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Synergistic Use of High and Low Thrust Propulsion Systems For Piloted Missions to Mars

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Abstract

Reduced transit times have been identified as desirable for piloted Mars missions. The demanding nature of these missions imposes stringent requirements upon space propulsion systems in terms of specific impulse and thrust/weight. The "ideal" propulsion system for fast trips to Mars would have both high specific impulse as well as high power density. To achieve these characteristics in a single propulsion system poses a dramatic technology challenge. An alternative to be considered is the combination of two relatively near term non-ideal systems such as nuclear electric propulsion and chemical or nuclear thermal propulsion in order to approximate the ideal. The use of high thrust, relatively low specific impulse systems, such as chemical or nuclear thermal propulsion, in conjunction with low thrust, high specific impulse nuclear electric propulsion, has been considered for a representative piloted Mars mission. Two modes were considered: 1. Use of high thrust at Earth escape only; 2. Use of high thrust for all planetary escape and capture maneuvers. Parametric variation of NEP characteristics over a range of specific mass, power, and specific impulse values was used, as well as variation in the amount of high thrust propulsion. These parameters were assessed for an opposition class mission over a range of trip times. Recommendations for system selection and further work are discussed.

Introduction

Piloted missions to Mars, in which trip time and initial mass are primary figures of merit to be minimized, impose stringent demands upon propulsion systems. The need to simultaneously reduce transit time and initial mass drive propulsion system requirements toward regimes of high specific impulse (Isp), high thrust/weight (T/W), and high power. High thrust/weight, relatively low Isp (Isp = 400 - 900 s) thermal systems such as chemical (Chem) and nuclear thermal propulsion (NTP), are driven to higher propellant temperatures and therefore greater material temperatures, ultimately requiring speculative materials and cooling technologies as exemplified by the gas core nuclear thermal rocket[1,2]. Similarly, electric propulsion systems are driven to low specific masses (ratio of propulsion system mass to electric power output) and high powers, which also lead to advances in technology in terms of high temperature materials and innovative system concepts.[3,4]

At present, without such advances in technology, both high thrust and low thrust systems have mission regimes in which they excel. For the high thrust, relatively low Isp systems, their high thrust/weight allows effective fast travel in the vicinity of planetary gravity wells. The low Isp is a penalty in interplanetary travel, where high mission energy requirements imply large propellant masses. Conversely, electric propulsion systems are inherently low acceleration, and thus require long trip times when travelling in planetary gravity wells. In interplanetary space, however, the high specific impulse allows significant reduction in propellant mass over the thermal systems, with less penalty in trip time.

The propulsion system "ideal" of high Isp, high thrust/weight might also be approximated through the use of separate systems, one providing high acceleration where it is needed for short transit in high gravity, and one operating at low acceleration, high specific impulse in heliocentric space. Such a combined system pays a system mass penalty in terms of multiple systems; however, on demanding missions the propellant mass savings may more than equal this penalty.

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Combined Propulsion Systems

The concept of combining propulsion systems is not a new one[5]. In the past, this option has often been referred to as "hybrid" propulsion; due to the multiple disciplines in which the term hybrid is currently used, a different nomenclature will be used herein to specify the alternatives to be considered.

The first approach is termed "Combined Propulsion." This is defined as the combination of two separate systems, one a high thrust thermal system, the other an electric system. Possible combinations would be

- Chemical/NEP, SEP
- NTP/NEP, SEP

The second option is called "Dual Mode Propulsion." This option is limited to the NTP/NEP combination, because the same reactor is used to provide power to both thermal and electric propulsion systems. The mass of reactor and shield for one of the two systems is eliminated at the expense of increased system complexity. In addition, the conflicting requirements of high temperature, burst operation and long life continuous power generation tend to impose performance limitations on both systems relative to their performance in a single mode[6].

When considering combined propulsion systems, it is important to remember the reason for approximating an "ideal" propulsion system: Reduced transit time for reasonable vehicle mass. It should be obvious that the use of two systems to perform a mission that is achievable by either single system will not show any benefit in terms of vehicle mass savings. For fast missions to Mars, the combined systems can fully exploit the respective benefits of thermal and electric propulsion to allow more mass efficient transit for short trip times.

Combined systems offer additional benefits in mission performance. High specific impulse systems generally have less variation with mission opportunity as compared to thermal systems with lower Isp. Similarly, some extension of launch window may be possible. The use of combined systems also reduces the operating demands upon the propulsion systems: the high thrust systems need not be pushed to extremes in Isp and temperature, and the low thrust systems do not require large power levels for reduced trip time. This reduction in EP power requirements allows for greater commonality with lunar and Mars cargo vehicles, as well as with surface power systems. In addition, the use of high thrust systems in planetary orbits significantly decreases the operating time of the low thrust system through elimination of long spirals. Finally, a combined system using separate high thrust and electric propulsion systems provides an added level of propulsion system redundancy for mission safety.

Review of Past Work in Combined Propulsion

Combined propulsion has been considered in myriad ways over the last three decades. Primary emphasis has been placed on the combination of NTP with NEP systems, both as combined and dual mode systems. These studies will be summarized in terms of mission design, system assumptions, and conclusions.

Mission Design: Two mission approaches were used in past studies. The first approach only uses the high thrust stage for Earth escape; all other propulsion for the rest of the mission was performed by the electric propulsion system. The second method used high thrust at planetary escape and capture, augmenting the impulsive maneuvers with additional electric propulsion impulse in heliocentric space. Another mission option used was a flyby Earth return trajectory, with an Apollo-type capsule reentry for crew return. This maneuver is essentially identical to that assumed for recent Space Exploration Initiative piloted Mars missions [7]. Variation of propulsion requirements with opportunity was considered by one reference for both the combined and all-NTP system [5].

System Assumptions: The NEP system assumptions were most crucial to the analyses, due to the effects that α (specific mass) has on trip time and vehicle mass. Due to the unknowns in space nuclear power systems and electric propulsion systems in the 1960's, the electric power systems were considered parametrically over a range of α. Values of 5 to 20 kg/kWe were considered. Isp values in the range of 5000 - 10000 seconds were used, assuming mercury ion engine efficiencies.

High thrust systems were modeled as massless relative to the NEP system. This assumption would be nearly true for chemical rockets; however, NTP systems are substantially heavier due to reactor and shielding masses, and can mass several metric tons. Isp values for chemical ranged from 425 to 450 seconds; NTP Isp levels varied from 800 to 850 seconds, as demonstrated by NERVA rockets at the time. Staging of high thrust systems was not addressed.

In many cases, an Earth Crew Capture Vehicle (ECCV) was used[5,8,9] to return the crew to Earth without costly propulsive braking of the entire Mars Transfer Vehicle (MTV). Entry velocities of 11 to 19 km/s were used, based on assumptions of advanced ablative aerobraking technologies. These assumptions are optimistic in light of the present day 9.4 km/s limit on aerobraking used in piloted Mars mission studies[7]. It should be noted that while the ECCV approach significantly reduces trip times, the reuse of the propulsion system is hampered or negated due to the nature of the trajectory.

Conclusions: In all cases, the use of combined systems was found to produce initial vehicle masses lower than either system used singly. Again, the studies focussed on fast trip times of 500 days or less. Several researchers noted the synergy of using both systems together, provided that the high thrust system was used to propel the vehicle beyond escape [8]. In one review, the combined propulsion mode was found to yield vehicle masses comparable to that of the high thrust Venus swing-by, with an 80 day reduction in trip time. NEP specific mass for this system was assumed to be 16 kg/kWe. The potential for extended launch windows, additional abort modes, and stay time flexibility was also identified[10]. In a comparison based on two different opportunities, Mascy, et. al. noted that whereas the all-NTP system mass varied by 30% with opportunity, the combined system variation was only 10%[5].

The mass benefit of the combined systems was attributed to two factors. First, the high Isp NEP systems reduced the propellant loading relative to the all high thrust mission. Second, the use of the high thrust systems to accelerate the vehicle beyond escape allowed a significant reduction in the power requirements of the NEP system, thus reducing the propulsion system mass.

NASA 90-Day Study Reference Mission Description

In an attempt to update the findings of the past 30 years, combined systems have been analyzed using mission ground groundrules from the NASA 90 - day study of 1989. Mission and system parameters used in the analysis of Chem/Aerobrake, NTP, and NEP systems were used in the analysis of combined systems, in order to determine their applicability to current missions.

The reference mission is an opposition-class, 30 day stay time mission. The 4 person crew and accompanying cargo travel together on a single vehicle, in the "all-up" mode. The nature of this mission, with its short stay time, makes it a demanding one in terms of velocity requirements. The short stay time means that Earth and Mars are not in an optimal position for either the outbound or return legs, increasing the mission difficulty. In contrast, a conjunction class mission would allow optimal outbound and inbound legs at the expense of 1-2 years of stay time waiting for the proper planetary alignment.

The mission time frame of interest is from 2010 to 2025, with 2016 identified as a reference case and 2018 and 2025 identified as the easy and difficult opportunities, respectively. At the time of the original study, slightly differing ground rules were applied to the use of high thrust systems and low thrust systems, in order to allow a reasonable grounds of comparison while recognizing the inherent differences between the two system types. For the study of the combined systems, the mission ground rules were applied depending upon the most sensible utilization of the system.

For the high thrust systems, departure was assumed to be from a 500 km Low Earth Orbit (LEO). Increases in ΔV incurred at departure due to gravity losses were minimized through the use of a 3 burn, perigee-kick maneuver. The trajectory parameters were optimized for the desired trip time, including Venus swingbys. In the case of the Chem/Aerobrake system, the mission trajectories were optimized to take full advantage of aerobraking at Earth and Mars. The Mars arrival and parking orbit was set at an elliptical orbit of 250 km X 1 sol. From this orbit, the aerobraked Mars Excursion Vehicle (MEV) descended to the surface for thirty days, followed by the crew return to the MTV via an ascent vehicle. Earth return was by Earth Crew Capture Vehicle, with the MTV flying by Earth. An ECCV velocity limit of 9.4 km/s was imposed. For the all-propulsive vehicle return, the Earth return orbit was a 500 X 1 sol elliptical orbit.

For the low thrust systems, both SEP and NEP, certain aspects of the mission profile were adapted to the needs of these propulsion systems. Although the low thrust vehicles also start at LEO, they require extensive spiral times on the order of months to escape the Earth. Extended exposure to the Van Allen Radiation Belts during this spiral phase prevents having the crew on-board at this time. Instead, the crew rendezvous with the vehicle using a chemical propulsion system, perhaps a Lunar Transfer Vehicle, at some point beyond the radiation belts. The low thrust vehicle then accelerates to escape and on to Mars.

Because of the time required to spiral in and out at Mars, a high circular orbit was selected to limit this period. For the study, a Deimos altitude of 20077 km was selected; this orbit is also close to the Areosynchronous orbit of 20430 km. The impact of this orbit on the MEV and ascent vehicle is expected to be small due to the use of aerobraking and the small ascent vehicle mass. Spiral times to and from this orbit were on the order of days[3].

The low thrust vehicle return to Earth differed from the fly-by maneuver of the high thrust systems; instead, the vehicle propulsively captures into Earth orbit and ultimately spirals down to LEO for refurbishment and reuse. Because of the Van Allen Belt exposure, the crew disembarks from the vehicle above the belts using either a chemical vehicle or an Earth return capsule. The difference in mission scenario at Earth and Mars requires a definition of trip time for these low thrust missions. The piloted trip time is defined as that time when the crew is on the mission; in this case, the heliocentric transit time and the stay time on Mars. In addition, the low thrust scenario introduces the concept of vehicle reuse, which is a characteristic of particular interest to low thrust systems due to their low propellant requirements.

In all cases, mission payloads are essentially equal. The outbound payload includes the MTV habitat, plus the MEV and associated scientific equipment. The high thrust missions also include an ECCV. These masses are shown in Table I.

Component	Mass (MT)
MTV Habitat	40.3
MEV(left at Mars)	84.0
ECCV	7.0

Table 1. Piloted Mars Mission Payload Masses.

The combined propulsion system mission assumed is similar to that of the all-propulsive NTP mission. The vehicle is assumed to start from LEO with a high thrust burn; the NEP system is then turned on for the heliocentric portion of the trip. In the case of the single burn combined mission, the high thrust system and tankage are jettisoned after this initial impulse. The NEP system then serves as the sole propulsion system, following the mission scenario outlined for the low thrust system. In the case of the full combined mission, the high thrust system is used for Mars capture and escape as well as Earth capture. The Mars orbit is the same 250 km X 1 sol elliptical orbit used for the high thrust mission. The Earth capture orbit is a 500 km X 24 hour elliptical orbit. The payloads are assumed with no ECCV.

System Assumptions

Three system types were used in the combined mission study: Nuclear Electric Propulsion (NEP), Cryogenic Chemical (Chem), and Nuclear Thermal Propulsion (NTP). The system details used in the mission analysis are described for each system.

Nuclear Electric Propulsion: Three nuclear electric propulsion systems were assessed for use in the combined propulsion mode. The three systems were characterized parametrically and were intended to span a range of possible values for MWe level NEP. The three parametric variations are shown in Table 2. The specific masses are based on power/propulsion system estimates available for a variety of reactor, power conversion, and thruster systems. The 10 kg/kWe system mass represents performance projected for either a scaled-up SP-100 reactor system with Potassium Rankine Power Conversion, or for a "Dual-Mode" NERVA derived Brayton system[3,6]. The 5 kg/kWe values are based on higher temperature reactor and power conversion concepts[11].

Alpha (kg/kWe)	Power (MWe)
10	5, 7.5, 10
5	5
5	10

Table 2. NEP System Characteristics

Although a wide variety of electric propulsion thruster options exist for high power NEP, argon ion thruster efficiencies and specific impulses were assumed in this study. Specific impulses of 6000 - 8000 seconds were assessed; the 6000 s value was found to allow the shortest trip times. Efficiency varied with specific impulse according to projections for MWe ion thruster performance. This variation of efficiency with specific impulse is well understood, having been demonstrated experimentally at kWe power levels. Scaling of ion thrusters to meaningful power levels for

MWe applications remains to be demonstrated, as does the assumption of 10,000 hours lifetime[12]. An argon propellant tankage fraction of 0.10 was assumed throughout the study. NEP tankage was jettisoned at the end of each leg in any mission study.

Cryogenic Chemical Propulsion: Hydrogen/Oxygen rocket engines were assumed. Initially, a specific impulse of 481 s was used in calculations for the single burn mission mode. For later mission analyses, a more conservative value of 450 s was assumed for an advanced space based engine. The mass of the chemical rocket was neglected in the mission analysis as relatively small. A propellant tankage fraction of 0.12 was assumed for the cryogenic propellants.

Nuclear Thermal Propulsion: A NERVA based, solid core nuclear thermal system was assumed. A uranium carbide - zirconium carbide composite fuel was assumed, in keeping with recent updated NTP performance projections. The increase in reactor and propellant temperature is projected to yield a specific impulse value of 900 - 925 s[13]. A hydrogen tankage fraction of 0.15 was assumed.

Reference Systems for Comparison

Two reference systems/missions are used for comparison purposes in this paper. The first is the all-propulsive NTP mission, which uses a 925 s Isp, 4:1 thrust/weight, 330 kN rocket. The 3-burn perigee kick maneuver is used at Earth departure. Earth return was to a 500 km X 1 sol elliptical orbit. Two opposition opportunities are considered: a less demanding, 2018 mission and a difficult 2024 one. A tankage fraction of 16% was used. Tanks were dropped after each burn. The results of these data will be shown for comparison to the combined propulsion results[13].

The second reference is an all-NEP mission, using a 5 kg/kWe power/propulsion system. The system power level was allowed to vary between 10 and 40 MWe for each trip time to determine the limits of the system in terms of mass and trip time. The same opportunities are considered. The round trip time used in the comparison consists of the heliocentric trip time and stay time, as described in the mission description. EP performance assumptions were described earlier. This system performance is also shown for comparison to the combined system results.

Combined Propulsion System Study

Analysis Approach: The mission analysis of combined systems introduces much more complexity into the trajectory optimization problem. Mission analysis and optimization of low thrust trajectories represents a difficult task in that the system assumptions such as α, Isp, Power, and efficiency play dramatic roles in determining an optimal trajectory. This broad parameter space enlarges significantly when considering the combined system, as the high thrust system parameters as well as the degree to which the high thrust is used at each point of the trajectory also play major roles in the trajectory optimization.

The approach used for this analysis was to vary NEP α, Isp, Power, and efficiency, as well as the degree of high thrust usage, parametrically, while allowing the trajectory analysis to optimize for minimum mass over a range of trip times. While an overall mission and system optimization is not achieved in this fashion, an applicable range is identified for further study with fewer variables. Initial attempts at optimizing over the NEP and high thrust space proved to be undesirable, as the trends in mission performance were obfuscated by the possible variability of the data.

The code used for this study is QT2, as developed at NASA Lewis Research Center. QT2 is based on the CHEBYTOP low thrust trajectory analysis programs. QT2 has the added capability to perform system analysis in conjunction with the trajectory optimization carried out by CHEBYTOP through the use of external multivariable non-linear optimizing subroutines[14]. Modelling of the high thrust trajectories in QT2 does not include assessment of gravity losses. A further refinement of this analysis would include either assessing these losses, analyzing the perigee burn option to reduce these losses, or designing the high thrust systems to generate enough thrust to eliminate the loss.

Combined Propulsion Study Results: As mentioned in the introduction, two modes of combined propulsion were considered for the reference mission described above. The first mode was the single burn option, in which the high thrust stage is used only for Earth departure. The high thrust stage and tankage are then jettisoned, and the NEP system is used for the rest of the journey. This mode was examined for the 2016 mission opportunity, which is similar in difficulty to 2018, for both chemical and nuclear thermal high thrust systems in combination with 10 kg/kWe NEP systems at power levels of 5, 7.5, and 10 MWe. An additional degree of freedom introduced by the combined system was the extent to which the high thrust system was used. This additional variable is expressed in terms of the hyperbolic excess velocity, Vh. Vh was varied from 2 to 6 km/s in the study. The results for the Chem/NEP combination are shown in Figure 1, and those of the NTP/NEP combination in Figure 2.

The use of the single burn option did not yield a dramatic reduction in trip time or mass over the NEP or NTP systems. This was primarily due to the all-propulsive nature of the mission, which stresses the ability of the NEP on the return trip and limits the gain in trip time. Further analysis of this option was not continued.

In the second mission mode, the high thrust system is used at all planetary escape or capture maneuvers. Some of the NEP acceleration and deceleration limits on trip time are thus avoided, allowing significant reductions in travel time. Because of the complex nature of the problem, involving a large number of independent system variables in addition to the trajectory optimization, a "broad brush" parametric approach was chosen to try and bracket the parameter space for the reference mission. NEP system parameters of 10 kg/kWe, 5 MWe; 5 kg/kWe, 5 MWe; and 5 kg/kWe, 10 MWe were assessed with Chemical and NTP high thrust systems. Two opportunities were chosen in keeping with data generated for the NTP system: 2018 and 2025.

The use of high thrust systems was varied parametrically through the excess hyperbolic velocity parameters. The multiburn mission mode introduces 4 Vh variables to be considered. Rather than allow free variation of these variables within the optimization process, some representative combinations were chosen for study. These Vh values are somewhat arbitrary, and do not represent optimal results. Some overall optimization of the Vh was attempted; however, the results were inconsistent. In general, Vh values ranged from 2 to 8 km/s.

The staging of the high thrust systems was also fixed over all missions. Chemical propulsion tanks were jettisoned after each burn, and low thrust tankage was jettisoned at the end of each leg. The mass of the chemical rocket was neglected. In the case of the NTP/NEP staging, different assumptions were made to address the question of minimizing gravity loss. Two stages were used: The first was assumed to be a large rocket, akin to the PHOEBUS class rocket of the NERVA period. This is used for Earth escape and Mars capture. A mass of 30 MT was assessed to this stage, which is jettisoned after Mars capture along with the outbound propellant tanks. The second stage was assumed to be the nominal, 330 kN NERVA engine. This stage is used for Trans-Earth Injection and Earth orbital capture. A mass of 10 MT was used for this system. As with the Vh values, this staging strategy is not intended to be the optimal one, but serves to provide a foundation from which to start.

Discussion of Results: Results of this parametric assessment for the two opportunities are shown in Figures 3 and 4 for the Chem/NEP combination and in Figures 5 and 6 for the NTP/NEP combination. The reference NTP and NEP mission results are also shown. The relative impact of chemical and NTP combined systems to piloted Mars missions is different, and will be discussed separately.

Chemical/NEP Combined System: Relative to both the NTP and NEP systems, the combined Chem/NEP system appears at best to provide a lower performance alternative to either of these options. This option might be considered if the NTP rocket cannot achieve the 925 s Isp level, or if NEP is unable to reach high power levels to reduce trip times. In terms of NEP systems, the 10 kg/kWe, 5 MWe option provides the ability to achieve missions of 475 - 500 days for either opportunity, with initial masses of 1000 - 1500 MT (2018) or 1500 - 1700 MT (2025). Although Chem/ Aerobrake is not considered explicitly in this study, the use of NEP in place of the aerobrake may provide yet another propulsion alternative between chemical and NTP. The Chem/NEP combination using 5 kg/kWe systems shows performance comparable to the NTP systems at trip times greater than 360 (2018) or 450 (2025) days.

Chem/NEP performance relative to the 5 kg/kWe, all-NEP systems is significantly heavier than the all NEP system; however, minimum trip time is extended from approximately 450 days down to almost 350 days in 2018, and from 500 days down to 450 days in 2025. Again, the Chem/NEP option appears to be viable relative to all NEP only in the event that multimegawatt (>10 MWe) space nuclear power is unattainable. With regard to variation with opportunity, the combined systems demonstrate characteristics in keeping with electric propulsion missions; a change in opportunity results in increases in trip time more than in vehicle mass. This benefit arises from the ability of the low thrust system to adapt to more difficult planetary alignments in a propellant efficient manner.

NTP/NEP Combined System: A more direct comparison can be made between the all-propulsive NTP reference mission and the NTP/NEP combined system. In this case, the use of a 10 kg/kWe system with NTP shows performance only marginally better than that of the all-NTP system. It was found in the course of the study that increased use of the NTP system with the 10 kg/kWe NEP system resulted in vehicle initial masses that were not competitive with the all-NTP option.

The use of a 5 kg/kWe system at either 5 or 10 MWe, however, showed a distinct advantage over the NTP system. In the case of the less difficult 2018 mission, an NTP/NEP mass benefit is found for trip times of 380 days or less over the all NTP system. For the difficult 2025 opportunity, this benefit is present at 480 days and less. This finding of a mass benefit only at specific masses less than 10 kg/kWe is in contrast to past findings that systems with α values as high as 15 kg/kWe. This can be explained by two factors. The first is that past assessments of NTP performance assumed an Isp of 850 s, as anticipated for the existing NERVA program. The second factor is the improvement in mission analysis since the 1960's, resulting in more optimized high thrust trajectories.

Comparison of the NTP/NEP system with the all-NEP system indicates that a combined system may provide NEP systems with the ability to reduce trip time by 100 days in either mission year, without requiring multimegawatt power levels. Even a 10 kg/kWe, 5 MWe NTP/NEP system allows decreased trip time relative to NEP with a relatively small increase in initial mass of ~200 MT, to IMLEO values comparable to the all NTP option. An important point to remember is that the reference NEP system used is assumed to have an a value of 5 kg/kWe, which is an optimistic value for future systems. It should also be noted that the NEP option requires 20 MWe to attain comparable performance to NTP in 2018, and 40 MWe in 2025. The combined systems remain at a 5 to 10 MWe power level. As with the Chem/NEP option, the NTP/NEP option demonstrates less change in initial mass with opportunity than the NTP mission, although the possible trip times increase with mission difficulty.

Conclusions

Based on this initial scoping study of combined high and low thrust propulsion systems, some general conclusions and research emphases can be derived for further consideration of these systems. Both chemical and nuclear high thrust systems have been considered for a common mission scenario, and the results have been compared to reference NTP and NEP missions. Further work in the areas of mission design, system analysis, and global optimization of the combined trajectory problem can be identified.

A mission analysis of combined propulsion systems for a piloted opposition class mission has yielded several initial conclusions of the utility of these systems:

1.) The single burn option in an all-propulsive mission scenario does not yield a significant performance advantage in reduced trip time for reasonable masses.

2.) The multiple burn option allows significant reductions in trip time relative to the NEP system, and may provide a performance advantage over NTP depending upon the system assumptions.

3.) The combined systems serve to reduce NEP power requirements for fast trip times, and to reduce high thrust systems' sensitivity to mission opportunity.

4.) With the exception of decreased opportunity sensitivity, specific masses of 10 kg/kWe do not yield strong performance benefits over the single systems. These systems might provide fall-back options if projected NTP or NEP technology projections cannot be demonstrated.

5.) 5 kg/kWe systems can provide significant improvements in mass and trip time over the single systems at power levels of 5 to 10 MWe.

Further work in the area of combined propulsion includes optimization of the cases considered herein, extending the analysis to assess the optimal Vh values and staging options for the combined systems. In addition, other mission scenarios must be evalutated, such as Earth Fly-bys with Earth Crew Capture Vehicle return, as well as the "Split/Sprint" mission option utilizing a piloted vehicle with a separate cargo vehicle. Another area of investigation is the vehicle design for a combined system, integrating the high thrust tankage and low thrust radiator designs in a feasible vehicle concept. This task will be particularly challenging in the case of the NTP/NEP combination, in which two nuclear radiation sources must be accommodated on a crewed vehicle.

This study has generally served to verify the conclusions of past mission designers, that the combined propulsion system options offer the potential for synergistic performance improvements over the single systems and should be considered in future interplanetary mission studies.

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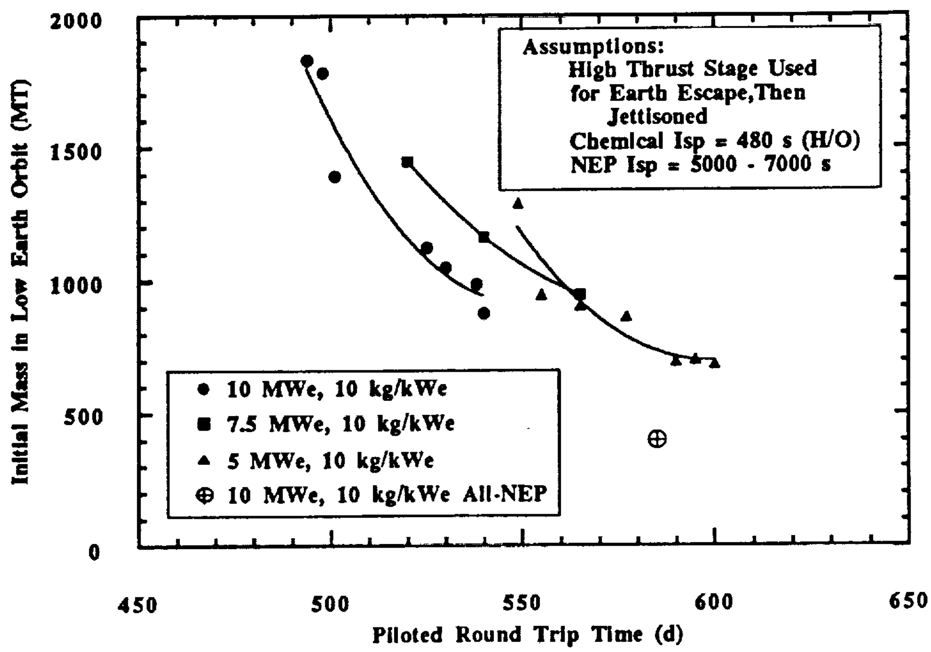

Figure 1. Single Burn Option Using Chemical Propulsion.

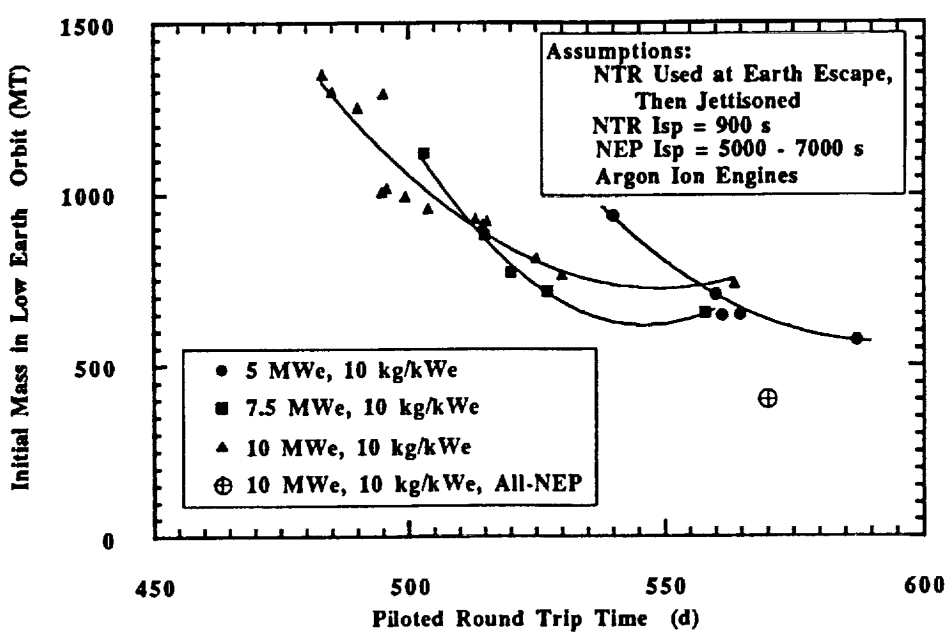

Figure 2. Single Burn Option Using Nuclear Thermal Propulsion.

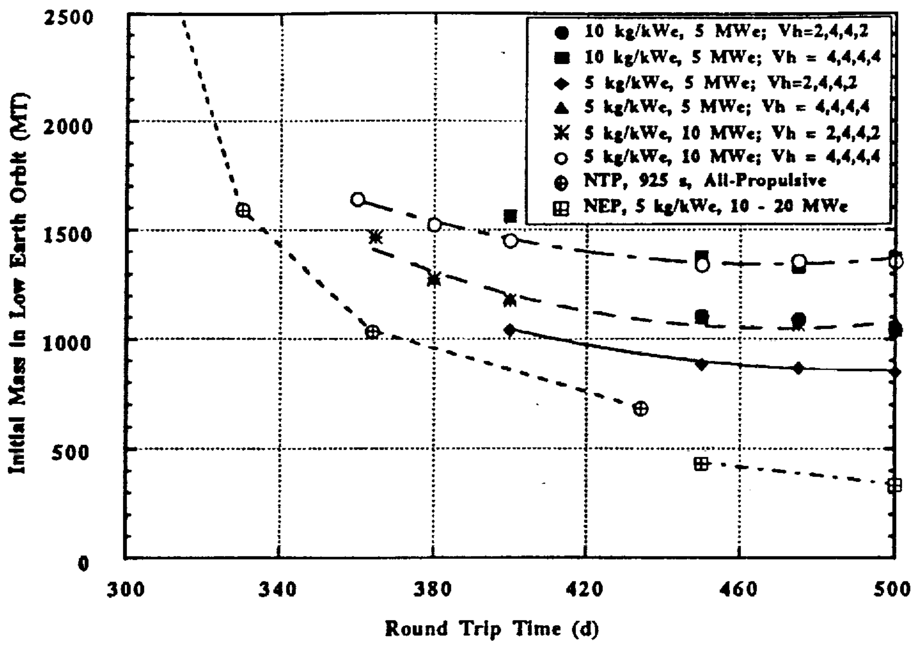

Figure 3. Multiple Burn Chem/NEP Option, 2018 Mission Opportunity. Vh in km/s.

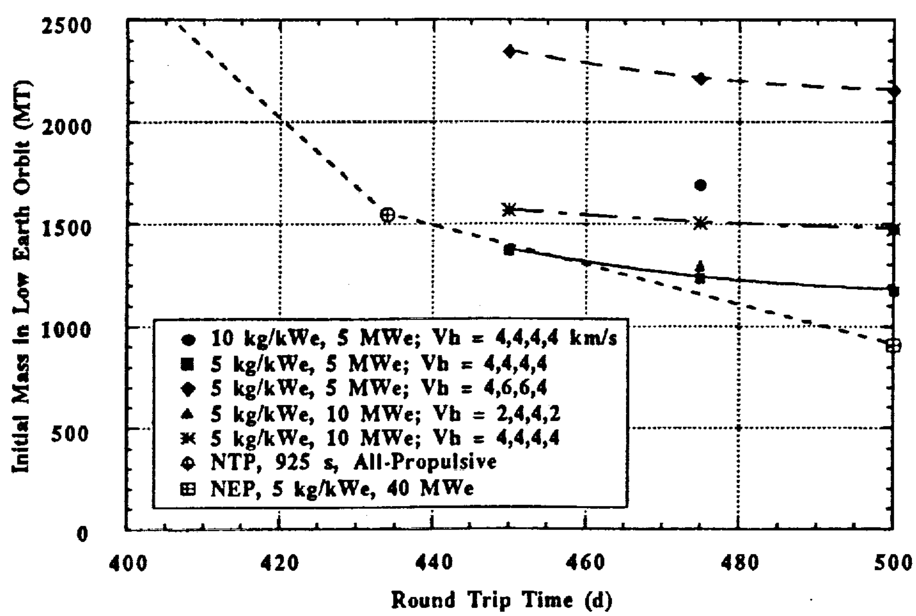

Figure 4. Multiple Burn Chem/NEP Option, 2025 Opportunity. Vh in km/s.

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13. ABSTRACT ***(Maximum 200 words)***

Reduced transit times have been identified as desirable for piloted Mars missions. The demanding nature of these missions imposes stringent requirements upon space propulsion systems in terms of specific impulse and thrust/weight. The "ideal" propulsion system for fast trips to Mars would have both high specific impulse as well as high power density. To achieve these characteristics in a single propulsion system poses a dramatic technology challenge. An alternative to be considered is the combination of two relatively near term non-ideal systems such as nuclear electric propulsion and chemical or nuclear thermal propulsion in order to approximate the ideal. The use of high thrust, relatively low specific impulse systems, such as chemical or nuclear thermal propulsion, in conjunction with low thrust, high specific impulse nuclear electric propulsion, has been considered for a representative piloted Mars mission. Two modes were considered: 1. Use of high thrust at Earth escape only; 2. Use of high thrust for all planetary escape and capture maneuvers. Parametric variation of NEP characteristics over a range of specific mass, power, and specific impulse values was used, as well as variation in the amount of high thrust propulsion. These parameters were assessed for an opposition class mission over a range of trip times. Recommendations for system selection and further work are discussed.

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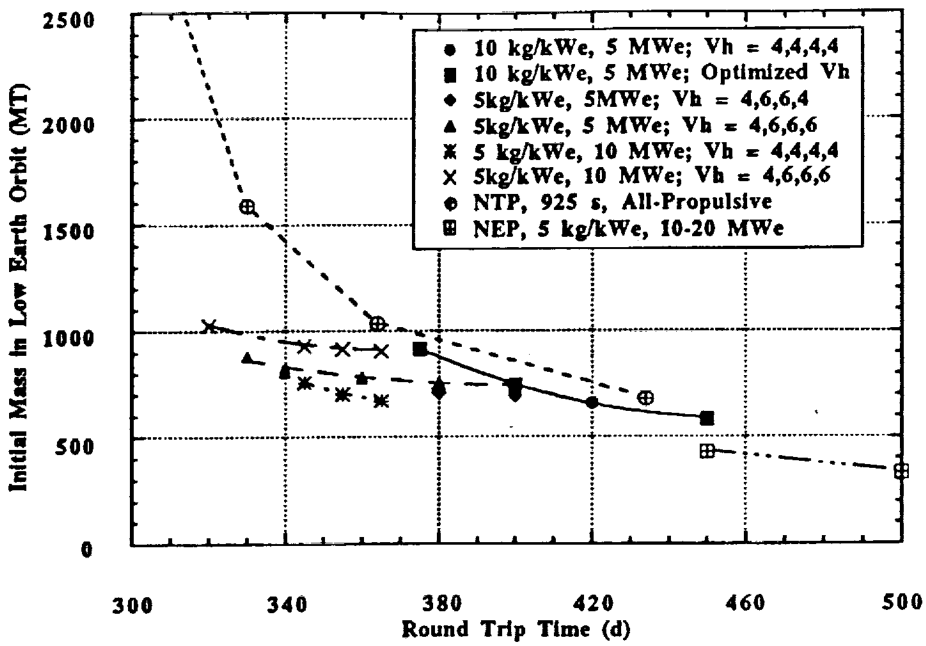

Figure 5. Multiple Burn NTP/NEP Option, 2018 Opportunity. Vh in km/s.

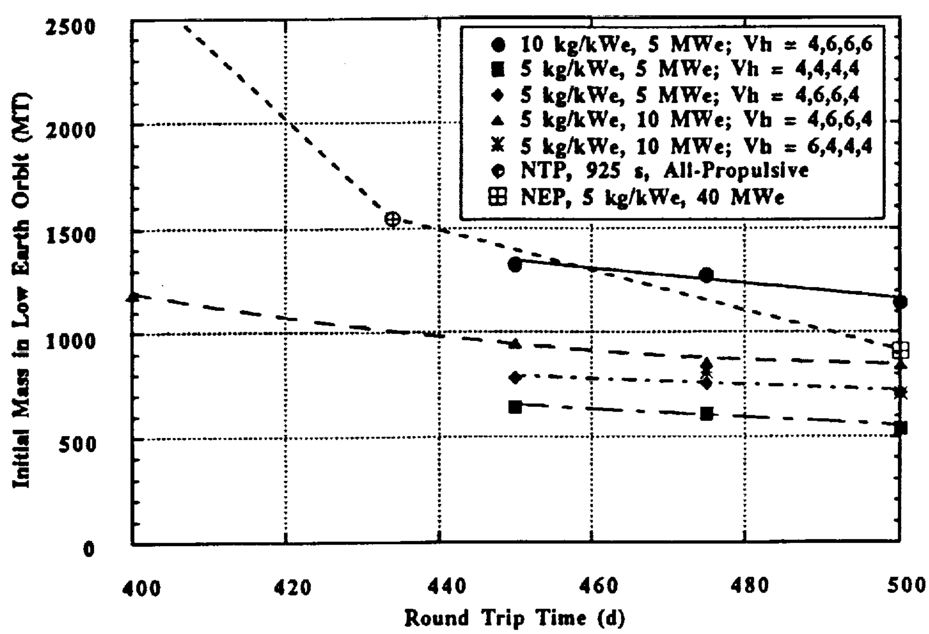

Figure 6. Multiple Burn NTP/NEP Option, 2025 Opportunity. Vh in km/s.