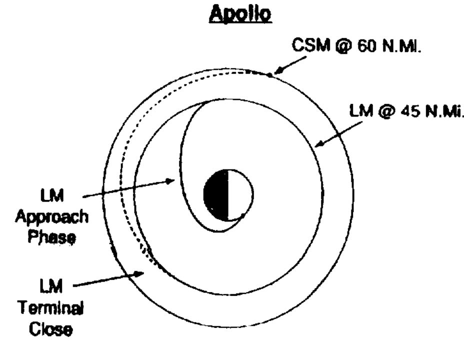
- Approach phase puts target and chase vehicles in circular, coplanar orbits with specified altitude separation, ΔH (can also be co-elliptic)
- Terminal closing phase performed manually, so standard initial conditions are very desirable:
  - approach direction
  - lighting conditions
  - line-of-sight rates
  - nominal ΔV budget

Gemini



- Chase Vehicle below and behind Target to commence Terminal Closing; Range ≅ 30 - 40 N.MI.

Apollo



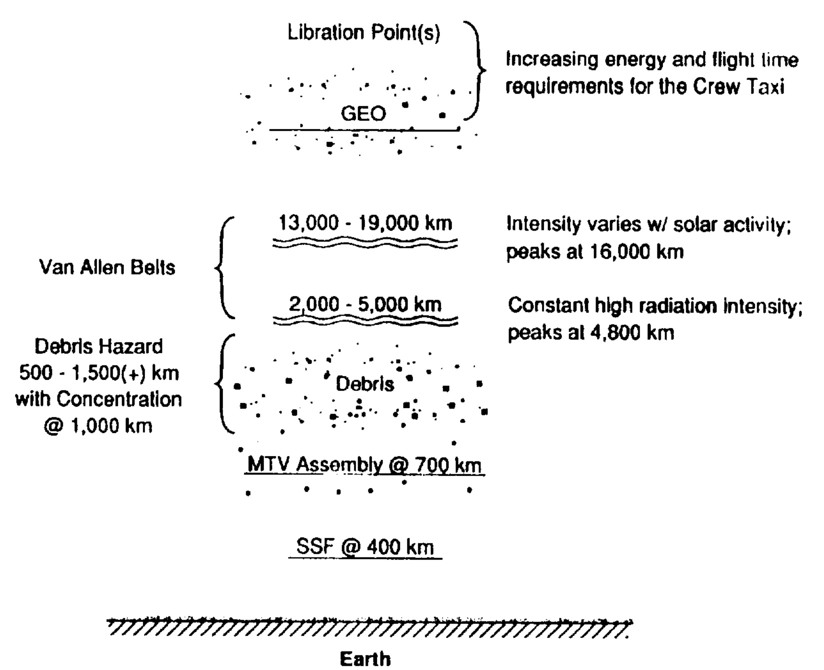
- LM ascends, injects to 60,000 ft x 45 N.Mi., then circularizes at 45 N.Mi. to start Terminal Closing
- 3.5 hours lift-off to docking

Rendezvous Selection Considerations

Crew rendezvous with a spiralling NEP transfer vehicle is complicated by hazard avoidance and timing considerations. Minimizing crew time traversing the radiation belts suggests a location above 19,000 km altitude. But higher orbits mean higher energy requirements for the crew taxi and, more importantly, longer phasing periods for the rendezvous sequence.

The list of operational constraints on the following chart suggests that considerable work will be needed to define near-optimal rendezvous strategies for an NEP transfer vehicle departing Earth. We consider four basic alternatives as a preliminary evaluation.

Rendezvous Selection Considerations



Crew Taxi Rendezvous with NEP Transfer Vehicle

Problem: Pick an Earth orbit location and an approach/rendezvous sequence that:

- minimizes crew exposure to natural and on-board radiation
- minimizes risk of orbital debris impact
- minimizes crew time on board the MTV
- minimizes vehicle design and propulsion requirements for the crew taxi and for the Mars Transfer Vehicle
- minimizes complexity of operational sequences for nominal and fallback modes
- minimizes crew time spent in rendezvous

Rendezvous Location Options

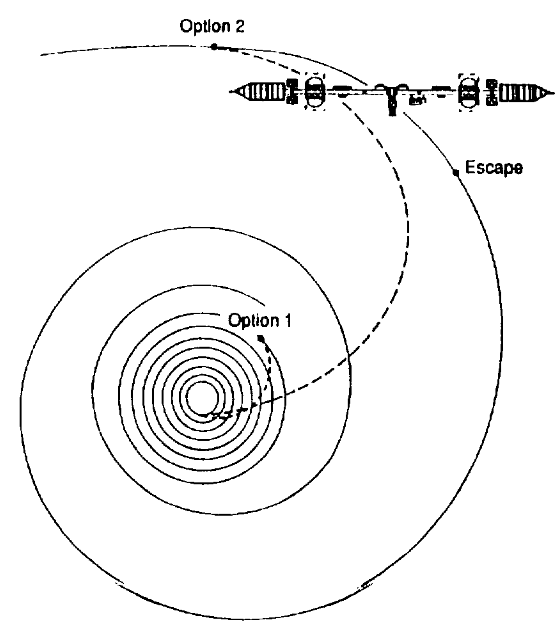
Three of the options proposed for rendezvous are shown opposite. The first is to select a high Earth orbit altitude, above the van Allen belts and free of debris collections. A controlled co-elliptic rendezvous sequence would build on our experience base from early manned programs.

The second option is to rendezvous post-escape, somewhat analogous to the direct ascent approach considered and rejected for Apollo. NEP thrusting would be suspended long enough (exact interval to be determined, but probably a few days) to reduce the radiation hazard and permit the crew taxi to chase a target with relatively stable orbit conditions. Since approach and terminal closing phases are combined, there is one less measure of control over the close approach conditions. Off-nominal burns from LEO departure create a broader range of possible approach conditions than the co-elliptic strategy. Moreover, there is only one chance to "catch the bus."

The third option, not diagrammed on the chart, is to deliver both the MTV and crew taxi to one of the Earth-Moon stable libration points, and rendezvous there. Previous studies (post-Apollo) suggested some advantages for the trans-lunar L2 point as a node, over the L1 point. However, the selection is moot in the case of the reference trajectory and spiral, because the MTV reaches escape conditions well before reaching lunar distance! To use either libration point would require modifying the spiral to use a non-optimal thrust program; this can be done, but at the expense of additional time and propellant for the spiral. This also adds thrust-on time to count against thruster lifetime limits.

The final option is to rendezvous in low lunar orbit. The crew would be sent out on a Lunar Transfer Vehicle, possibly as "hitchhikers" on a regular lunar mission, to board their MTV waiting in orbit. Feasibility of this approach depends on the lunar exploration manifest and infrastructure to support it. A ΔV of about 2-3 km/s would be needed for NEP orbit capture/departure, but this is likely to produce only a small increase in propellant loading. Of course, this approach adds some operations complexity in scheduling concurrent lunar and Mars flights.

Rendezvous Location Options



Option 1: High Earth Orbit

- Suspend NEP thrusting program anytime before reaching escape
  - establish target vehicle orbit
  - power output decay (10- day delay, per MMAG)
- Crew taxi departs LEO to co-elliptic orbit position below and trailing the target NEP vehicle
- Perform co-elliptic terminal rendezvous sequence and dock with NEP
- Continue NEP spiral to escape

Option 2: Post-Escape

- Suspend NEP thrusting program only as long as required for crew safety
- "Direct ascent" trajectory to rendezvous
- Combined approach and terminal closing phases

Option 3: Libration Point Rendezvous

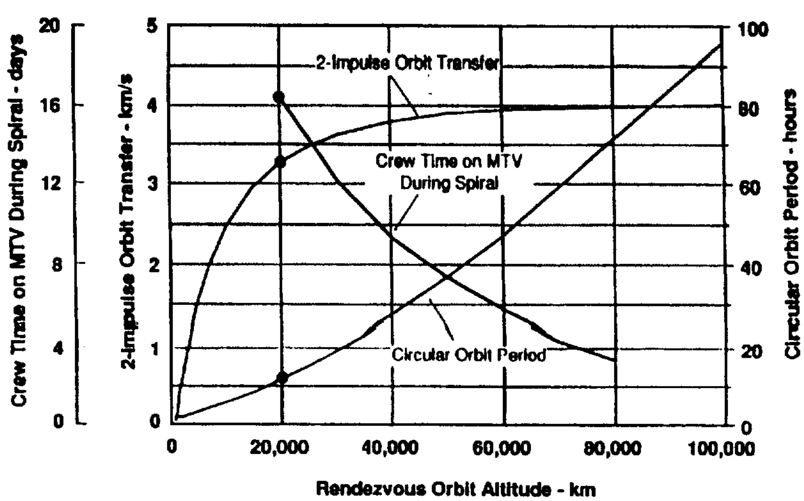
- Both vehicles transfer to L1 (or L2)
- Not shown opposite because this optimal thrust program reaches escape conditions well before lunar distance

Considering the high orbit (Option 1 on the previous page), there are performance impacts of selecting an altitude. A two-impulse transfer from LEO would use the first burn to raise the orbit apogee to the selected altitude, and the second burn to circularize there. Assuming this burn sequence, the ΔV requirement increases rapidly with altitude, but flattens out above geosynchronous altitude (35,786 km). However, the radiation hazard of the van Allen belts forces a selection higher than 19,000 km, so the crew taxi must be able to handle in excess of 3 km/s impulse from the main engines.

At the same time, orbit period is increasing from a few hours at lower altitudes to significant fractions of a day at higher orbits. A longer period implies a longer rendezvous and docking sequence, especially for fall-back options that require more than one or two revolutions. Therefore, even though there is a limited energy savings to be gained from using the lowest possible orbit above the radiation belts, there is an operational advantage. We propose an altitude of 20,000 km, assuming a roughly circular orbit for crew transfer to the departing MTV.

The third curve on the opposite page shows the additional time the crew will spend aboard the MTV if this co-elliptic approach is used. The suggested altitude requires an extra 17 days on board the MTV in addition to the Earth-Mars transfer time.

Mission Performance Impacts of Rendezvous Orbit Selection



- Crew Taxi impulse increases rapidly with altitude; hits a "knee" at ~20,000 km
- Orbit period (circular) increases linearly with altitude. The longer the period, the longer the terminal rendezvous sequence for a co-elliptic rendezvous.

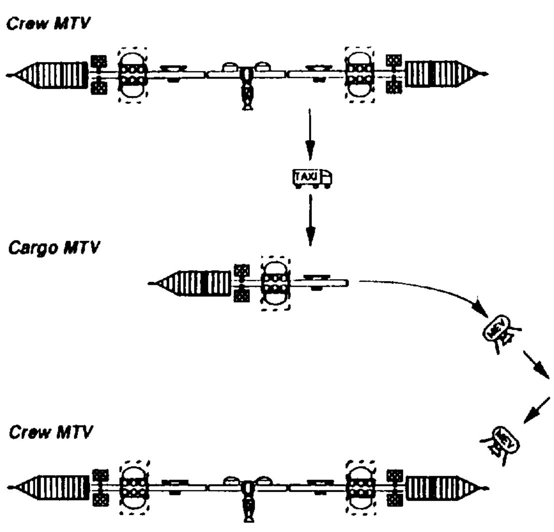
Mars Orbit Operations: MEV Deployment & Return

Several rendezvous an docking operations in Mars orbit are required to support the surface mission and return trip. The cartoon opposite illustrates one approach that may minimize the complexity of each step, but at the expense of adding at least one step to the process.

To begin, the crew MTV spirals to capture at Mars in an orbit that approaches the cargo MTV which has arrived earlier and has already deployed part of the surface payload. From this rough matching of orbit parameters, the crew taxi or another element designed for this purpose completes the terminal closing phase to transfer the crew to the MEV brought out by the cargo vehicle.

After conducting the surface mission, the crew returns directly to the crew transfer vehicle in the MEV, completes a co-elliptic rendezvous, and readies for departure.

Mars Orbit Operations: MEV Deployment & Return



- Crew MTV spirals to rendezvous orbit
- Allow delay of several (≤ 10) days after reactor shutdown before crew movement begins
- Crew Taxi shuttles crew to Cargo MTV for transfer to MEV
- MEV separates and begins descent sequence
- Surface mission
- MEV ascends to co-elliptic rendezvous with Crew MTV
- Crew MTV spirals to escape on Earth return trajectory

The advantage to this approach is eliminating the need to dock the crew and cargo MTVs. The only transfer requirement for the baseline mission profile is to move the crew from transfer element to excursion element and back again; no propellant transfer is required for the crew's return.

Mars Orbit Operations

Several independent rendezvous operations with different active partners

- Crew MTV must perform the gross maneuvers of approach to match orbit parameters with the cargo MTV, already in orbit
- Crew Taxi (or similar element) must perform terminal close and docking to transfer the crew to the MEV.
- MEV must perform complete rendezvous and docking sequence upon return from Mars surface.

Alternative: Crew MTV and Cargo MTV rendezvous

- Requires close maneuvering of two large structures, and appropriate scarring for all operational sequences at Earth and Mars.
- Complicates crew safety on approach: must avoid 3 radiation sources

NEP Rendezvous Approach and Design Implications

Earth Escape

- Rendezvous at Earth-Moon L2 may be incompatible with the optimal thrusting program for spiral escape; spiral time could be extended, but at the cost of extra thrust time.

- Select a high Earth orbit altitude (20,000 km) for co-elliptic approach/rendezvous
  - standard, controlled rendezvous sequence
  - permits delay for power decay after shutdown, before crew approaches

- Crew taxi must have ECCV capability and be able to handle ΔV of 3.5 km/s

- Increases crew time on board MTV by a few days (17 in this case)

Mars MEV Separation/Approach

- Use crew taxi to ferry crew from their MTV to the MEV

- Eliminates the need to rendezvous and dock two large structures

On-orbit Support Requirements

- PLATFORM in a 720 km Orbit [*Study Indicates Operational Advantages*]
  - Reboost
  - Attitude Control
  - Ops Power
  - CTV Storage/Dock
- CTV
  - Cargo Transfer
  - NEP Repositioning/Reboost Backup
  - MPV Rendezvous & Dock
- Mission Control
  - Deployment Verification
  - Next Function GO
  - Rendezvous/Docking Calculations
  - Auto Sequence(s) Overrides
- Space Station Interface (contingencies, backup, CTV?)

TS920825.1

NEP Weight Statement

To assess the ability of the FTS as presently designed to handle specific items, the weight statement as shown was used. Each item was viewed from a mass aspect to see if it is a contender for handling by the FTS. The FTS task column indicates the results. In the case of the power distribution system, the 10000 kg are probably devided between various components, each of which could be handled adequately. However, to finalize such an assessment, the design to at least a conceptual level, for each subsystem component, must be defined. It is the location of each item that will determine how long it takes for the FTS to get to it, what motion is required to twist/pull/push/lift etc. for handling each item, and thus establish requirements on the FTS and the subsystem components. Obviously this is a very interactive and iterative process.

The same discussion as above applies to the Taxi and Crew Habitat handling since they will consist of components.

Repair operations where pull and push functions by the FTS are probably desired, will impact the design requirements placed on these components. Particularly in this group would fall the solar pannel mechanisms, the thrusters, and propellant/electrical connectors.

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TS-812.4-FP

NEP Weight Statement

MCV/LCV	Mass kg	FTS Task
• Reactor/Radiator Assembly	23285	N/A
• Solar Pannel Assembly	163 each	√
• Flight Telerobotic Servicer	700	N/A
• Engine Pod	3000	√
• Propellant Module	10000 dry	√
• Power Distribution	10000	?
• Miscellaneous Structure	4xxx	
+		
• 2 x MD/AV (Cargo)	75000 x 2	
MPV		
• Taxi(with ECCV capability)	57000	?
• CTV Docking Assembly	2000	√
• Crew Habitat Module (with ECCV)	50000	?
MCV/MPV OPTIONS		
• CTV Docking Port	500	N/A
• CTV Docking Adaptor	2000	√
• CTV (Wet)	6000	√

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TS920812.4

Rendezvous, Prox Ops, FTS & Other References

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TS 819.1-FP

Rendezvous, Prox Ops, FTS & Other References

RENDEZVOUS & PROX OPS: (Bill Jackson / JSC [713]483-8303)

- Space Transfer Vehicle, Lunar Transportation Study NAS8-37856, ΔV Allocations, Timelines, and Earth/Lunar Orbit Rendezvous
- NLS Cargo Transfer Vehicle Guidance and Targeting Strategies, Wayne Deaton NASA-MSFC, 8 April 92
- CTV Briefing #3 to MSFC (Martin Marietta Proprietary)

FTS:

- Max Load Carrying Capability Final Report; MMAG Memo FTS-SYS-90-473
- An Analytic Solution for Robotic Trajectory Generation, MMAG Memo FTS-SYS-90-452
- Contract # NAS5-30689

OTHER

- 1 KW SUPER Design for the P91-1 Program

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TS920819.1

FTS - Timeline Considerations

The referenced FTS documents were used for showing a boundary of of how item mass relates to maneuver time including general considerations as listed. This only addresses the motion of lift/move itself. To develop total task timelines, the design (at least at a concept level) is needed.

Note that denser objects can be moved faster since th[illegible] be smaller and their CG closer to the attach point, therefore a shorter lever arm.

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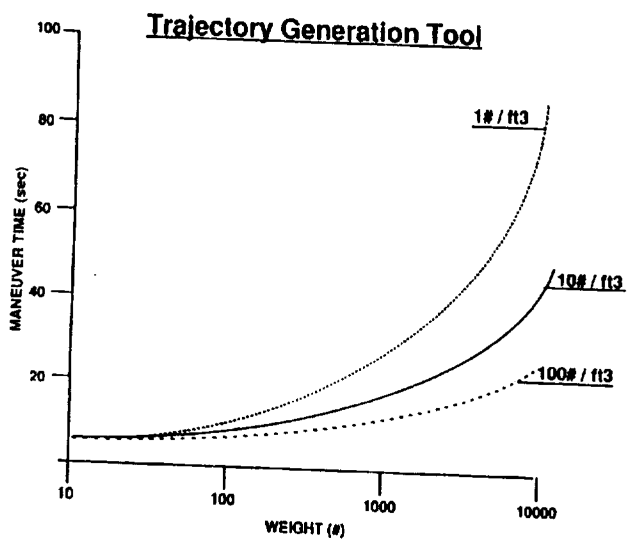
TS-729.1-FP

FTS - Timeline Considerations



CONSIDERATIONS INCLUDED:

1. Joint Torque Limits
2. Joint Velocity Limits
3. Mass Properties
4. Maneuver
5. Position Loop Bandwidth
6. Simulation Model
7. Safe Velocities

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TS920729.1

NEP Orbital Ops Summary - FTS

The tasks listed is a beginning of a long list that needs to evolve as the vehicle conceptual design evolves. The specific item single maneuver time needs to be connected with the task timeline, which requires the knowledge of location, reach distance, etc. and thus leads to the recommendation that a conceptual design for the subsystems and therefore the total vehicle be undertaken.

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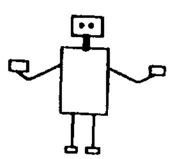
TS-820.6-FP

NEP Orbital Ops Summary - FTS

CONTINGENCIES

- Cargo Secure
- Power Deploy



SINGLE MANEUVER TIME

ITEM	lbs/ft3	sec
• Engines	9.4	15
• Engine Pods	9.4	30
• Power Cond.		
• Solar Panel	3.3	12

MAINTENANCE

- Engines @750kg/5m3
- Engine Pods (4 engines) @3000kg
- Power Conditioner 10000kg/?
- Solar Panels @ 111 kg each

NOTE: 35.32 ft3/m3
2.21 lbs/kg

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TS920820.6

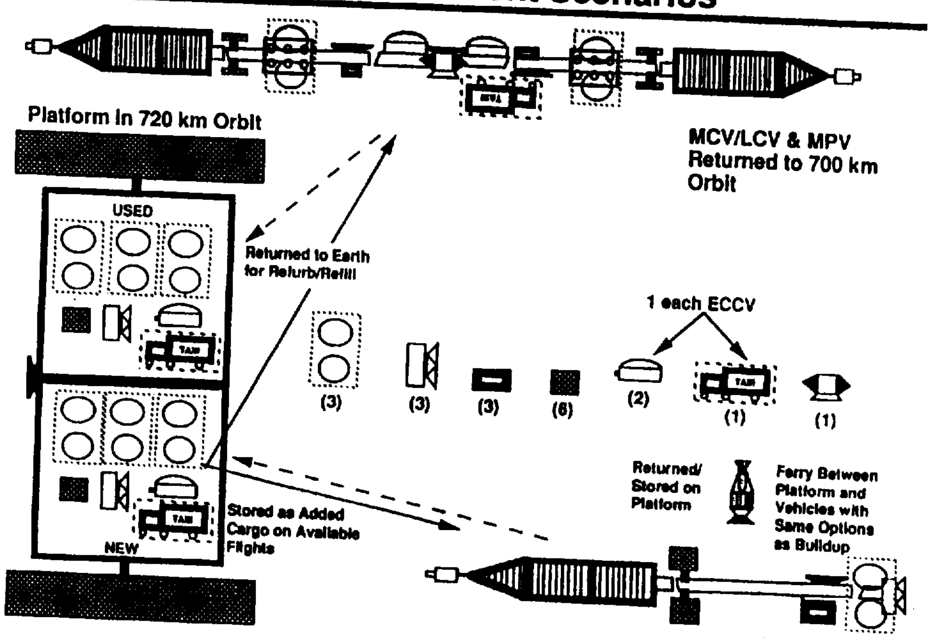
Maintenance & Refurbishment Scenarios

The NEP vehicle is basic for the Mars cargo, Lunar cargo, and the Mars piloted flights. Variations in vehicle configurations depend on the specific mission. As was seen from previous discussions on cargo rendezvous and docking sequences and their relationship to manifests, it appears that a unmanned, passive platform could be of operational advantage. The platform could also have a dedicated FTS to perform such tasks as thruster replacement where the remainder of the pod is operational (failures that have occured before expected end of life).

The numbers under each type of equipment indicate the total number recommended for use in accomplishing a given Mars mission.

TS-819.3FP

Maintenance & Refurbishment Scenarios



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Vehicle Refueling

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TS-819.4-FP

Vehicle Refueling

- Fluid Transfer NEP Veh. (trade study required - does NOT look favorable)
  - Propellant in Module Form for Initial Vehicle Configuration
  - Maintain Propellant Module Synergism
- Fluid Transfer CTV Appears Favorable

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TS920819.4

Thruster Replacement

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IS-819.5FP

Thruster Replacement

- Thruster OR Engine Pod Replacement is Feasible with FTS Design
  - Mass drives maneuver time
  - Component design will drive:
    - Accuracy Req.
    - Force Req.
    - Dexterity Req.
    - Reach Req.

These and Moving Distance Determine Total Task Timelines

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TS920819.5

Non-nuclear System Repairs

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TS-819.5-FP(1)

Non-nuclear System Repairs

- In General Possible and Desirable (specific dynamics have been analyzed)
  - Specific Design Dependent
  - Mass Density Dependent
- FTS May be Usable in Conjunction with the CTV

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TS920819.5

Refurb & Maintenance Schedule

Some of the possible candidates for refurbishment and maintenance are identified and their potential schedule suggested. Again, until at least a conceptual level of subsystem design is performed, specific component replacements, their projected reliabilitiy and buildup of that particular function, as shown in this list, can not be accomplished.

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TS-918.3-FP

Refurbishment and Maintenance Schedules

REFURBISHMENT ITEMS	SCHEDULE
• Solar Power - Replace Panel Assembly (2/vehicle)	Each Mission
- Replace Battery Assembly (2/vehicle)	As Req.
• Crew Habitat	Each Mission
• Engine Pods	Each Mission *
• Propellant Module	Each Mission
• Taxi	Each Mission
• CTV Docking Adaptor	Upon Failure
• FTS	10 yrs/Failure
• CTV	As Req.

MAINTENANCE ITEMS	
• Solar Power - Drive Mechanism Inspect/Replace	As Req.
• Crew Habitat - Selective Items	As Req.
• CTV - Selective Items	As Req.

NOTE: * An option of taking extra pods to Mars for scheduled replacement should be considered

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TS920818.3

Decay Power of a 5 MWe NEP

Upon return and subsequent to shutdown of each 5 MWe module, the decay time and power were tabulated. On the basis of these results it is recommended that a minimum of 10 days be allowed before any cargo or propellant loading is initiated. One can see that a further wait to 100 days would only further reduce the doses by a factor of 0.4.

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908.2-FP

Decay Power of a 5 MWe NEP - AFTER SHUTDOWN

Time (days)	Fraction of P rated	Decay Power (kWt)
0.1	0.01	244
1.0	0.005	122
10.0	0.0015	37
100.0	0.0006	15
1000.0	0.0003	7

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920908.2

10 MWe NEP Radiological Inventory if Re-entering

The worst case scenario for a Mars piloted vehicle failing in all aspects upon return to a 700 km LEO orbit would have a radiological inventory as shown. The vehicle has two 5 MWe modules for a total power of 50 MWt. The Mars mission is assumed to last for three full power burn years for a total reactor usage of 150 MWt-years. Since re-entry from a 700 km orbit for this type of vehicle (ballistic coefficient of 200 kg/m2) is expected to be around 54 years, the radiological hazard would be ≈100,000 Ci.

The probable health consequences are ZERO, since odds are 75% that the system will land in the ocean and sink through the bottom immersing 50 to 100 m below the sub-sea bed, thus safe disposal. If the reactor were to re-enter over prime farm land, breaking up and dispersing, the prime hazard will come from the bone seeking isotopes Sr90 and Cs137, both with half-lives of ≈30 years. Typical crop condemnation level is ≈1 Ci/km2. Thus under the worst smooth scattering possible, about 100,000 km2 could conceivably be contaminated. If the crop were wheat, assuming $2.50 per bushel at 40 bushels to an acre, economic losses would be $2.5 B/yr. Clearly this would not be acceptable and an infrastructure to assure prevention of this type of an accident is recommended.

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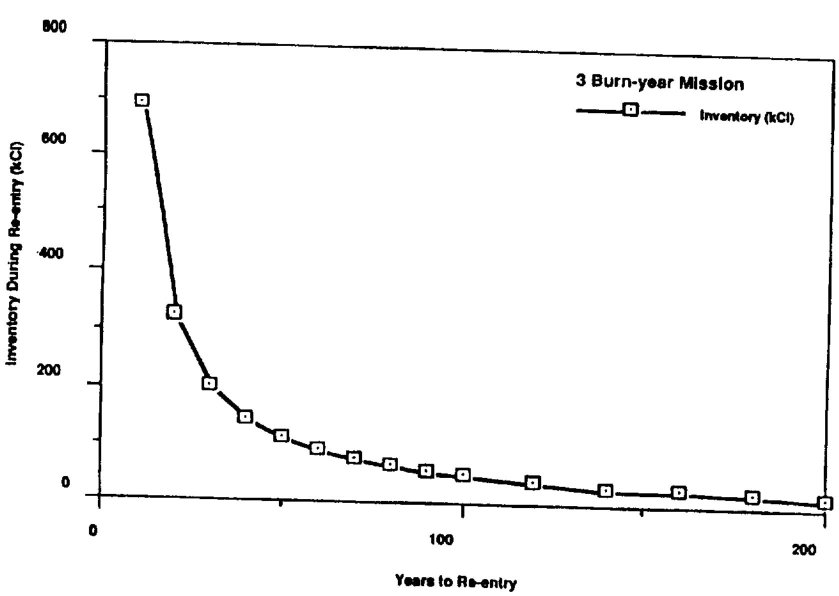
911.1-FP

10 MWe NEP Radiological Inventory if Re-entering



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Further Study Recommendations

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MARTIN MARIETTA

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Further Study Recommendations

- SIZE CARGO TRANSFER VEHICLE (Opt.1=take allong; Opt.2=leave in EO)
  - Control System
  - Propellant (Cryo, Space Storable Cryo, Storables TRADES)
  - Communications
- SIZE FLIGHT TELEROBOTICS SERVICER
  - Cargo Assist
  - Routine Maintenance
  - Potential Contingencies
- POWER SUBSYSTEM DESIGN/TECHNOLOGY REQUIREMENTS
  - Component Performance
  - Component Simulation Models (Transfer Functions)
  - System Design Requirements Based on Simulations
- TRADE CTV vs ATTITUDE CONTROL ON THE MPV
  - Type of Attitude Control
  - Location & Size of Attitude Control (Soft and Hard Dock)
- TOP CUT AT GROUND PROCESSING COSTS
- POTENTIAL FTS ACTIVITY DETAILS (Push, Pull, Twist, etc.)

NOTE:May Establish Synergistic Requirements with Other Systems (BENEFIT)

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TS920818.2

Ground Processing Cost Estimate

Studies performed and on-going in the areas of STV and HLV have generated data for facility sizing, task planning, ground support test and simulation equipment identification, and the associated projected costs. There are cost and task trade and sensitivity models at KSC and MSFC. These could be exercised to gain a feel for the cost bounds associated with processing a NEP vehicle.

The chart shows a sample of the kind of information that can be made available and could be worked in conjunction with a vehicle concept design task.

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TS- 812.6-FP

Ground Processing Cost Estimate

TASK DESCRIPTION	LOCATION	DURATION (hrs)	MANPOWER (#)	COST-$
MCV				
Assemble Slider Radiator Sections	HVPF	8	5	xxxx
Install Reactor Assembly	?			
Install CTV Docking Port	HVPF			
Install FTS	HVPF			
Install Engine Pod	HVPF			
Assemble Cargo Modules				
Install CTV				
MPV				

OPTIONS

Standard Tasks:

Mating 2 items ——— 4hrs ——— mech, fluid, electr, sys, qual.

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TS920812.6

[illegible]

[illegible] location [illegible] solutions [illegible] approach [illegible] that may be [illegible] more fully [illegible] assumed to be [illegible] complete system failure [illegible] event.

For example, [illegible] case of failure in Earth orbit [illegible] on board radiation [illegible] may be small enough [illegible] during the spiral-in phase of a transfer vehicle returning for refurbishment when a substantial fission product inventory will have accumulated. Disposal in both cases will be treated the same, recognizing that the former case may allow less drastic measures than scrapping the entire investment.

Disposal Scenarios - Status and Location of Transfer Vehicle

Normal End of Life

- Piloted MTV: on Earth approach/flyby after ECCV separates
- Piloted or cargo MTV: in Earth orbit, after return and capture (option)
- Cargo MTV: in Mars orbit

After Propulsion System Failure

- In Earth orbit
  - during initial system start-up; limited fission product inventory on board
  - during spiral in/out operation, between designated Earth orbit and escape conditions
  - after return from Mars
- During trans-Mars cruise
- In Mars orbit
- During trans-Earth cruise

Disposal Options - Where to Put It?

Two planetary orbit classes and two heliocentric orbit classes are considered for temporary storage and permanent disposal locations. Each has advantages for certain disposal scenarios, but each also has limitations. This study evaluates all four, and proposes a basic disposal strategy that considers safety, feasibility, and ease of operation.

Planning a solar system ejection or "crashing" into the Sun as a nominal disposal mode demands too much energy, and too much autonomous operations time to be practical. It is possible that the last use of an NEP module could be to power a robotic planetary explorer or a high-energy execliptic mission. However, this introduces further operational complexity and timing issues that are not relevant for preliminary propulsion technology planning.

Disposal Options - Where to put it?

- Earth orbit
  - Orbit lifetime is a function of altitude and the ballistic coefficient of the vehicle or system configuration
  - "Nuclear-safe" must be defined relative to the nature of the risk for each case; altitude of 700 km selected for this case based on lifetime and risk
- Mars Orbit - presumably no closer than Deimos
- Heliocentric transfer flight path
  - Leaves the reactor or vehicle in some interplanetary flight path
  - Most will cross both Earth and Mars, but still have very long life times
- Stable heliocentric orbit
  - Starts out at 1.19 x 1.19 AU - between Earth and Mars
  - Predicted not to be perturbed into a planet crossing path for a <u>very</u> long time; after that, same characteristics as previous case

Earth Orbit Lifetime Versus Orbit Altitude

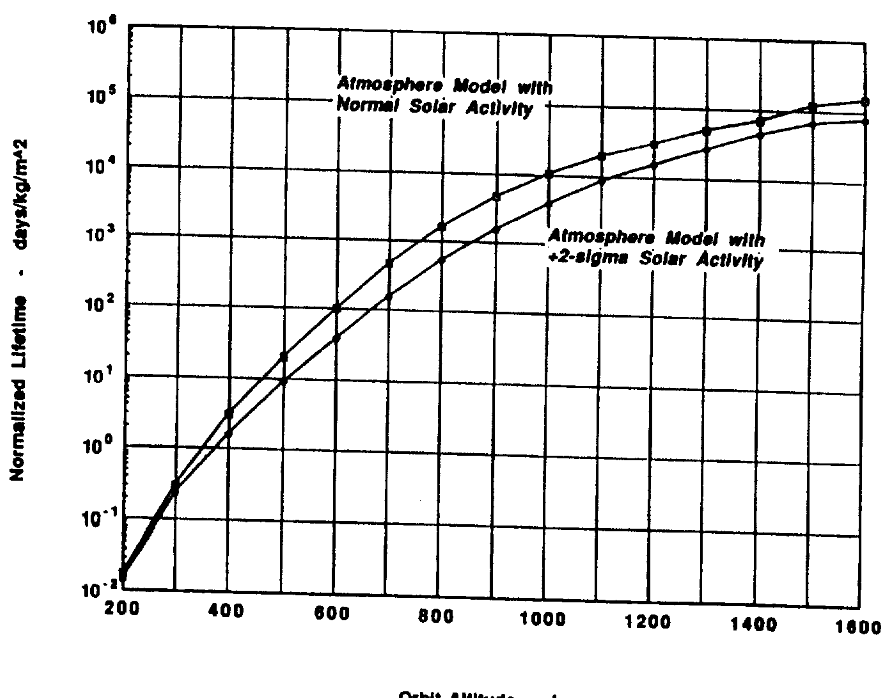
The first, and most critical disposal option is an Earth orbit. This option is included de facto for initial reactor startup and for any reuse scenarios, so the question is how to pick an orbit altitude that matches the risk factors and that is within Earth-to-orbit capability.

Analysis by Martin Marietta in another section of this report indicates that a 700 km altitude is well within the reach of anticipated heavy lift launch vehicles for SEI. In fact, ETO capability degrades only slightly from 400 km to 700 km. Maximum orbit lifetime favors a higher altitude, as the graph opposite will show.

Orbit lifetime is plotted versus orbit altitude for circular orbits from 200 km up to 1600 km. The lifetime is normalized with respect to the ballistic coefficient of the vehicle in orbit. The two curves represent different atmospheric density models: the upper curve assumes normal levels of solar activity, while the lower curve factors in most of the observed high solar activity periods. Both curves will be used to estimate a lifetime range, with the normal activity showing a longer lifetime, and the high activity showing a more conservative shorter lifetime.

To use the curves, the mass and physical dimensions of the orbiting vehicle must be known, and a drag coefficient must be supplied. The table on the next page shows calculated lifetime ranges for some cases of interest for the NEP vehicle.

Earth Orbit Lifetime vs. Altitude



Selected Orbit Lifetimes

Four possible disposal configurations have been evaluated, from a fully loaded MTV to a single propulsion module. Masses for each are shown, as is the area presented if we assume that the largest possible plane area is perpendicular to the direction of motion. Areas are approximate, and the assumption that the largest area will always be presented to produce drag will produce conservative results. Drag coefficients shown are for rough shape equivalents; a complete calculation for this situation is beyond the scope of this study. These quantities are used to calculate a ballistic coefficient for each disposal configuration, which is then multiplied by the normalized lifetime (read off the preceding graph), and converted to years.

The results in the table opposite show the value of higher altitudes for extended life in orbit without reboost procedures. Based on this preliminary analysis, we select a 700 km circular Earth orbit for all operations. This location is also suitable for temporary storage, but probably not for permanent disposal of a spent nuclear reactor.

Selected Orbit Lifetimes

Area based on longest 2 dimensions

Disposal Configuration	Mass kg	C_D	Area m^2	β kg/m^2	Predicted Orbit Lifetime (Yrs) for the Specified Altitude		
					400 km	700 km	1000 km
Mars Transfer Vehicle Fully Loaded	325,000	2	1,525	107	0.5 - 0.9	40 - 140	1110 - 2950
Mars Transfer Vehicle w/o Payload, Propellant	90,000	2	1,425	32	0.1 - 0.3	10 - 40	350 - 880
1 5 MWe Module	36,285	2	710	26	0.1 - 0.2	10 - 30	280 - 720
1 Reactor only	3,500	1.3	10	269	1.2 - 2.2	110 - 350	2800 - 7400

Notes: 1. Estimated area assumes largest plane area is perpendicular to the velocity vector
2. Drag coefficients are only rough approximations by shape
3. Lifetime range determined by using both atmospheric density models

Disposal On an Interplanetary Flight Path

Another disposal possibility, especially suited to a transfer vehicle already in interplanetary flight, is to simply leave the vehicle in some interplanetary flight path. The path selected might be the current one, or it might be specifically designed to minimize the possibility of a future reencounter. This option could also be used for a vehicle in planetary orbit, by accelerating it to escape conditions. This strategy is the NEP equivalent of "jettisoning" a spent propulsion stage after use: leave it where it is, and accept the small possibility of a reencounter.

Because interplanetary transfers cross one or more planet orbits, they set up the possibility of either a direct collision or, more likely, a close encounter (within a few planet radii) that creates a gravity-turn and so perturbs the vehicle's original path. The more close encounters, the greater the perturbations, and the greater the possibility of terminating the vehicle's orbit. Termination may be in the form of a collision with a planet, impacting the Sun, or ejection from the solar system. While not all of these are bad, the process is uncontrolled without further human intervention.

Lifetimes of bodies in planet-crossing paths may be estimated with a Monte Carlo simulation technique, such as SAIC's Planetary Encounter Probability Analysis (PEPA) code. This analysis suggests that, with few exceptions, leaving an NEP vehicle in a typical interplanetary orbit produces a risk no greater than the natural risk of collision with one of the Earth-approaching asteroids.

Disposal on an Interplanetary Flight Path

- Typical Earth-Mars low thrust trajectories (outbound or inbound):
  - lie slightly out of the ecliptic plane
  - graze the orbits of Earth and Mars
- If the MTV is left in a typical flight path, Monte Carlo simulation using SAIC's PEPA Code predicts:
  - Mean orbit lifetimes of 10^7 - 10^8 years
  - Chance of collision with Earth in 10^6 years is low in all cases - nearly zero in most
- So, the risk of a nuclear-powered Mars Transfer Vehicle colliding with Earth is of approximately the same order as the risk of colliding with a near-Earth asteroid

Predicted Orbit Lifetimes for Typical Low Thrust Trajectories

The table opposite summarizes the results of several simulation runs, using various points along typical low-thrust trajectories between Earth and Mars, and to a particular heliocentric disposal orbit to be described later. The low-thrust path must be sampled at several points, since the orbital parameters are subject to continuous change during periods of thrusting. Three samples were selected for the Earth-Mars and Mars-Earth transfers, corresponding to post-escape, transfer time midpoint, and target approach just prior to initiating spiral capture.

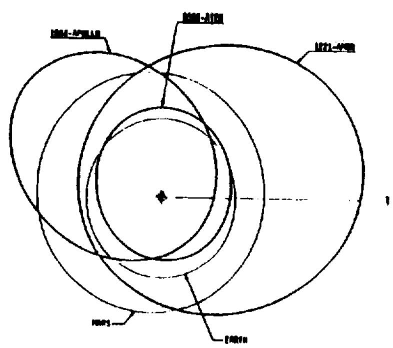
Each row shows a different simulation case: the calculated orbit parameters of interest, namely perihelion, aphelion, and inclination; the mean simulated orbit lifetime in years before termination; the number of trials out of 500 that the simulation resulted in an Earth collision; the mean time to Earth collision for that subset of cases; the probability of an Earth collision in the first one million years after start of simulation. All the times are reassuringly long, and most of the collision probabilities for the first million years are low. The exceptions are those cases just after Earth escape, when the NEP orbit is very close to Earth's orbit.

The following page shows the same statistics for simulation trials with several near-Ea... ..steroids. The slightly longer expected lifetimes are the result of more highly inclined orbits for the asteroids than for the transfer vehicles. However, the overall risk appears to be of the same magnitude for both groups. We conclude that leaving the NEP vehicle in some unspecified transfer orbit may incur a reasonable risk.

Predicted Orbit Lifetimes for Typical Low Thrust Trajectories

Trajectory Leg		Orbit Size $R_P \times R_A$ (A.U.)	Incl. (deg)	Mean Orbit Lifetime (Years)	Expected Earth Hits in 500 Trials	Mean Time to Hit (Years)	Earth Hit Chance in 10^6 Years
Earth-Mars	Start	0.98 x 1.25	0.0	5.6×10^7	266/500	1.6×10^7	16 %
	Middle	0.85 x 1.64	1.2	4.7×10^7	200	4.4×10^7	3 %
	End	0.61 x 1.51	1.8	4.0×10^7	160	3.1×10^7	2 %
Mars-Earth	Start	0.48 x 1.40	3.0	4.2×10^7	146	3.6×10^7	2.6 %
	Middle	0.50 x 1.89	1.3	4.2×10^7	123	3.3×10^7	1 %
	End	0.51 x 1.02	1.3	9.2×10^7	194	2.2×10^7	5.2 %
Earth-Disposal	Start	0.98 x 1.02	0.1	3.9×10^7	270	1.7×10^7	18 %
	Middle	0.99 x 1.02	0.0	3.9×10^7	266	2.1×10^7	17 %
Mars-Disposal	Start	1.28 x 1.66	2.1	7.5×10^8	148	4.4×10^8	0 %
	Middle	1.22 x 1.61	2.0	6.0×10^8	166	3.5×10^8	0.2 %

Predicted Orbit Lifetimes for Selected Near-Earth Asteroids



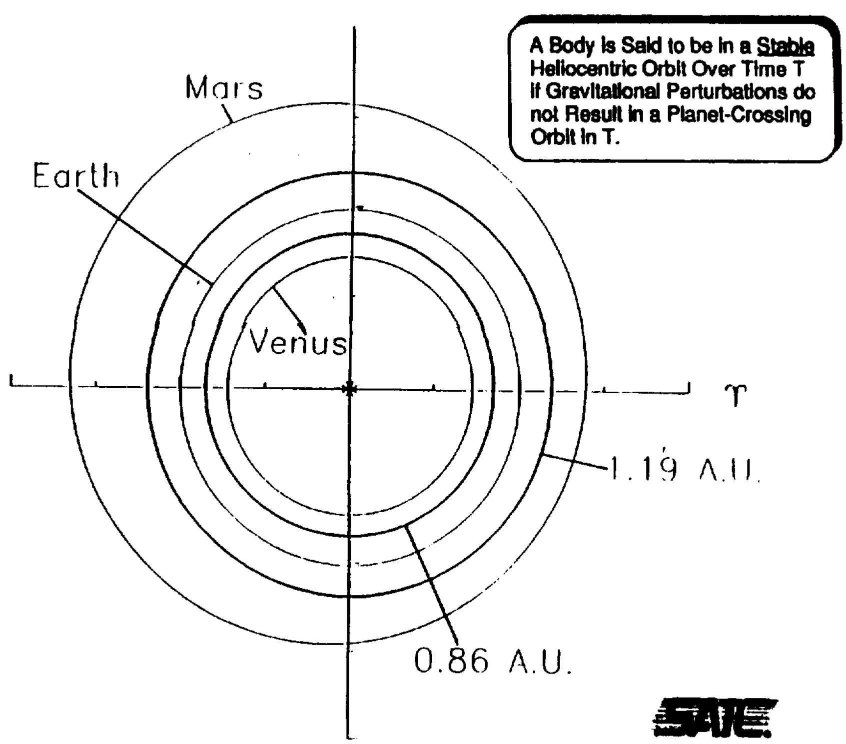
Body	Mean Orbit Lifetime (Years)	Expected Number of Earth Collisions (in 500 Trials)	Mean Time to Earth Collision (Years)	Chance of Earth Collision in 10^8 Years
2062 - Aten	5.27×10^7	177/500	4.46×10^7	1.6 %
1862 - Apollo	7.73×10^7	111	2.75×10^7	0.6 %
1221 - Amor	9.88×10^8	126	7.16×10^8	0
1943 - Anteros	7.48×10^8	203	1.98×10^8	0
1982DB	7.68×10^7	264	2.95×10^7	4.4 %
1989ML	3.87×10^8	194	1.95×10^8	0
1980AA	3.89×10^8	200	1.99×10^8	0
1982XB	6.25×10^7	267	3.44×10^7	5.2 %

Stable Heliocentric Circular Orbits

The second category of interplanetary orbits was identified by SAIC as a possible permanent storage location for hazardous waste in space.[1] This analysis was one part of a large effort to explore space-based alternatives for nuclear waste disposal conducted during 1977-79. These orbits are of interest because they are predicted to endure for a very long time without becoming planet-crossing orbits. Two bands of these stable orbits have been identified, as shown opposite. The one of most interest for Earth-Mars cases is a circular orbit at 1.19 A.U., between Earth and Mars. The orbit starts out circular, but becomes elliptic "quickly" in the long view of the situation, as shown on the next page.

1 Friedlander, A. L. and D. R. Davis, "Long-Term Risk Analysis Associated With Nuclear Waste Disposal in Space," SAIC Report No. 1-120-062-T12, prepared under contract NAS8-33022 for NASA/MSFC, December 1978.

STABLE HELIOCENTRIC CIRCULAR ORBITS

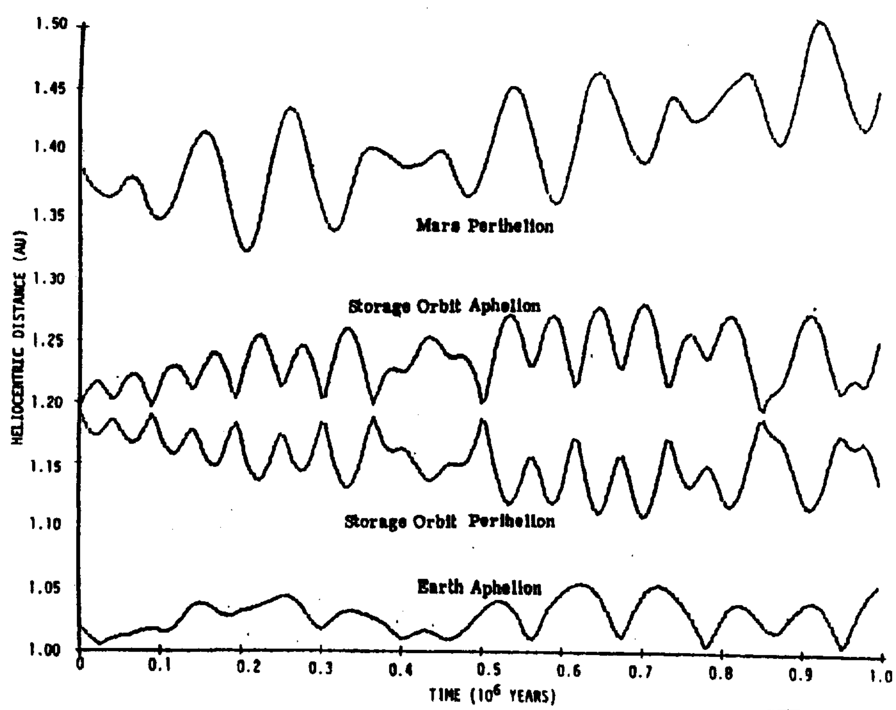


Science Applications International Corporation

Variation of a Stable Orbit at 1.19 A.U.

This chart plots heliocentric distance as a function of time (note the x-axis scale!) for the periapse and apoapse of the stable orbit. The Mars peripase and Earth's apoapse are also plotted. All four show significant variations over the one million year time frame, but the stable orbit never crosses its closest planetary neighbors' paths. This means that, with no further active management, placing an object in the stable orbit is sufficient to remove the real risk of the on-board radiation hazard.

VARIATION OF A STABLE ORBIT AT 1.19 AU

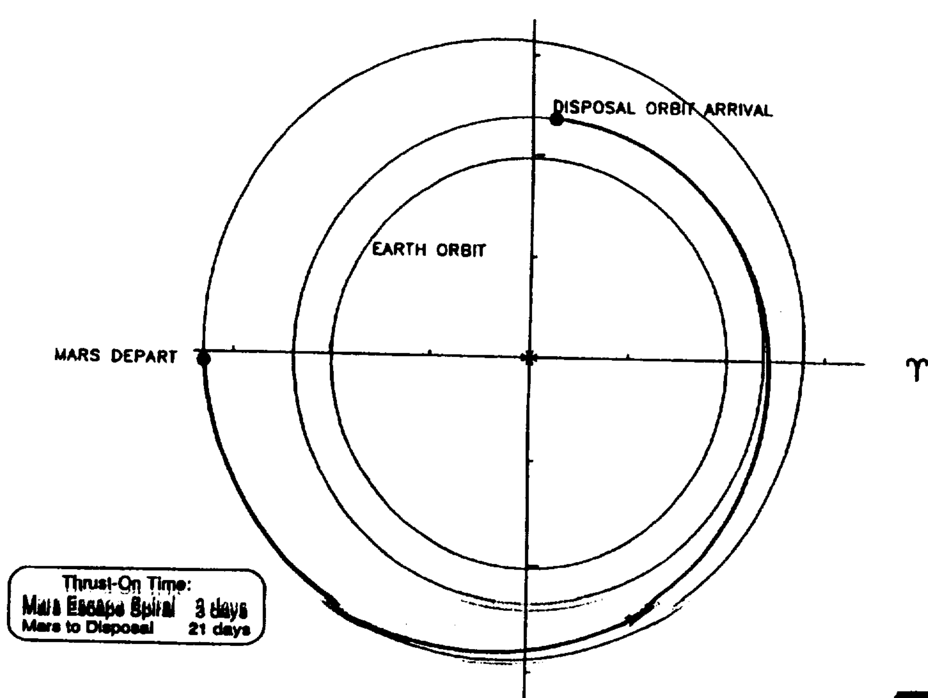


SAIC
Science Applications International Corporation

Typical NEP Transfer From Mars to Disposal Orbit

Here is a typical transfer to the stable orbit just described. We have selected a very long flight time to minimize propellant needs and additional thrust-on time. If a transfer vehicle were to leave Mars orbit for the stable disposal orbit, propellant and tankage needs would be a few tonnes, and thrust time would be about 24 days. Faster disposal legs can be traded for increased propellant.

Transfer to NEP Reactor Disposal Orbit (420 days)



Summary of Proposed Disposal Modes

This table summarizes preliminary evaluation of each of the four disposal locations for the cases examined. The comments indicate proposed use as temporary or long-term storage sites, with the preferred long-term selection for each case highlighted by a shaded box.

Earth orbit is recommended as a temporary storage location only, even though boosting the NEP vehicle or some part of it to higher altitude significantly mitigates the real risk. Since perceived risk is not so easily removed, a more distant storage location would be preferable for the baseline. For all cases of normal end of life, we propose that the stable heliocentric orbit be the baseline disposal location. This site could also be used for any partially disabled vehicle that can be moved to the stable orbit. However, recognizing the inherently low risk involved in leaving the vehicle in a transfer flight path, the proposed baseline for total system failures is the interplanetary flight path. Even a modest alternate propulsion system on board could maneuver to a higher inclination, or otherwise reshape the orbit of the derelict vehicle to make reencounter less likely.

Summary of Proposed Disposal Modes

Temp = temporary storage (1-5 years) until permanent disposal is arranged
Long = long-term disposal; "permanent" solution to the potential nuclear risk

			NEP Reactor Disposal Location			
			Earth Orbit	Mars Orbit	Interplanetary Flight Path	Heliocentric Stable Orbit
NEP Status at Disposal	Normal End of Life	Earth Approach	No	--	Temp - ok Long - ?	
		Earth Orbit	Temp Only	--	Temp - ok Long - ?	
		Mars Orbit	--	Temp - ok Long - ?	Temp - ok Long - ?	
	Propulsion System Failure	Earth Orbit	Temp Only	--		Long Option
		Earth-Mars Cruise	--	--		Long Option?
		Mars Orbit	--		Long - ?	--
		Mars-Earth Cruise	--	--		Long Option?

Proposed Baseline Disposal Mode

Disposal Mode Impact on Vehicle Performance

This chart is the companion to the previous one, showing the cost in propellant and thrust time to achieve some of the disposal locations of interest. In every case, the impact is very modest. The largest requirement shown opposite is for an Earth escape spiral to remove a fully operational NEP vehicle from Earth orbit. If the system has failed in Earth orbit and is to be moved, the cost will depend on the nature of the failure - full or partial - and selection of any additional propulsion that may be needed. Note that transfer to the stable orbit from Earth orbit calls for a thrust interval of about 10% of the expected thruster lifetime, so there may be some additional cost in thruster changeout.

Disposal Mode Impact on Mission and Vehicle Performance

NEP Status at Disposal			NEP Reactor Disposal Location: Earth Orbit	Mars Orbit	Interplanetary Flight Path	Heliocentric Stable Orbit
NEP Status at Disposal	Normal End of Life	On Earth Approach	--	--	None	M_{PROP} = 7 t ΔTh = 13 days
		In Earth Orbit	Small ΔV to raise orbit*	--	M_{PROP} = 18 t ΔTh = 36 days	M_{PROP} = 27 t ΔTh = 49 days
		In Mars Orbit	--	None	M_{PROP} = 2 t (1% of IMLEO) ΔTh = 1.4 days	M_{PROP} = 13 t (6% of IMLEO) ΔTh = 24 days
	Propulsion System Failure	In Earth Orbit	Small ΔV to raise orbit*	--	Depends on Implementation	
		Earth-Mars Cruise	--	--	[illegible]	
		In Mars Orbit	--	None		
		Mars-Earth Cruise	--	--	None	

M_{PROP} = propellant & tank mass penalty for disposal

ΔTh = Incremental NEP thrust-on time for disposal

* ~ 150 m/s to transfer from 700 x 700 km to 1,000 x 1,000 km

Recommended Approach for Disposal

The next two charts summarize the recommended approach to managed disposal of NEP reactors or transfer vehicles. These are to be viewed as a preliminary recommendation for further evaluation, concurrent with more detailed understanding of operational and performance impacts.

The stable heliocentric orbit is generally easy to reach, and is the most conservative risk management approach evaluated. Selecting this disposal mode for nominal end-of-life seems to greatly reduce both real and perceived risk for very little additional cost.

If a transfer vehicle should become completely disabled, its interplanetary path is almost certainly acceptable as a temporary storage location. It may also be adequate for long-term storage, especially if on-board auxiliary propulsion can be used to control the path.

Earth orbit need not be used for long-term disposal, thus avoiding additional controversy over use of nuclear energy in space. The operational orbit selected appears to support temporary storage readily. However, the NEP module design should incorporate sufficient auxiliary propulsion to handle orbit raising burns over a limited number of years. This could be further supplemented by a design that could separate a disabled reactor from the rest of the vehicle to increase the lifetime of the most critical subsystem, and to reduce propellant required to boost just the reactor to a higher orbit.

As a final precaution, some independent orbital transfer vehicle, possibly the Lunar Transfer Vehicle, could be available to push a derelict NEP to escape conditions, or to a stable orbit.

Recommended Approach for Disposal - 1

Location:

- Pick the **stable heliocentric orbit for nominal missions**
  - Modest propellant requirements for all cases examined
  - Conservative approach to risk management avoids programmatic problems
- Use interplanetary path disposal for a completely disabled vehicle
  - Every case we considered shows a predicted orbit lifetime of 10^7 years or better
  - Reencounter probability for most cases is of the same order as near-Earth asteroids
  - No ΔV required
- **Earth orbit for temporary storage only**; not for long-term disposal
  - 700 km altitude seems a reasonable compromise among: launch capability, predicted lifetime for typical configurations, and on-going operations
  - Include independent propulsive capability to raise orbit of MTV
  - Avoid most controversial location for long-term storage

Recommended Approach for Disposal - 2

Transfer Vehicle Design:

- **Include auxiliary propulsion system** in baseline 5 MWe module design
  - Sufficient to raise Earth orbit from 700 km to 1000 km (ΔV ~ 150 m/s)
  - System design and propellant required depends on how much of the module is boosted to the higher orbit

- Consider adding capability to **separate a disabled reactor** from the rest of the module; auxiliary propulsion remains with the reactor

Transportation Infrastructure

- Assured removal from Earth orbit may require a separately deployed orbital transfer vehicle - possibly an LTV or similar element