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4.2 Mars Transfer Vehicle Studies -

Gordon Woodcock, Boeing

Earth-to-Mars distances vary from 60 to 400 million kilometers over a 14-year cycle. This complicates Mars mission design as a function of calendar time. Stay times at Mars are also strongly driven by opportunities for a return flight path which are within the limits of delta-V associated with practical space vehicles.

The biggest difference between Mars and lunar transfer missions is mission time, which grows from a few days for the moon, to as much as a few hundred days for Mars missions. As a result, modules for similarly sized crews must be much larger for Mars missions than for transfer to lunar orbit.

Technology challenges for one Mars mission scenario analyzed by Boeing include aerobrakes, propulsion, and life support systems. Mission performance is very sensitive to aerobrake weight fraction and, as a result, there is an incentive to use high performance materials such as advanced composites and thermal protection systems. Lander aerobrake would be used twice (for both planetary capture and descent to the Mars surface), and it would need to survive temperatures up to 3500 degrees.

The ascent from the lunar surface could use a cryogenic propulsion system to maximize performance. Cryogenic storage concepts such as a vacuum jacket combined with multi-layer insulation could be used to insulate the cryogenic tank. Otherwise, storable propellants would need to be used.

Boeing has examined various propulsion systems. Nuclear propulsion systems offer good potential performance, but aerobrakes are still needed for the descent vehicle even if the transfer vehicle uses propulsive orbital capture at Mars.

Nuclear thermal propulsion systems use all-hydrogen fuel. Because of its low density, these nuclear thermal systems are sensitive to hydrogen tank fraction, which depends greatly on tank structural and thermal control technologies.

Studies at LeRC have shown that acceptable trip times can be accomplished by nuclear electric propulsion systems with powers on the order of 15-20 MW. Nonetheless, high power nuclear electric propulsion systems can also involve serious technology challenges such as high power dynamic power conversion, assembly in space of large mechanical structures and fluid systems, long-term performance of liquid metal systems, and overall complexity.

Solar electric systems are, in many respects, simpler to deal with than the alternatives. Although they are large, fabrication involves repetitive operations, they have minimal fluid systems, and they are inherently redundant. Technology challenges include the need to reduce the cost of the arrays by a factor of about 10 (from approximately $2000 to $200 per watt) to make solar electric systems affordable. Terrestrial solar arrays are currently available for about $2 per watt.

Assuming an ETO launch vehicle with a capacity of 100-150 tons, it would take six or seven launches to stage in LEO a transfer vehicle with a nuclear thermal propulsion system. Assembly would also require establishment of a platform as a base for the assembly process. New concepts and technologies are needed to facilitate in-space construction. For example, it may be possible to use some of the systems and structures of the Mars transfer vehicle to support the assembly platform, rather than first constructing a separate and self-contained assembly platform.

Aerobrakes have their own set of construction issues which vary somewhat with aerobrake design parameters such as the L/D ratio.

Boeing has studied the challenges associated with the need to place large cargos on the Martian surface. Assuming a cargo diameter of seven-to-eight meters and a length of 15 meters, the size of the cargo drives the overall size of the lander. If more than one lander is used to deliver, for example, separate sections of a Martian base, then the landers will also need some ability to relocate on the surface (so that the payload elements may be joined after delivery) unless the mission also includes a separate surface transporter.

It would be possible to deliver a Mars lander to LEO in a single piece using a 150-ton class launch vehicle. However, the launch vehicles included within the proposed NLS program will not be able to accommodate the mass and configuration of the Mars lander analyzed by Boeing.

Mission requirements for Mars are not yet fixed. Mass requirements seem to be growing with each new study. As mass requirements grow, it increases the advantage of using a separate, electrically-driven vehicle to deliver cargo in advance of the crew vehicle. Solar electric propulsion could be used, especially if it was augmented by a beamed power system using a terrestrial laser beam. Such a system could increase the power density of the solar array by a factor of five-to-ten over solar illumination and greatly shorten the time required to escape from Earth orbit as well as reduce the size (and cost) of the solar array .

The trade-off analyses for Mars transfer vehicle concepts are, obviously, very complex. Options such as solar and nuclear electric offer high reusability and low launch mass. Chemical propulsion systems using cryogenic expendables require higher launch mass and feature less reusability, but have significantly lower development costs.

MARS TRANSFER VEHICLE STUDIES

Gordon Woodcock
Boeing

Nuclear Ops Working Group Mission Ground Rules

Mission #1 - 2014

- Outbound direct, conjunction-like profile.
- Window close (latest) departure 2456690 = 2/2/2014
- Mars arrival 2456840; 90-day stay.
- Earth return via Venus swingby 2457240; total duration 550 days.
- Aborts: (1) powered, on nominal trajectory; (2) unpowered Venus swingby 720-day total duration.
- Mission options:
  (1) All-up, single mission.
  (2) Surface cargo sent ahead prior opportunity, NTP all-up test.
  (3) Surface cargo and crew MEV sent ahead prior opportunity, rendezvous in Mars orbit.
  (4) Like (3) but extra propellant sent ahead for fast return trip.

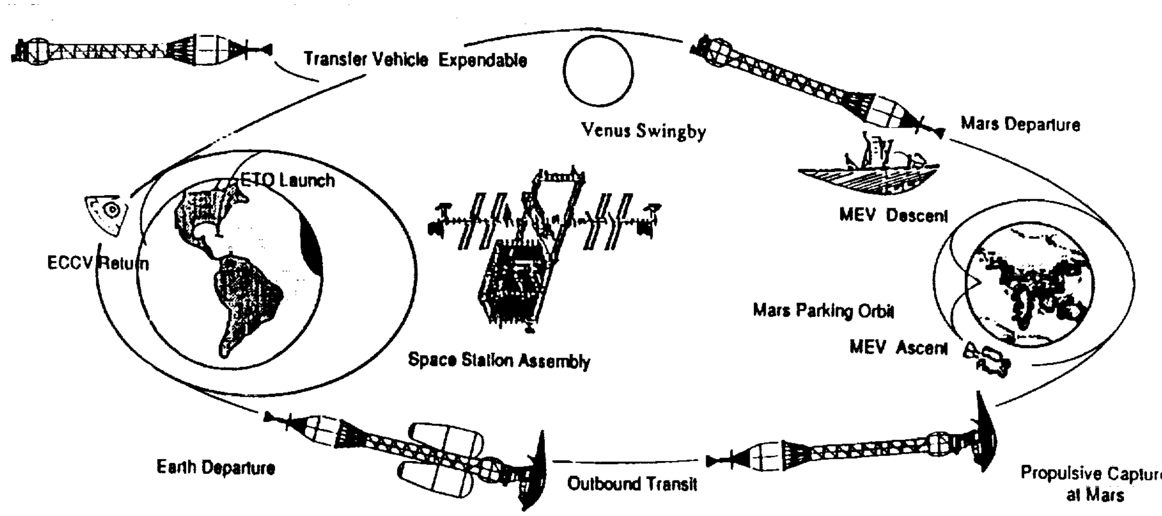
- Delta Vs

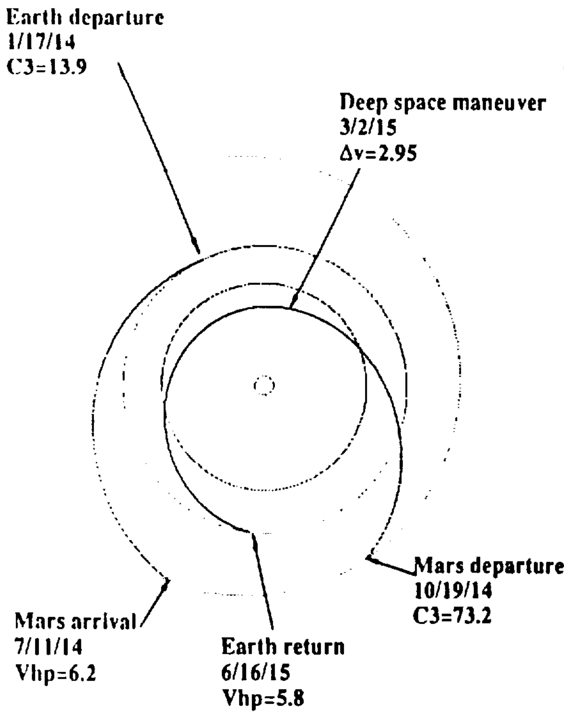
Earth depart impulsive (max at window close)	4240 m/sec
Finite burn (est.)	300
Plane change	100
Total Earth depart	4640

Mars arrival	4170
Finite burn (est)	100
Total Mars arrive	4270
Mars depart	3260
Line of Apsides	150
Total Mars depart	3410

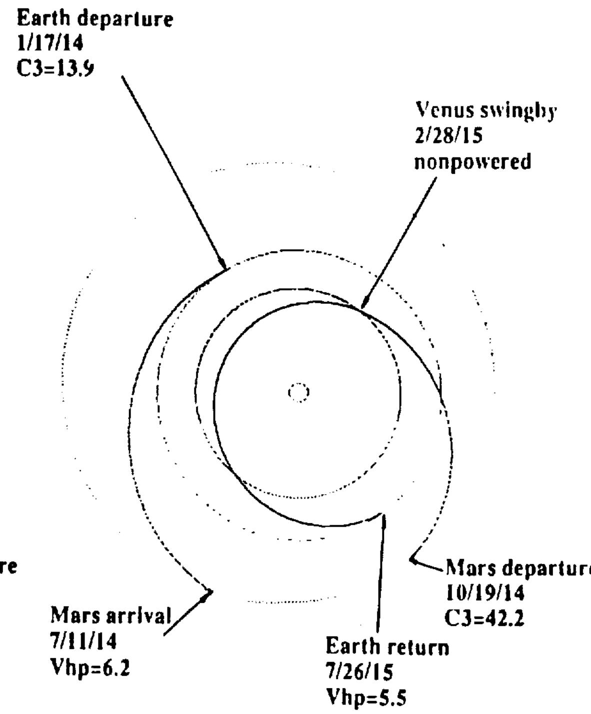
24-hr capture at *Earth return* 1440

Mission Profile



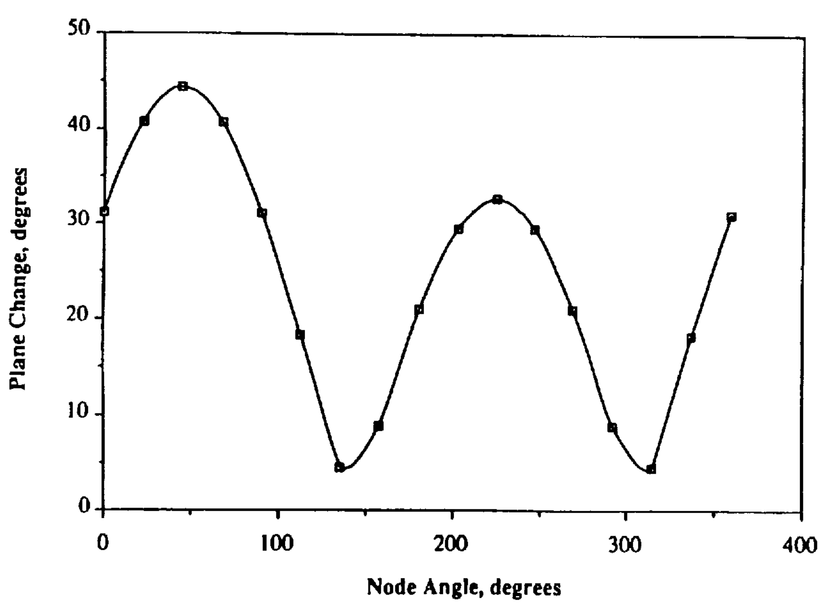


2014 Manned Mission ;
Deep Space Maneuver

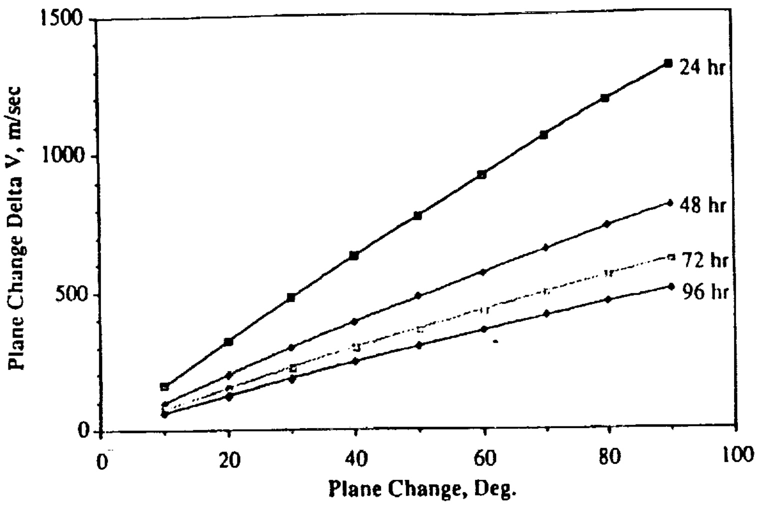


2014 Manned Mision,
Venus Swingby

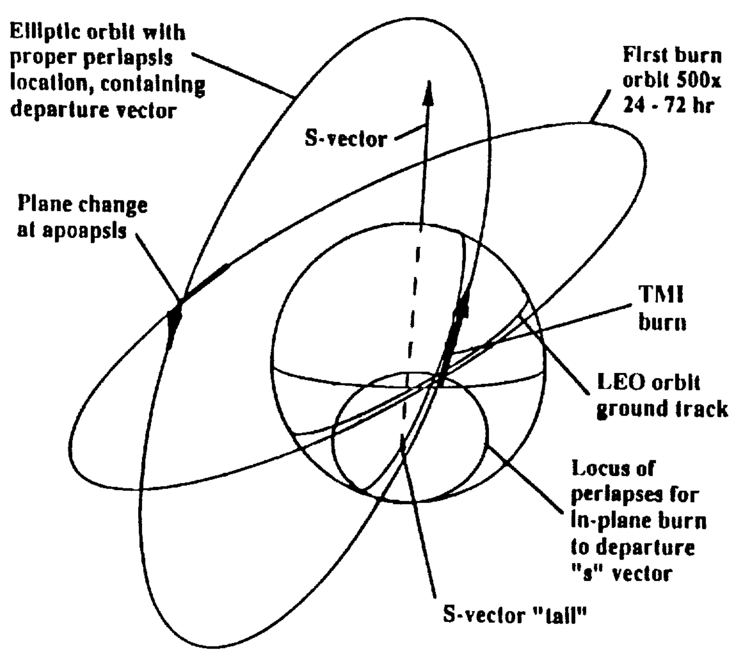
Plane Change Requirements for 2014 Mars Opportunity, 150-day Transfer



Plane Change Delta Vs for Range of Elliptic Orbit Periods

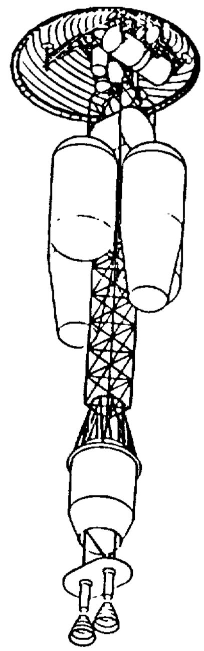


Three Burn Departure Opens Launch Windows



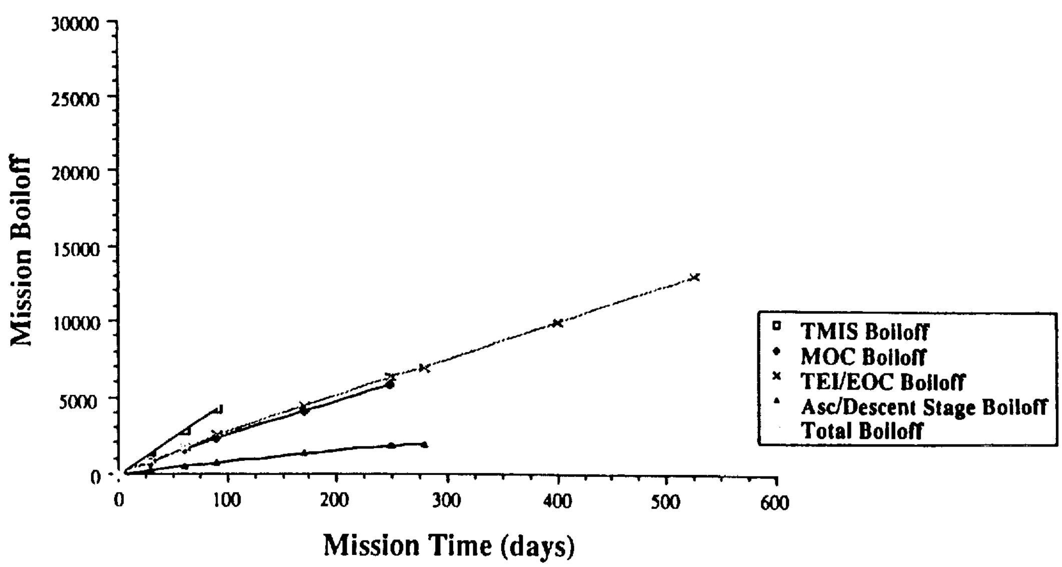
Nuclear Thermal Propulsion Vehicle
2013 Opposition (100 d stay) 175 d Outb Transfer Mass Statement

Reusable, crew of 6, two 75k lbf thrust PBR engines at 925 Isp, T/W=20, MEVs:43 tons cargo minus asc stg

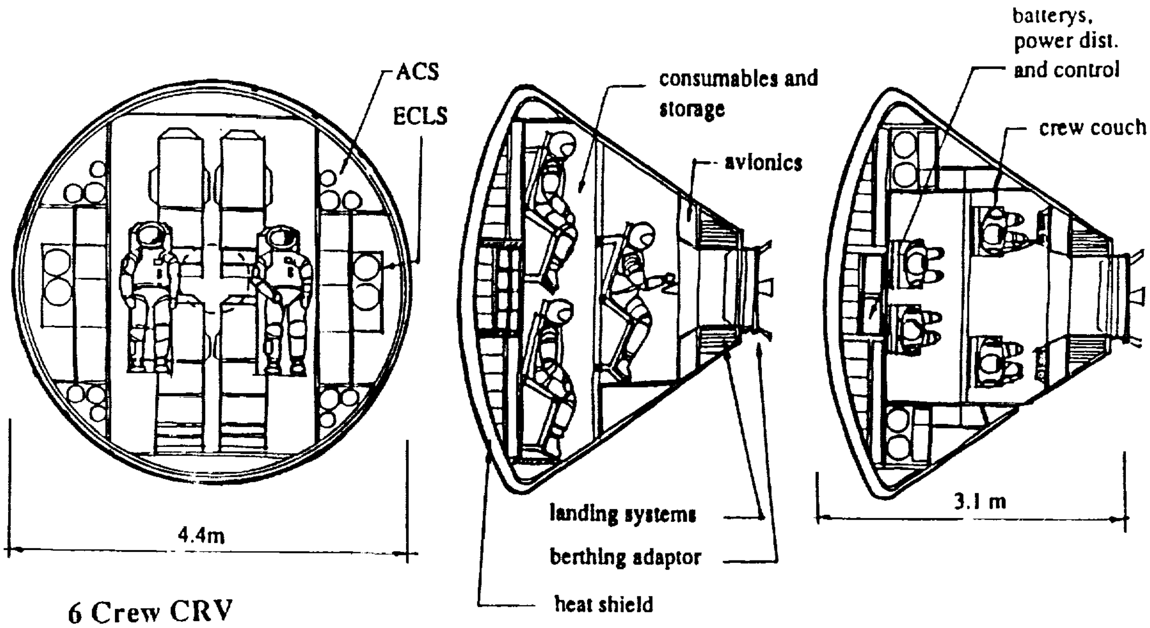


Element	Number of MEV's : 0	1	2
MEV total	0	72236	144472
MTV crew habitat system tot	54900	54900	54900
MTV frame, struts & RCS inert wt	5200	5200	5200
Reactor/engine weight	3402	3402	3402
Radiation shadow shield weight	9000	9000	9000
EOC propellant (dV= 1756 m/s)	24830	24830	24830
TEI propellant (dV= 3840 m/s)	72426	72426	72426
TEI/EOC common tank wt (1)	15862	15862	15862
MOC propellant (dV= 3457 m/s)	108930	148470	188280
MOC tanks (2)	20094	25216	30356
TMI propellant (dV=4318 m/s)	237250	320220	405200
TMI tanks (2)	36986	47105	58405
ECCV	8000	8000	8000
IMLEO	596700	806687	1020153

Cumulative Mission Boiloff vs. Time for Reference NTR Vehicle



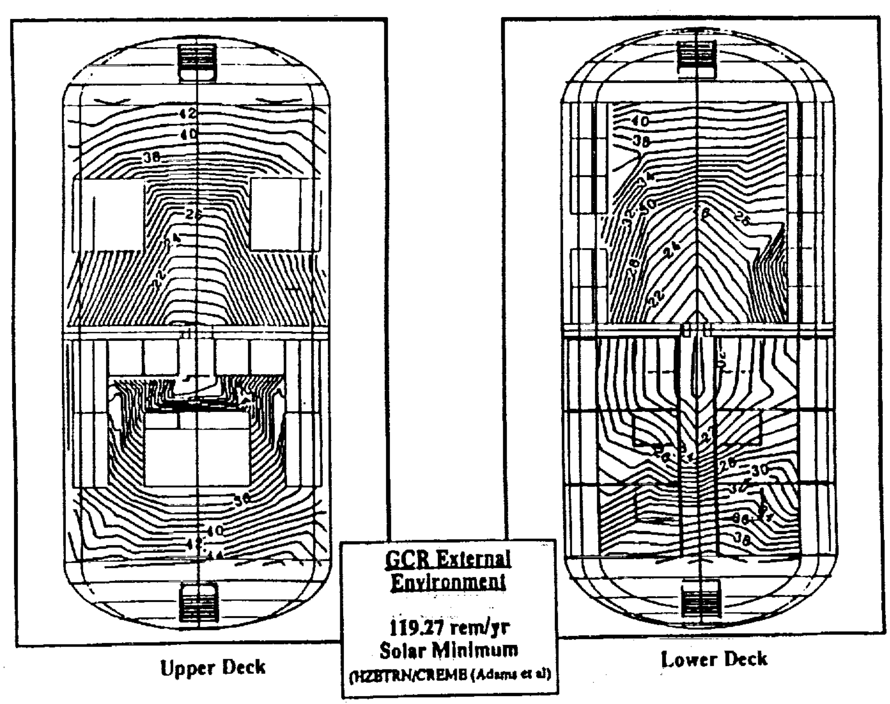
CRV Configuration



6 Crew CRV

Habitable volume : 12 m^3

rem/yr to BFO



NTP Reference Mission Description P. 1

Mission Event/Sequence	Issues and Open Questions
1. Multiple ETO launches to assembly station - sequence: • Assembly station (first time) • Habitat • Truss • Engine & aft tank assembly • MEV(s) (if needed) • Expendable tanks, loaded • Top-off tank, if required	• Lift capacity and shroud size for ETO vehicle; number of launches. • Whether mission is split; how many MEVs go on crew mission. • Location of assembly station re Space Station Freedom (presumably co-orbital). • How much EVA is needed (presumably very little).
2. Cargo Transfer Vehicle (CTV) serves as ferry from ETO delivery orbit to assembly station.	• Where CTV is based and how refueled. (Recommend basing at SSF & refueling by fuel pod on each ETO MTV cargo launch).
3. Checkout crew delivered to MTV for pre-launch tests and checkout.	• Tests performed after assembly complete, or incremental crew-aboard testing? • Means of crew delivery (presumed CTV).

NTP Reference Mission Description P. 2

Mission Event/Sequence	Issues and Open Questions
4. Mission crew delivered to MTV for countdown and launch.	• Delivered by ETO launch or from Space Station Freedom (SSF)? (Presumed SSF.)
5. First burn to 72-hr elliptic orbit. Finite burn raises perigee to about 1000 km.	• OK to depart from assembly orbit at ~ 500 km? (Not clear that moving to "nuclear-safe" orbit measurably improves safety.)
6. Coast to apogee.	
7. Second burn at apogee for plane change.	• Is it OK (safety) to depress perigee on this burn to reduce third burn delta V.?
8. Coast to third burn start point, approx. 1000 km. altitude 9. Third burn accomplishes TMI. TMI tanks jettisoned.	• If either NTR engine fails before or immediately after TMI, mission rules call for crew abort return to Earth. Reactor disposal means in this event needs to be determined.

NTP Reference Mission Description P. 3

Mission Event/Sequence	Issues and Open Questions
10. Coast to Mars; midcourse corrections accomplished by GH_2RCS using compressed boiloff.	• If abort decision prior to Mars capture, first choice is powered abort to fast return trajectory. Second choice is free-return; nominal trajectory or longer return time (opportunity dependent).
11. NTP capture into elliptic orbit at Mars. Period between 12 and 24 hours to optimize mission. MOC tanks jettisoned.	• One or more reactor disposal options may prohibit NTP capture at Mars.
12. If the mission is split such that both MEVs go earlier, a rendezvous with the cargo mission is required.	• Is there a feasible cargo mission parking orbit that enables minimum- energy rendezvous?
13. MEV descent(s) to Mars using aerobrake.	• Cargo MEV lands first. One candidate split mode sends the cargo MEV earlier with automatic landing.

NTP Reference Mission Description P. 4

Mission Event/Sequence	Issues and Open Questions
14. Crew conducts surface mission.	• Does the entire crew land or is it necessary to leave one or more crew in orbit to tend the MTV? Assumed that entire crew lands.
15. Crew returns to MTV using crew MEV ascent stage. MEV-active rendezvous.	
16. Nuclear propulsion for TEI.	• One or more reactor disposal options may prohibit NTP return to vicinity of Earth.
17. Coast to Earth; midcourse corrections accomplished by GH_2 RCS using compressed boiloff.	
18. Crew separates in Crew Return Vehicle ~ 1 day before Earth arrival; direct entry to Earth landing.	• In-plane return to Space Station Freedom orbit is generally not possible due to misalignment of lines of nodes.

NTP Reference Mission Description P. 5

Mission Event/Sequence	Issues and Open Questions
19. NTP vehicle propulsively captures into 500 km by 24-hour orbit at 28.5° inclination.	• One or more reactor disposal options may prohibit NTP return to vicinity of Earth. Assumed that return to Earth orbit is OK.
20. Wait up to 55 days for nodal alignment with Space Station Freedom orbit.	• See discussion of reactor disposal options.
21. NTP vehicle refueled by cryo. LTV; about 30 t. LH_2	
22. NTP vehicle deorbits to 500 km. circular; rendezvous with assembly node for refurbishment and reuse.	• This must be carried out quickly (~1 day) because differential nodal regression is about 6° per day.

Nuclear Reactor Disposal Options, NTP

- Assumed that NTP including reactor captures into safe Earth orbit (500 km x 24 hr) if nuclear engine has enough life for next mission. Otherwise, engine/reactor require safe disposal.

- Dedicated disposal vehicle, delivers reactor from safe Earth parking orbit to safe disposal orbit, e.g. between Earth and Venus.
- NTP serves as disposal vehicle, delivers reactor from safe Earth parking orbit to safe disposal orbit, e.g. between Earth and Venus. Crew cab can be removed for reuse prior to disposal mission.
- NTP vehicle performs Earth swingby/gravity assist at Earth return. Subsequent maneuvers may be required to avoid Earth-intersecting orbit. Crew hab could be separated and aerocaptured (unmanned).
- NTP left in long-life Mars orbit; cryo propulsion for trans-Earth injection.
- NTP performs Mars swingby/gravity assist at Mars arrival. Aerocapture used for Mars orbit capture and cryogenic propulsion for trans-Earth injection. Subsequent maneuvers may be required to avoid Mars-intersecting orbit.

Mission Planning Issues

- How do we deal with space assembly and ground ops overlap between cargo and crew missions?
- Should we plan the first cargo mission as an all-up test of the nuclear thermal propulsion system, including propulsive return to LEO?
- Is direct entry and landing (DEL) of MEVs an option for later cargo missions?
- What additional equipment does the MEV need to fly the DEL mode?
- Can cargo be prepositioned in elliptic parking orbits compatible with later rendezvous by crew missions?
- Is it acceptable to plan on powered aborts where a timely free return is not available?
- Assuming cargo is predeployed on Mars' surface, what health monitoring implications follow from the need to have the payload powered down (to a power level consistent with deployable array) until the crew arrives?