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Mission Design Considerations for Nuclear Risk Mitigation

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&

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• Safe Return of NTR to Earth Orbit	Pulsed cooldown propellant can be used to lower capture orbit to selected operations altitude
• Lunar/Mars NTR Disposal	Modest cost, low risk disposal to heliocentric orbits for all transfer trajectories

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Aim Point Bias Offsets Targeting Errors

One of the operational safety concerns for nuclear propulsion is how to manage safe return of a nuclear powered transfer vehicle to Earth orbit. Although the mission profiles used in this study call for crew return by an Earth Crew Capture Vehicle (ECCV), capturing the transfer vehicle offers the added flexibility and possible cost savings of reuse. The return orbit must be low enough to be accessible from Earth launch at reasonable cost, yet high enough to ensure safety

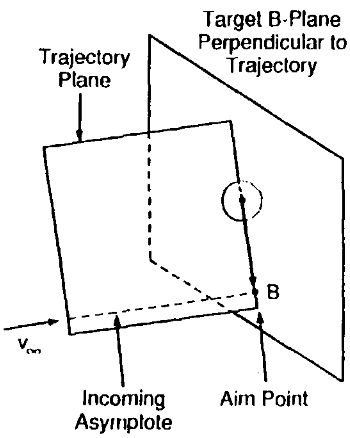
Experience shows that orbit insertion errors are caused by some or all of the following factors:

- Errors in Trajectory Correction Maneuvers (TCM), resulting from off-nominal thrust level, direction, or duration. These may be caused by the propulsion or attitude control subsystems.
- Inherent uncertainty in determining the spacecraft's orbit
- Small errors in precise location of natural bodies

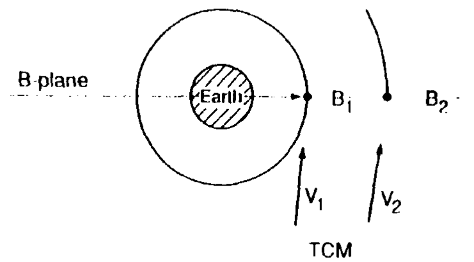
However, the resulting variations in spacecraft orbit parameters are small; orbit insertion altitudes vary by only a few kilometers. The performance of a nuclear thermal rocket should be similar to past experience with chemical systems. The critical item, then, is to select a nominal return orbit that matches lifetime characteristics with the needs of short-term storage in Earth orbit

The aim point can be biased so as to raise the distance of closest approach, and capture into some orbit higher than the desired one. After exact position and status of the vehicle is determined, a series of smaller burns lowers the orbit to match the final size. This approach will be the basis of a proposed strategy for making effective use of pulse-mode cooldown propellant.

Aim Point Bias Offsets Targeting Errors



- Targeting errors result from off nominal TCM burns, uncertainty in orbit determination
- Typical injection errors are small: altitude dispersions of a few kilometers
- Damp out dispersion effects by changing the aim point to a higher orbit (elliptic or circular), then use small impulses to lower to desired final orbit



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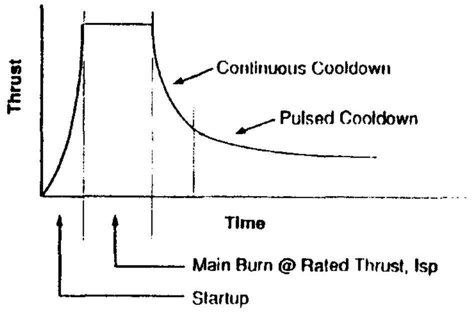
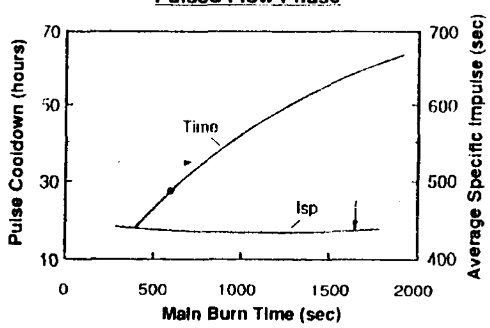
Cooldown Propellant Characteristics

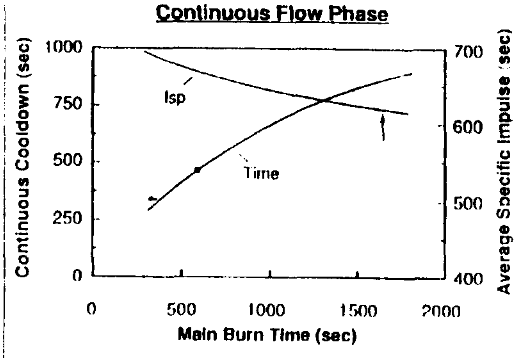
Since NTP systems must cool the reactor with flowing hydrogen after every main burn, it would be desirable to use as much as possible of this propellant for productive thrust. The continuous cooldown flow lasts for a few minutes, and is assumed to handle part of the required capture impulse. The pulsed flow lasts over several hours, with the exact profile depending on the main burn duration. Pulsed flow averages a specific impulse of about 440 seconds, but at a very low thrust level.

The table in the lower right corner opposite shows the four phases for a main burn of 600 seconds, typical of Earth orbit capture burns for return from the Moon. In this case, the pulsed flow must occur over 31.5 hours to keep the reactor within the specified temperature range.

Cooldown Propellant Characteristics







Phase	Δ Time	Propellant (kg)	Average Thrust (lbf)	Average Isp (sec)
Startup	60 s	3,127	17,411	737
Main	600 s	24,737	75,000	825
Continuous	458 s	1,748	5,635	670
Pulse	31.5 h	1,483	12.7	438

Source: Flight Engine Program (FEP) Runs by Aerojet, Aug. 1970

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Altitude Profile During Pulsed Cooldown

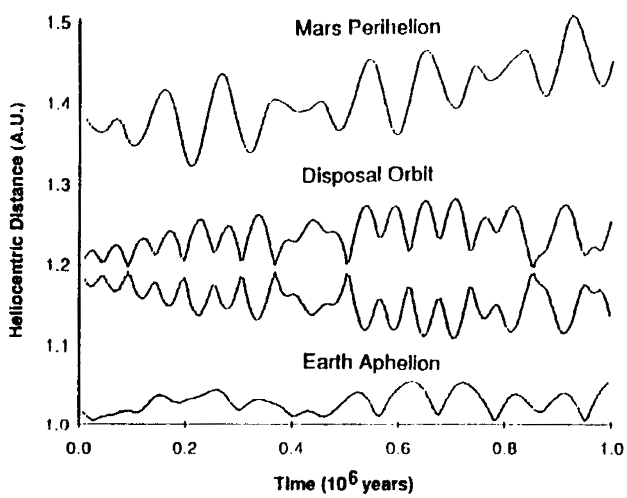
The baseline profile for a piloted mission to either the Moon or Mars is to separate the crew in an ECCV for direct reentry at Earth return. This eliminates the operational concerns of crew safety on board during the extended cooldown time interval. Modeling of the pulsed flow shows a total propellant requirement of 1,473 kg for cooldown purposes. From the LTV mass requirements, shown elsewhere in this study, this translates to a ΔV of 117 m/s, assuming the maximum effective thrust could be imparted by the propellant flow.

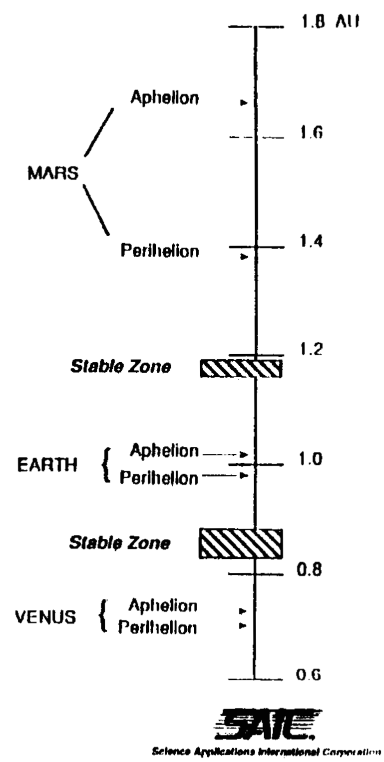
The problem is to match the required cooldown propellant flow with an orbit modification strategy that meets mission requirements, while deriving maximum value from the available ΔV. The approach used here is to accept the pulsed flow profile as given in the Aerojet FEP output runs referenced on the previous page (although it may be possible to modify it), and to use each low thrust impulse to lower the altitude of the initial capture orbit. We begin with a circular orbit at some altitude, and proceed to apply a sequence of many small impulses to lower to the desired 500 km orbit at the end of pulsed cooldown. Starting with a circular orbit at 716 km will produce the desired final altitude of 500 km at the end of this thrusting program.

This use represents one example of how the pulsed cooldown propellant may be used for transfer vehicle thrust. A complete characterization for the range of engine sizes considered in this study will require burn simulations for various thrust levels, burn times, and numbers of engines staged together.

Stable Orbits

- An orbit is stable over time T if a body in that orbit doesn't cross a planet's path in T
- Starts at 1.19 x 1.19 A.U., becomes elliptic, but doesn't cross Mars or Earth





NTR Disposal for Mars Missions

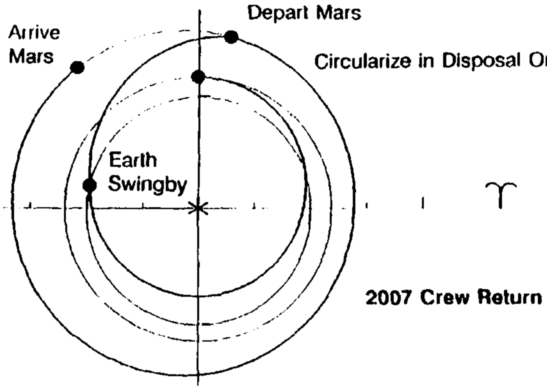
Two options are considered for Mars missions: the stable heliocentric orbit, or disposal along the interplanetary trajectory that the transfer vehicle is following. For the former, the ΔV requirements for two split/conjunction mission pairs are shown on the facing page. Cargo missions need two impulses to leave Mars and to circularize. Crew mission trajectories are modified to perform Earth gravity assist after ECCV separation, saving roughly 2 km/s impulse. The orbit plot show the 2007 crew return profile, with Earth swingby to final capture burn at 1.19 A.U.

The second option is to leave the transfer vehicle in its flight path. In all cases, the flight path crosses at least one planet's path, setting up possible unintended gravity assists in the future. However, predicted chance of Earth reentry in one million years is generally of the same order as the likelihood of colliding with a typical near-Earth asteroid. The only exception is the near-Hohmann transfer leg from Earth to Mars for the cargo vehicle.

NTR Disposal for Mars Missions

- Consider Stable orbit, or disposal on interplanetary path

Mission	Disposal Starts From	Required Maneuvers	ΔV
2005 Cargo	Mars orbit, after rendezvous	Depart Mars Orbit Circularize at 1.19 A.U.	0.664 km/s 0.998
2007 Crew	Earth approach, after ECCV separates	Earth Gravity Assist Circularize at 1.19 A.U.	0 2.954
2007 Cargo	Mars orbit, after rendezvous	Depart Mars Orbit Circularize at 1.19 A.U.	0.665 1.000
2009 Crew	Earth approach, after ECCV separates	Earth Gravity Assist Circularize at 1.19 A.U.	0 3.017



		Chance of Earth Reentry in t ≤10^6 years - %	
	Leg	2005/07	2007/09
Cargo	E-M	12.0	12.0
	M-D	0.0	0.0
Crew	E-M	3.8	3.8
	M-E	2.2	2.6
	E-D	1.2	1.4

E = Earth M = Mars D = Disposal

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