

Human Mars Mission Transit Abort Options for Ballistic High Thrust and Hybrid Transportation Systems

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Throughout the entire history of human spaceflight, astronauts have never been more than a few days' journey from Earth. For missions to the International Space Station, or even to the Moon, aborting the mission and returning home is a relatively straightforward operation in the event of a life-threatening contingency. But on the journey to Mars, a mission abort is complicated by a single factor: the sheer distance to Mars that will take time to cover regardless of how powerful the propulsion system is. In a significant departure from the entire human spaceflight experience to date, a Mars mission abort will not mean an immediate return to Earth due to the heliocentric nature of the transit. After escaping Earth's gravity and entering heliocentric space, aborting a mission to Mars will be measured in months not days even if the abort is initiated relatively early in the mission. This represents a fundamental shift in the way mission aborts are utilized to reduce mission risks and this change must be part of the narrative when discussing reliability, crew risk, contingency planning, and mission operations. Abort capability will vary between transportation propulsion systems depending on final design, operational implementation, and actual mission parameters such as departure date, but the difference is relatively insignificant given that "mission abort" in the heliocentric frame of reference is a wildly different paradigm than that historically used for Earth-centric missions which rely on abort as a risk mitigation strategy. The primary objective of this paper is to provide a clearer definition of human Mars mission aborts from a celestial physics and orbital mechanics perspective in the context of different propulsion systems.

Nomenclature

AU	Astronomical Unit
ESDMD	Exploration Systems Development Mission Directorate
MAT	Mars Architecture Team
NTP	Nuclear Thermal Propulsion
NEP	Nuclear Electric Propulsion
SAC	Strategic Analysis Cycle
SEP	Solar Electric Propulsion

I. Introduction

NASA's Exploration System Development Mission Directorate's (ESMD) Mars Architecture Team (MAT) is continuing the agency's efforts to study and refine the nation's plan to field a sustainable human Mars campaign as part of NASA's Moon2Mars directive. Building upon the success of the Design Reference Architecture[1] and the Evolvable Mars Campaign[2, 3], the group is further developing capabilities to improve the fidelity of the Mars mission architectures and to continue exploring the design trade space to assess the impact of technology investments and architecture decisions for missions to Mars. Throughout the history of human spaceflight, astronauts have never been more than a few days (and usually only a few hours) from Earth. For any piloted missions throughout history, the

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ability to abort the mission in the event of an anomaly has been a critical risk mitigation tool[4–6]. For missions to the International Space Station, or even to the Moon, aborting the mission and returning home from Earth orbit is a relatively straightforward option in the event of a life-threatening contingency. Past experiences in human space flight have reinforced the criticality of abort options during all phases of the mission. Most abort scenarios focus on high energy events, where failure is most likely to occur.

In October of 2018, the Soyuz MS-10[7, 8] spacecraft experienced an anomaly during ascent which prompted the on-board computer to initiate the abort sequence. The crew and the spacecraft returned to Earth roughly 20 minutes after launch, and the search and rescue team reached the landing site shortly to retrieve the crew. Abort scenarios for missions that are already in space typically involve longer duration than aborts during the ascent phase. For example, during the Apollo 13 lunar mission, an anomaly in the fuel system caused an explosion that necessitated the crew to abort their mission to the lunar surface[9]. With great perseverance by both the crew and the ground controllers, the crew safely returned to Earth four days after the anomaly. Current human exploration missions focus on the International Space Station, with a multitude of abort to Earth options for the expedition crew in the event of an anomaly on station. These abort scenarios typically involve a rapid return to Earth’s surface using one of the reentry spacecrafts that are always on standby on station, with the crew returning to Earth within a few hours of the abort initiation.

But on the journey to Mars, a mission abort is complicated by a single factor: the sheer distance to Mars that will take time to cover regardless of how powerful the propulsion system is due to the heliocentric nature of the transit. For human missions to Mars, one must reset the frame of reference of both time and distances. The Apollo 13 mission[10], during the abort trajectory, set a human spaceflight altitude record by traversing to the far side of the Moon, reaching a distance of approximately 400,000 km from Earth. In comparison, the average distance between Earth and Mars is 225 million km, roughly 550 times longer than the human spaceflight altitude record. A typical trip between Earth and the Moon is on the order of a few days, while a typical trip between Earth and Mars is six to twelve months each way. Similar to the abort duration increase from the launch abort scenarios to in-space mission scenarios, resetting the frame of reference from Earth-centric to Sun-centric (or Heliocentric) means the abort scenarios are drastically different from current human spaceflight experiences. Abort durations for human Mars missions will not be measured in hours or even days, but in months or years, even if the abort is initiated early on in the mission. This requires an entirely new operations paradigm for human Mars missions relative to our Earth-centric experience. In most cases, simply aborting the mission will not be a practical response to an emergency because the time to effect crew return will exceed the crew’s ability to stave off the effects of the emergency. In addition, due to the nature of celestial mechanics, abort maneuvers are inherently more challenging compared to nominal mission maneuvers. This often leads to an intuition-based perception that only very powerful, high-thrust transportation systems such as Nuclear Thermal Propulsion (NTP) are capable of such maneuvers.

To explore this topic, MAT evaluated abort capability for three scenarios for a representative 850-day total duration, short Mars vicinity stay class roundtrip mission to Mars. The primary objective of this paper is to provide a clearer definition of human Mars mission aborts from a celestial physics and orbital mechanics perspective. In addition, the analysis aims to understand the abort capabilities of different propulsion systems to complement previous work on Mars abort approaches[11, 12] and provide high level comparisons between the propulsion options. A companion paper will explore the value proposition of these types of aborts and the potential utility of aborts in the overall risk mitigation for human missions to Mars in a future publication.

II. Analysis Reference Mission & Systems

ESDMD’s MAT is developing numerous transportation system concept of operations to help the agency define the trade space for human Mars missions. In addition to transportation options, MAT is also evaluating how the transportation systems perform in different reference missions, with varying mission duration and specific implementation to achieve roundtrip missions to Mars. For this paper, a moderate duration mission was chosen as an initial study reference for abort analysis. This moderate duration mission has a nominal interplanetary duration of 850 days, with a minimum stay of 50 Martian sols in Martian orbit to support surface operation. The nominal trajectory can be achieved either with ballistic high thrust systems or Hybrid systems that combine high and low thrust propulsion systems[13, 14]. Figure 1 shows the visualization of the reference trajectories used for this analysis.

For the Hybrid trajectory (Figure 1a), the low thrust portion of the trajectory is highly dependent on the specific propulsion system performance. Similarly, the feasibility of the abort trajectory is also highly dependent on the performance of the propulsion system. Therefore, it is necessary to define a reference propulsion system. NASA

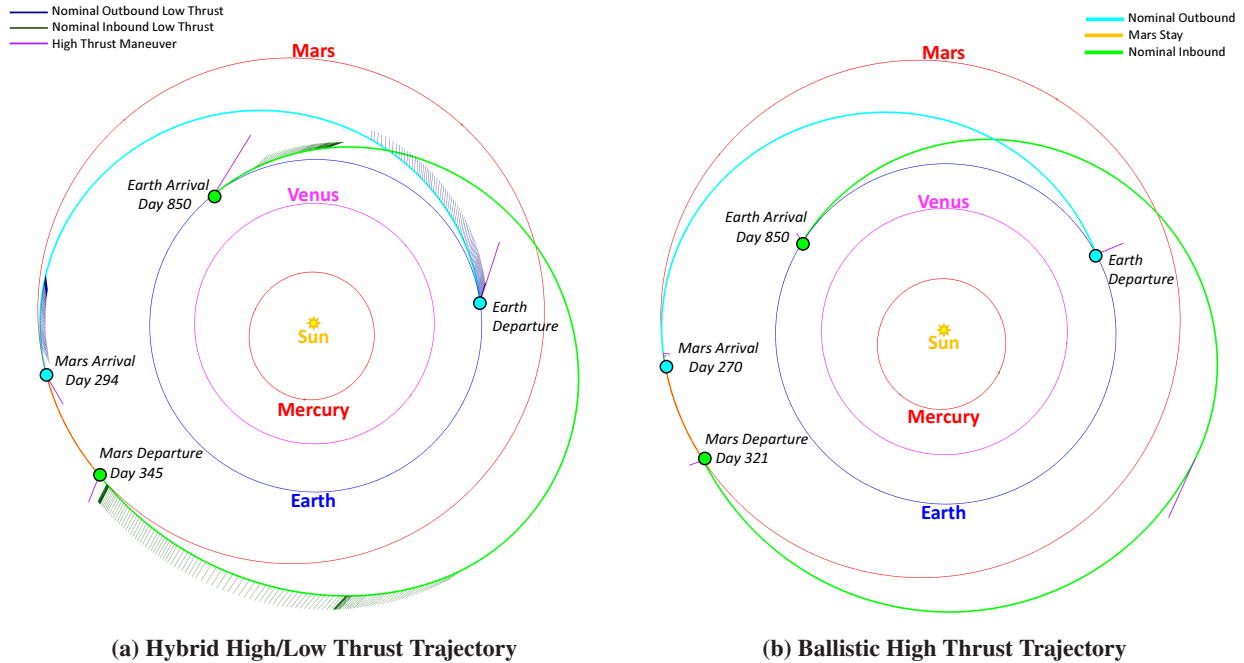


Fig. 1 Analysis Reference 850-Day Roundtrip Trajectory to Mars for 2039 Mission Opportunity with 50-Sols (51.4 Days) in Mars Vicinity

has been investigating and analyzing Hybrid electric / chemical propulsion systems to enable human missions to Mars[13, 15, 16]. By combining chemical and electric propulsion into a single spacecraft and applying each where it is most effective, the Hybrid architecture enables a series of Mars trajectories that are more fuel efficient than an all chemical propulsion architecture, without significant increases to trip time. A Hybrid Nuclear Electric Propulsion (NEP) / Chemical Propulsion system[14] was defined in ESDMD’s previous analysis cycle[17, 18] and serves as the basis of the analysis in this paper.

The ballistic trajectory (Figure 1b) is not specific to any particular propulsion system design, as it’s purely a function of orbital mechanics. The only requirement is the deployment of a high thrust propulsion system, where gravity loss is relatively minimal. Therefore, the ballistic trajectory and its associated abort scenarios can be achieved either with NTP[19, 20] systems or any All Chemical[21, 22] propulsion systems. Regardless of the abort scenarios and the type of trajectory flown, the parameters of interest from a design trade space definition perspective are when the abort was initiated, and how long it takes to return the spacecraft back to Earth as compared to the nominal mission. For the current analysis cycle’s reference trajectories, the total duration of the nominal mission has interplanetary duration of 850 days, and the mission aborts defined by this analysis focused on the scenarios which would return the crew back to Earth sooner than the nominal mission, utilizing the propulsion system to return the crew back to Earth as soon as possible.

III. Abort Scenario Definition

Ideally, to enable transit aborts from the nominal trajectory, the primary propulsion system should be utilized to perform the required maneuvers. However, there may be potential options to recover and abort back to Earth in the event of a propulsion system failure, but these types of scenarios will be specific to the nature of the failure and the specific design choice of the propulsion system, such as engine out capability. Regardless, once the spacecraft is in interplanetary space, the options to return to Earth without the use of its primary propulsion system are limited. The availability of a secondary propulsion system may provide additional opportunity for abort; in fact, for the Apollo 13 mission, without the Lunar Excursion Module’s functioning propulsion system, the crew would likely not have had the options to return safely to Earth[10].

Three abort scenarios can be identified for each propulsion system depending on the status of the propulsion system, and these are summarized in Figure 2. For both systems, the “Nominal Propulsion” abort scenario is defined by a

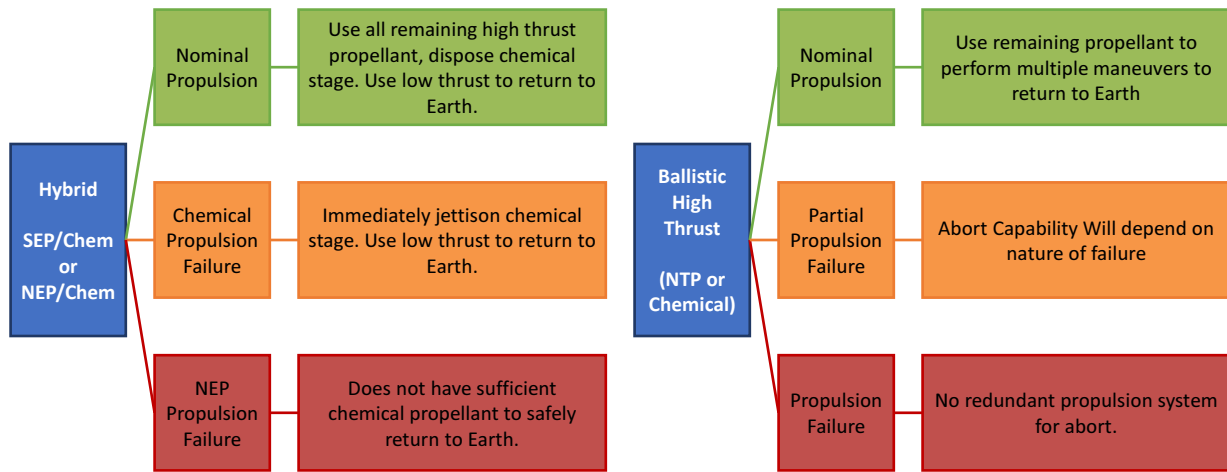


Fig. 2 Definition of Abort Scenarios for Hybrid and Ballistic Transportation Systems

desire to return the system and the crew back to Earth as soon as feasible with fully functional propulsion systems. The “Partial Propulsion” abort scenario is more complex. For the Hybrid system, because there are two separate propulsion systems, the feasibility of the abort is dependent on the availability of the propulsion system. There is potential to recover and return the crew back to Earth, but only if the NEP system is fully functional. For the ballistic high thrust propulsion systems, there is only a single propulsion system, so abort option in the event of propulsion system failure will be highly dependent on the nature of the failure. For example, if design of the propulsion system allows for independent operation of the high thrust engines and there are multiple engines on board, then a potential abort scenario might be to utilize the remaining functional engine to perform longer duration maneuvers to abort back to Earth.

For this paper, three transit abort scenarios are defined and analyzed, two for the NEP/Chemical Hybrid Propulsion system, and one for a Ballistic style trajectory that can be achieved by either Nuclear Thermal Propulsion or All Chemical Propulsion system. For the NEP/Chemical Hybrid Propulsion System, both the “Nominal Propulsion” and the “Partial Propulsion” scenarios are analyzed. For the ballistic high thrust system, only the “Nominal Propulsion” abort is analyzed. This isn’t to say that the ballistic system could not abort in the partial mode, it’s just out of scope of this analysis as it would require a specific definition of the failure mode and the result would only be specific for that particular failure.

IV. Hybrid Propulsion Transit Abort with both High & Low Thrust Systems

For this abort scenario, if the abort is initiated while the electric propulsion system is performing the nominal thrusting maneuver, the abort would halt the thrusting profile immediately and compute the Earth return solution while preparing the chemical propulsion system to begin the main abort maneuver. Once the abort maneuver solution has been computed, the chemical engine is utilized to perform a major maneuver to begin the abort sequence. This maneuver will expend all the remaining chemical propellant that the spacecraft is carrying, nominally for the Mars orbit insertion, departure, and the Earth orbit insertion maneuvers. Once all the chemical propellant is expended, the empty chemical propulsion system is jettisoned in space to reduce the overall system mass. The lower system mass will help the performance of the low thrust electric propulsion system, which will begin thrusting for the remaining duration to return the spacecraft back to Earth. Without the high thrust chemical propulsion system, the spacecraft does not have the capability to perform a nominal Earth orbit insertion maneuver, therefore, the low thrust system will continuously thrust to target an Earth arrival condition with low relative velocity (or energy) to enable an Earth capture maneuver utilizing a Lunar flyby to insert into a lunar distance high Earth orbit. Once in this Earth orbit, an Orion spacecraft is assumed to be waiting and ready to rendezvous with the transit habitat to return the crew safely back to

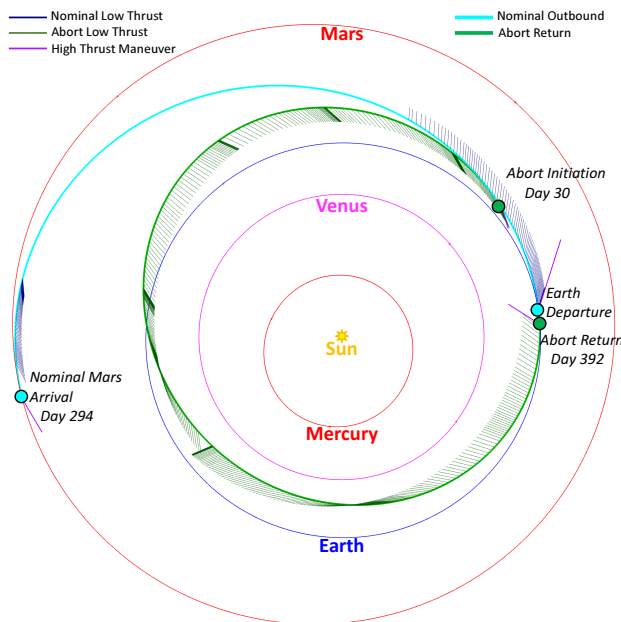


Fig. 3 NEP/Chemical Hybrid Propulsion Abort Trajectory Using Both High and Low Thrust Systems for Analysis Reference 850-Day Trajectory, with Abort Initiation on Mission Day 30 and Earth Return on Mission Day 392

Earth.

Figure 3 shows an example trajectory for the NEP/Chemical propulsion system abort for the 850-Day reference trajectory using both high and low thrust systems. In this example, the abort is initiated on mission day 30 (or 30 days after the initial trans-Mars injection maneuver). Earth encounter occurs on mission day 362, or 332 days after abort initiation. An additional 30 days in cis-lunar space is required to perform the low energy capture into the final Earth parking orbit using lunar gravity assist maneuver, so the earliest possible rendezvous with the Orion spacecraft to return crew to Earth is on mission day 392, or 362 days after abort initiation. This trajectory represents the earliest possible Earth return for abort initiation on mission day 30, as the spacecraft expends all its propellant to return the spacecraft to Earth. This abort represents a mission duration savings of 458 days as compared to the 850-day nominal mission, cutting the mission roughly in half.

Expanding upon the example abort trajectory, Figure 4 shows the sweep of the minimum duration aborts as a function of the abort initiation day. The x-axis shows the mission abort initiation day, and the corresponding y-axis shows the return day for that abort, given that the spacecraft expends all its remaining propellant to achieve the return trajectory. As the chart shows, there's a continuous increase in the Earth return day for later abort initiation, which is expected. As the spacecraft travels further away from Earth and the Hybrid propulsion system expends propellant to achieve the nominal mission, it becomes increasingly difficult to achieve a short duration abort back to Earth. Comparing two example points, for the abort at mission day 30, which has an Earth return day of 392, and the abort at mission day 60, which has a return day of 463, a delay in abort by 30 days delayed the Earth return day by 71 days, which means that the transit duration back to Earth increased by 41 days. This increase trend is continuous through mission day 145, in which a clear delineation point exists for the abort option.

Aborts up until mission day 145 return to Earth by pushing the trajectory closer to the Sun to increase the relative velocity of the spacecraft to Earth (as it orbits the Sun) to catch up to Earth for a fast return. This requires a significant amount of energy to achieve. For the day 145 abort, shown in Figure 5a, the propulsion system as designed for the 850-Day reference trajectory and mission reaches its limit to achieve this type of fast return to Earth. For aborts initiated after mission day 145, the only option for Earth return is to instead decrease the relative velocity of the spacecraft to Earth (as it orbits the Sun) and allow additional time for the spacecraft and the Earth to phase properly for a rendezvous. This type of longer duration abort is shown in Figure 5b.

There are a few key points for consideration with regards to these abort trajectories. For the fast return abort trajectories that can be initiated prior to mission day 145, the trajectory pushes closer to the Sun, which presents

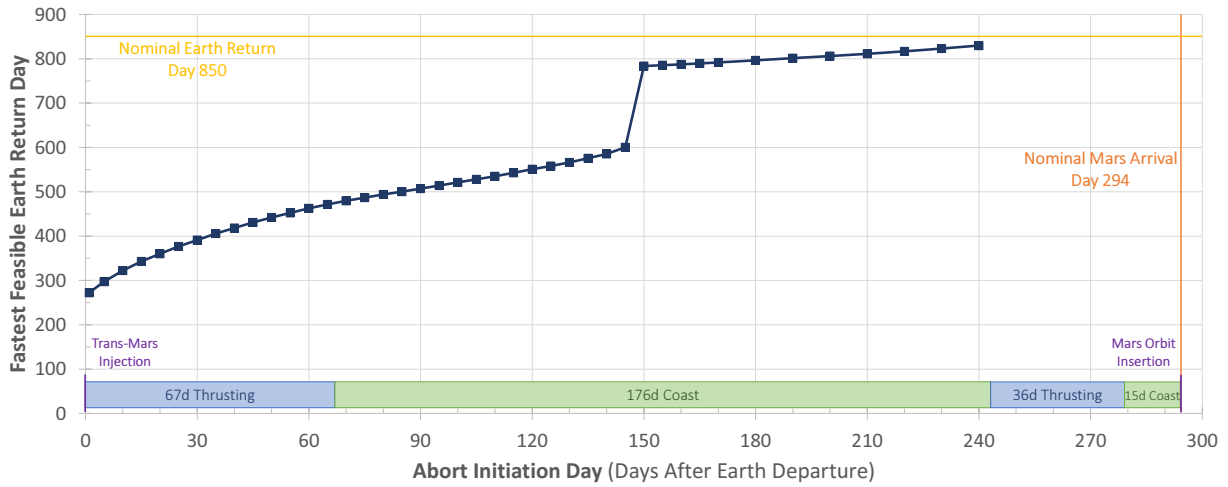
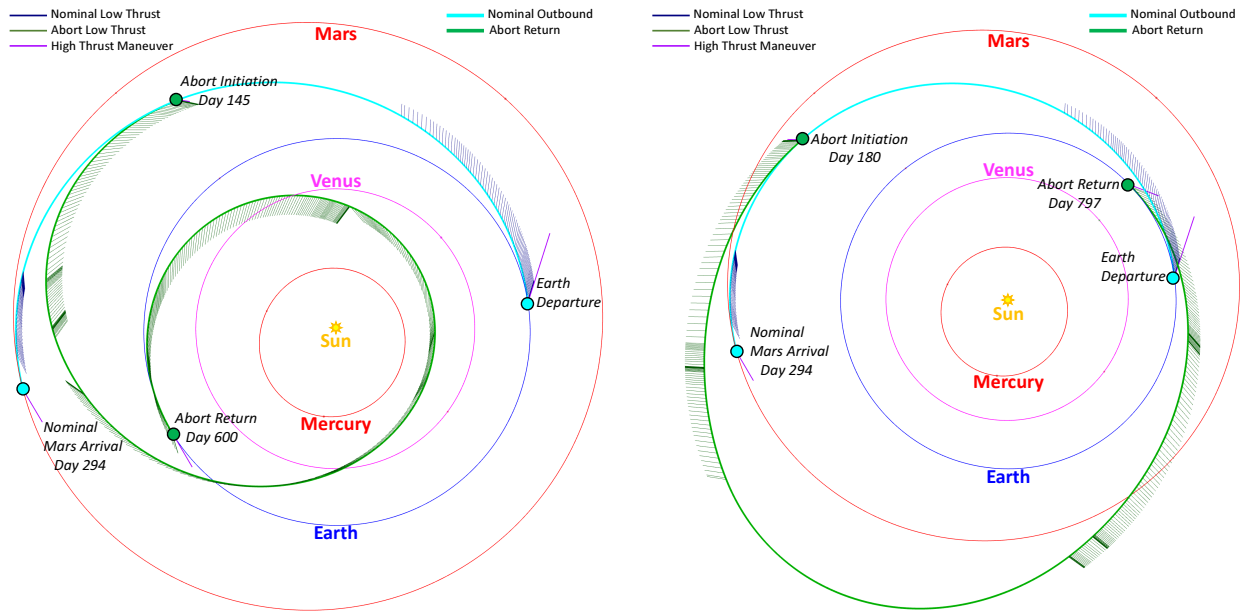


Fig. 4 Fastest Feasible Earth Return as Function of Abort Initiation Day for NEP/Chemical Hybrid Propulsion System Using Both High and Low Thrust Systems



(a) Abort Initiation on Mission Day 145 and Earth Return on Mission Day 600

(b) Abort Initiation on Mission Day 180 and Earth Return on Mission Day 797

Fig. 5 NEP/Chemical Hybrid Propulsion Abort Trajectories Using Both High and Low Thrust Systems for Analysis Reference 850-Day Trajectory

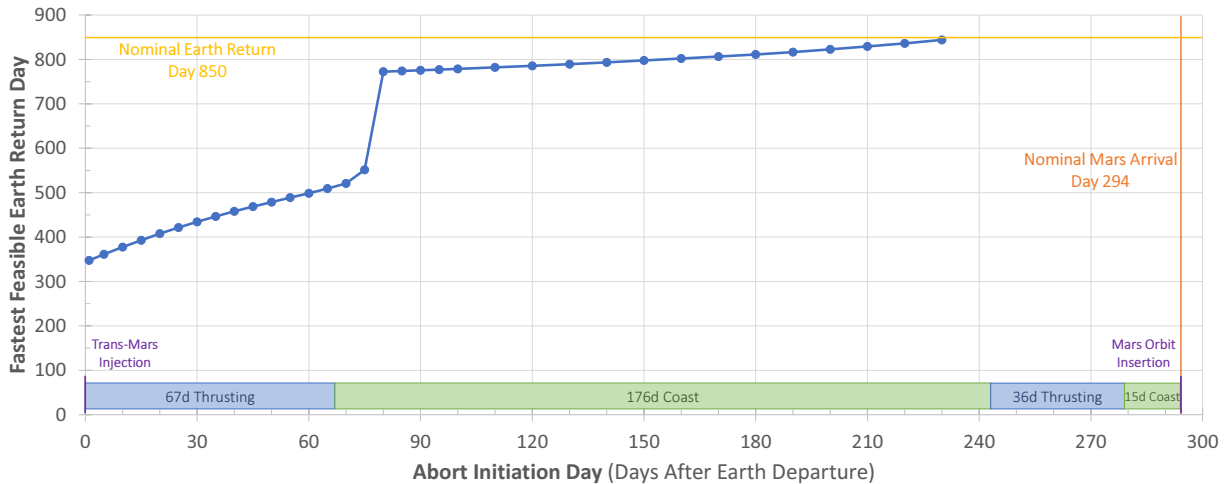


Fig. 6 Fastest Feasible Earth Return as Function of Abort Initiation Day for NEP/Chemical Hybrid Propulsion System Using Low Thrust System Only

a challenge to the overall system design from both a thermal and radiation protection perspective. The reference trajectory for the nominal mission has close solar approach of 1 astronomical unit (AU), meaning the worst thermal and radiation environment is the same as cis-lunar space, outside the Van Allen belts. To enable these fast aborts, the full Mars transportation stack, including the transit habitat, must be able to tolerate solar close approach that is less than 1 AU, and in a few instances, significantly lower than 1 AU. In the mission day 145 abort example, in Figure 5a, the trajectory’s solar close approach is less than 0.5 AU, as the trajectory pushes significantly lower than even Venus’ orbit to increase the relative velocity as compared to Earth to force the fast return. This abort scenario might be valid from a propulsion system and trajectory feasibility perspective, however, it’s clear that additional system level design constraints such as thermal and radiational protection must be considered when discussing various abort scenarios.

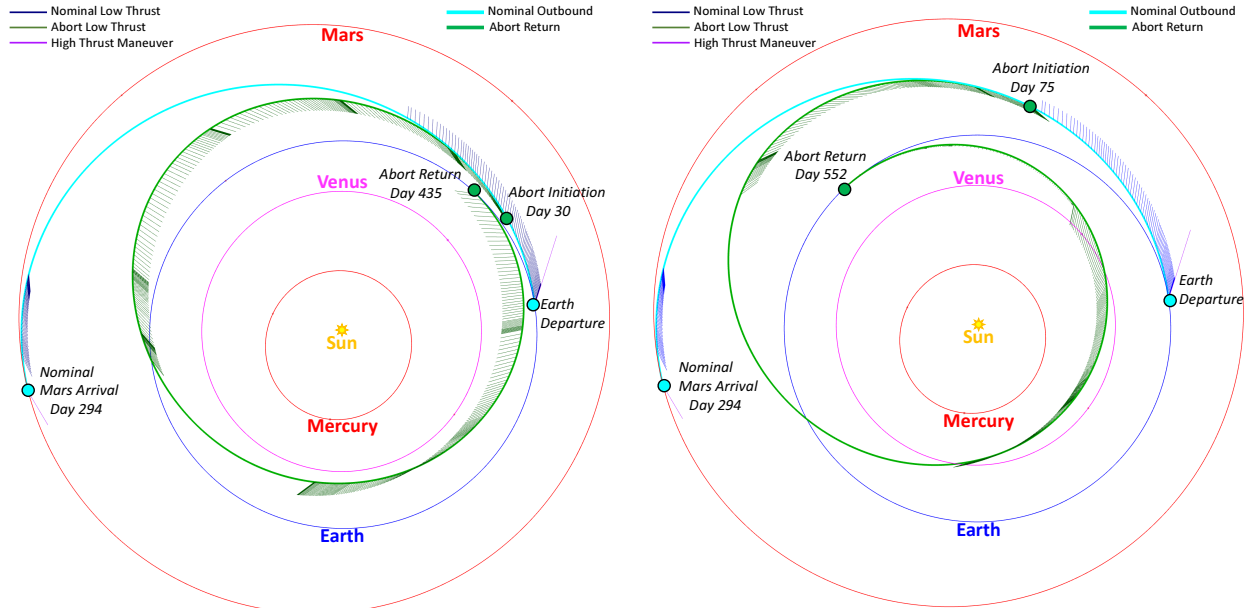
For aborts that are initiated after mission day 145, the trajectory pushes further away from the Sun to enable lower energy, longer duration transit back to Earth. For these aborts, the total time spent away from Earth is not significantly different from the nominal 850-day mission. For example, as shown in Figure 5b, an abort initiated on mission day 180 has a return day of 797, with a 587-day return transit plus 30 days needed to perform the low energy capture back to Earth orbit. This represents only a 53-day reduction in the total time spent away from Earth for the crew, at the cost of not achieving any part of the nominal mission as the spacecraft never reaches Mars orbit.

Utilizing the full complement of the NEP/Chemical propulsion systems, the latest available abort back to Earth is around mission day 240, just 52 days prior to the nominal Mars orbit insertion maneuver. At this point, the spacecraft is too far away from Earth, and with significant depletion of the primary propulsion system propellant, abort back to Earth in an “off-nominal” trajectory is simply not feasible, especially if the objective is to return to Earth earlier than the nominal mission duration. There are potential trajectory solutions that skip the Mars rendezvous, if initiated after day 240, and return the crew back to Earth significantly later than day 850, however, this scenario would not satisfy the primary goal of an abort, which is to return the crew back to Earth as early as possible.

V. Hybrid Propulsion Transit Abort with only Low Thrust System

In this scenario, the abort conditions are slightly different than the previously described abort. This scenario assumes a failure of the chemical propulsion system. This leads to the inability of the spacecraft to perform the nominal Mars orbit insertion and departure as well as the Earth insertion maneuver, prompting the necessity for abort. This abort scenario differs from the previous one as the chemical propulsion system is not available to perform the initial maneuver to kick-start the abort. Due to its failure, the chemical propulsion system is jettisoned in space to reduce the overall system mass to improve the effectiveness of the low thrust propulsion system. Similar to the previous scenario, the low thrust system performs thrusting to target a low energy rendezvous condition to enable lunar swing by capture into the high Earth orbit for the final Orion rendezvous to enable safe crew return to Earth’s surface.

As previously described, in the event of a chemical propulsion system failure, the electric propulsion system



(a) Abort Initiation on Mission Day 30 and Earth Return on Mission Day 435

(b) Abort Initiation on Mission Day 75 and Earth Return on Mission Day 552

Fig. 7 NEP/Chemical Hybrid Propulsion Abort Trajectories Using Low Thrust System Only for Analysis Reference 850-Day Trajectory

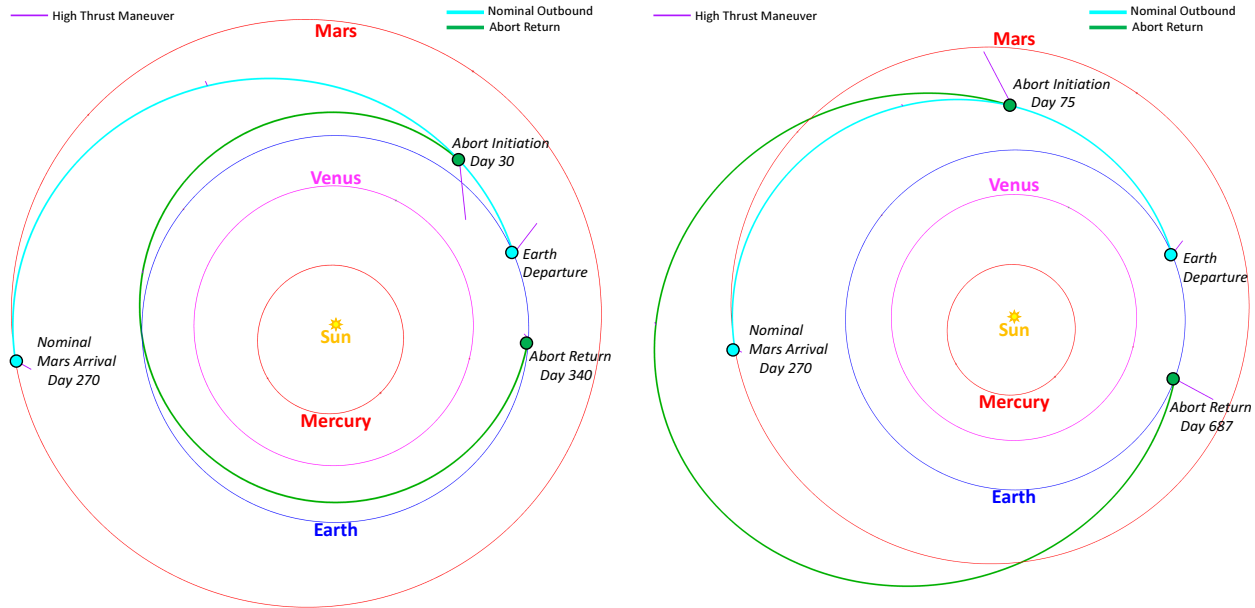
powered by the nuclear electric reactor still has propulsion capability to perform aborts back to Earth. The two types of trajectories flown are similar to the abort using both high and low thrust systems, however, without the chemical propulsion system to provide a kick start to the abort, the duration of the aborts is longer compared to aborts using both propulsion systems. The minimum duration abort options for the NEP low thrust only aborts are shown in Figure 6.

As a point of comparison, the “nominal” NEP/Chemical propulsion system abort initiated on mission day 30 returns to Earth on day 392, while the low thrust only abort initiated on the same day returns to Earth 43 days later, on mission day 435, shown in Figure 7a. This trend follows across the entire abort feasibility trade space. Additionally, the latest short abort available date moves from mission day 145 to mission day 75 (Figure 7b, which is a significant reduction in the abort capability. Similar to the “nominal propulsion” system aborts, aborts initiated after this delineation point are significantly longer in duration and provide significantly lower value in terms of days saved as compared to the nominal mission.

VI. Ballistic Trajectory Abort for Nuclear Thermal or All Chemical Propulsion

For the ballistic high thrust trajectory, because the abort scenario in the event of propulsion system failure is highly dependent on the nature of the failure and therefore would only apply to the specific failure mode, only the nominal propulsion system abort is examined in this analysis. In this scenario, the high thrust propulsion system is utilized to perform a multi-maneuver trajectory back to Earth. It requires a minimum of two maneuvers, an abort initiation maneuver, and an Earth capture maneuver. Though in practice, it likely requires one or more deep space course correction maneuvers to achieve the return trajectory to Earth. For this analysis, a three-burn sequence is assumed in the trajectory optimization.

For the ballistic style trajectory that is available to high thrust systems, such as a chemical propulsion system or a NTP system, the abort scenarios presented here require the propulsion system to provide maneuvering capability throughout the abort portion of the trajectory. Figure 8a shows an example abort trajectory for the reference ballistic high thrust trajectory, with abort initiation on mission day 30. The abort is initiated by a high thrust maneuver, followed by a mid-course correction maneuver, and then finally completed with an Earth capture maneuver. For this example, the return trajectory has a transit time of 309 days, with Earth rendezvous on mission day 339. With the availability of the high thrust propulsion system, the spacecraft can perform a nominal Earth capture maneuver, negating the need



(a) Abort Initiation on Mission Day 30 and Earth Return on Mission Day 340 (b) Abort Initiation on Mission Day 75 and Earth Return on Mission Day 687

Fig. 8 High Thrust Ballistic Propulsion System Abort Trajectory for Analysis Reference 850-Day Trajectory

for the additional 30 days for cis-lunar maneuvering to capture back to Earth orbit in the Hybrid abort scenarios. This represents a total mission duration reduction of 511 days. Compared to the Hybrid style trajectories, the ballistic high thrust abort returns the crew to Earth 3-6 months earlier for this example.

Examining the sweep of the minimum duration abort for the ballistic trajectories, shown in Figure 9, the capability of the high thrust propulsion system can be seen, with significantly shorter Earth abort return in the immediate days after Earth departure. The low thrust systems require significant time to utilize the highly efficient propulsion system to produce thrust to affect the spacecraft's trajectory, but the high thrust system can achieve higher performance in a significantly shorter time. However, the delineation point between the fast abort and longer duration abort is significantly earlier as compared to the Hybrid aborts. Compared to the Hybrid aborts, where the latest available short aborts are on mission day 145 and 75 for the "nominal" NEP/Chemical and low thrust only options, respectively, the latest short abort available for the high thrust system is on mission day 40. After mission day 40, any abort initiated by the high thrust system will result in return to Earth in the 2+ years duration, with only a minor reduction in the total crew time away from Earth.

Additionally, the latest possible abort for both the "nominal" NEP/Chemical and the low thrust only options is on mission day 240 and day 230, while the latest possible abort for the ballistic trajectory is on mission day 160. Abort options that initiate after day 160 either do not exist or will have significantly longer durations than the nominal 850-day mission. One final note on the ballistic high thrust trajectory is that in the nominal trajectory, a deep space maneuver is required on mission day 112, which expends a portion of the propellant. After the deep space maneuver, the abort options become even more limiting, culminating in the end of abort options on mission day 160.

VII. Transit Abort Analysis Summary

Figure 10 summarizes the minimum duration abort options for the three abort scenarios for the study reference 850-day nominal trajectory. As discussed, the high thrust ballistic trajectory can abort back to Earth faster as compared to the Hybrid trajectory options, however, the availability of this fast abort is limited to the first 40 days of the mission. After mission day 40, the high thrust ballistic trajectory's abort option is limited to the longer duration aborts, while the Hybrid trajectory continues to have the ability for short aborts through day 75 for the low thrust only case and day 140 for the "nominal" propulsion case. However, these short duration aborts have significant challenges associated with both thermal and radiation environments, as the trajectory pushes significantly closer to the Sun than the nominal 850-day

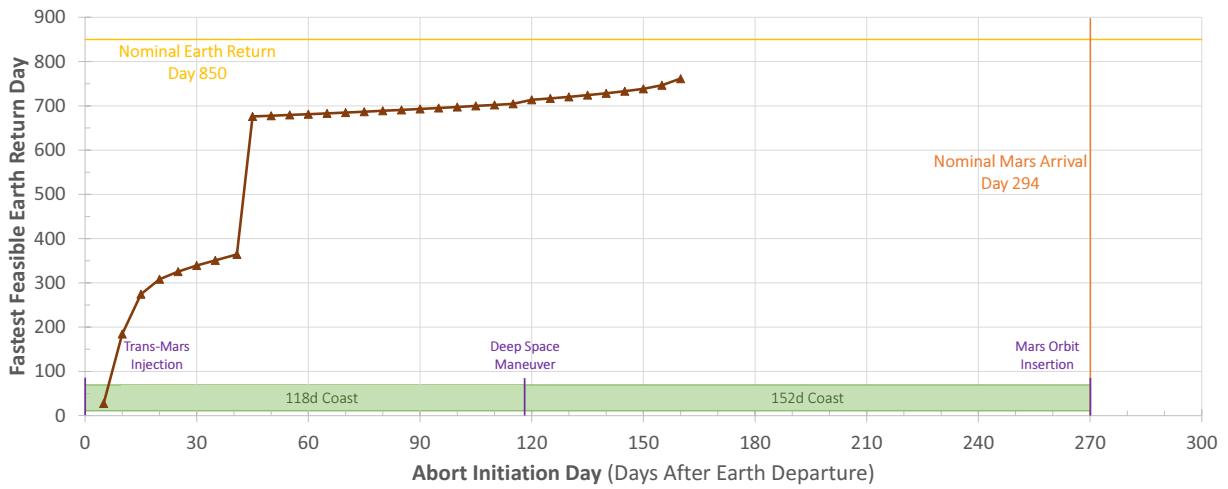


Fig. 9 Fastest Feasible Earth Return as Function of Abort Initiation Day for Ballistic High Thrust Propulsion Systems

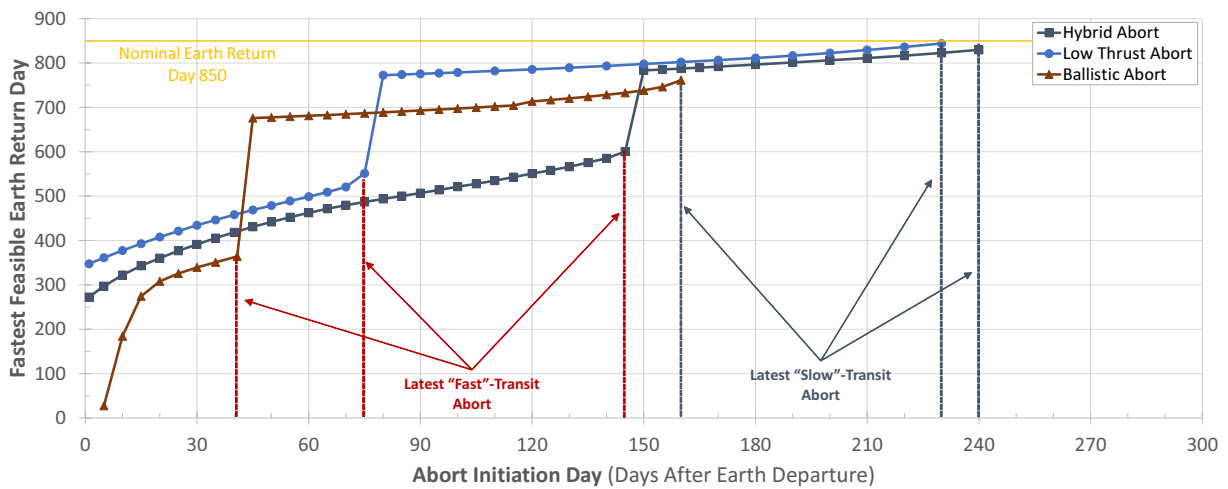


Fig. 10 Fastest Feasible Earth Return Comparison Between NEP/Chemical Hybrid Propulsion System, NEP Low Thrust Only Propulsion System, and Ballistic High Thrust Propulsion System

mission. The spacecraft system design will need to be modified to enable these off-nominal contingency scenarios to enable crew and system survival. The Hybrid trajectories also have a wider abort window for the long duration aborts as compared to the ballistic aborts, however, these aborts are significantly longer in duration and provide significantly less value in mission days saved.

VIII. Conclusions

In a significant departure from our entire human spaceflight experience to date, a Mars mission abort will not mean an immediate return to Earth. After escaping Earth's gravity and entering heliocentric space, aborting a mission to Mars will be measured in months not days, even if the abort is initiated relatively early in the mission. This is a fundamental shift in the way mission aborts are utilized to reduce mission risks and this change must be part of the narrative when discussing reliability, crew risk, contingency planning, and mission operations. Abort capability will vary between transportation propulsion systems depending on final design, operational implementation, and actual mission parameters such as departure date, but the difference is relatively insignificant given that "mission abort" in the heliocentric Mars frame of reference is a wildly different paradigm than that historically used for Earth-centric missions that rely on abort as a contingency and risk mitigation strategy.

Through MAT's assessment of the transit abort options, three primary findings are drawn. First, Mars transit abort does not mean immediate Earth return, as time from abort initiation to Earth return will be measured in months. All human spaceflight experience to date has been in the Earth centric frame, with an abort from nominal mission in a matter of days. This is a fundamental shift in the way mission aborts are utilized to help reduce mission risks, and this change must be part of the narrative when discussing abort options. For example, a mission abort initiated on Day 30 of a nominal 850-day roundtrip mission using high performing Nuclear Thermal Propulsion returns the crew back to Earth 309 days later (see Figure 8a), assuming full functionality of the propulsion system. If the abort was prompted by a life-threatening event, that 511-day savings is moot if crew are unable to survive the 309-day post-abort transit.

Second, transit abort is not a unique feature to Nuclear Thermal Propulsion. The assertion that Nuclear Thermal Propulsion system, and its high performance, is the enabling factor for transit abort is inaccurate. Due to the nature of celestial mechanics, abort maneuvers are inherently more challenging compared to nominal mission maneuvers. This led to the intuition-based perception and generalization that only high performing transportation systems are capable of such maneuvers. The analysis clearly disproved this perception. Not only can a Hybrid propulsion system using Nuclear Electric and Chemical propulsion system perform abort maneuvers back to Earth, but the ability to utilize both systems enables a wider abort window as compared to a high thrust system like Nuclear Thermal or Chemical Propulsion. In addition, even without the high thrust chemical propulsion system, the low thrust electric propulsion system can also perform abort maneuvers using the long transit time back to Earth to shorten the nominal mission by several hundred days. An all-chemical propulsion system can provide similar abort maneuvers as the Nuclear Thermal Propulsion system, depending on the exact implementation of the overall mission architecture. The two systems are not fundamentally different, apart from level of performance.

Third and finally, transit abort is not a particularly good discriminating factor for propulsion system selection, especially in the context of crew risk mitigation as it may not reduce crew risk. Abort trajectories are fundamentally high energy events. To return to Earth from heliocentric space, celestial mechanics dictates that the spacecraft must either fly closer or further away from the Sun (than Earth) to phase the orbit for rendezvous. Flying closer to the Sun will enable faster returns but change the thermal and radiation environment that the spacecraft and crew will experience, which may negate the primary purpose of the abort especially if the spacecraft is not designed for such close approach to the Sun. Pushing farther away from the Sun will increase the flight time required to return the crew back to Earth, which, depending on the nature of the abort, can also negate the goal of the abort.

These three primary findings demonstrate one facet of the highly complex and integrated nature of Mars transportation mission planning. Utilization of transit abort options as a primary discriminating factor between transportation options will miss out on the integrated nature of this problem and can lead to erroneous conclusions based on incomplete view of the integrated problem. The point is not that one nuclear option is better than another, or that nuclear options are superior to non-nuclear options; the point is that abort performance is not a particularly good metric to base a selection decision, because any transportation system could be optimized for aborts at the expense of other metrics and still not result in a safer transportation system in the context of crew risk mitigation. The design of the system to be much more robust to failure and to allow the crew to be much more independent and self-sufficient for the long duration journey to Mars may provide more value in the overall risk mitigation. An integration evaluation of all of the metrics of interest is paramount in evaluation of the different transportation concepts.

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