NASA-TM-111567

Abort Options for Potential Mars Missions

P. V. Tartabini, S. A. Striepe, R. W. Powell

Reprinted from

Journal of Spacecraft and Rockets

Volume 31, Number 4, Pages 543–549

A publication of the
American Institute of Aeronautics and Astronautics, Inc.
370 L'Enfant Promenade, SW
Washington, DC 20024-2518

JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 31, No. 4, July–August 1994

Abort Options for Potential Mars Missions

Paul V. Tartabini,* Scott A. Striepe,* and Richard W. Powell*
NASA Langley Research Center, Hampton, Virginia 23681

Mars trajectory design options were examined that would accommodate a premature termination of a nominal manned opposition class mission for opportunities between 2010 and 2025. A successful abort must provide a safe return to Earth in the shortest possible time consistent with mission constraints. In this study, aborts that provided a minimum increase in the initial vehicle mass in low Earth orbit (IMLEO) were identified by locating direct transfer nominal missions and nominal missions including an outbound or inbound Venus swing-by that minimized IMLEO. The ease with which these missions could be aborted while meeting propulsion and time constraints was investigated by examining free return (unpowered) and powered aborts. Further reductions in trip time were made to some aborts by the addition or removal of an inbound Venus swing-by. The results show that, although few free return aborts met the specified constraints, 85% of each nominal mission could be aborted as a powered abort without an increase in propellant. Also, in many cases, the addition or removal of a Venus swing-by increased the number of abort opportunities or decreased the total trip time during an abort.

Introduction

IN 1991 the Synthesis Group on America's Exploration Initiative recommended a continuing human exploration of the planet Mars beginning around the year 2014. To support this recommendation, many studies have been conducted to identify optimized interplanetary trajectories.[1–3] These studies have shown that when state-of-the-art propulsion systems are used, vehicles with an IMLEO of less than 2 million kg can complete round-trip missions to Mars in under 2 years. For complex missions with long trip times, there is an increased threat of solar flares, medical emergencies, and system failures. One way to anticipate such an event is to provide a means of terminating the mission and returning the crew quickly and safely back to Earth. The Apollo 13 lunar mission dramatically demonstrated that mission planning must include an effective mission termination or abort strategy that will provide the crew with a safe return to Earth in the shortest possible time. For a Mars mission, this can be accomplished by changing the interplanetary trajectory so that Earth is encountered as soon as possible. To minimize the vehicle design effort and avoid mass penalties associated with carrying additional propellant, trajectories can be chosen so that any changes attributable to a mission abort could be made with the same amount of propellant allotted for the round-trip mission. Therefore, by careful trajectory selection, it is possible to design nominal missions, that is, minimum IMLEO, all-propulsive, round-trip piloted Mars missions, that can be aborted without an increase in IMLEO.[4]

At least two abort strategies can be considered in the mission-planning process. First, free return trajectories can be identified in which no postlaunch propulsive maneuvers, ΔVs, are needed to return the vehicle to Earth. Wolf[5] showed that free return trajectories to Mars are neither plentiful nor economical in terms of launch energy. Also, in almost all cases, encounter dates that result in a free return trajectory provide less than optimal transfers for a nominal mission where a stay time at Mars is required. An alternative approach is to identify nominal round-trip missions that minimize IMLEO. Once these optimal missions are found, the encounter dates can be modified and propulsive maneuvers can be added at appropriate times to allow for aborts.

The disadvantage of the former approach is in the lack of free return trajectories that were already scarce when using optimal free return dates.[6] That is, the use of free return aborts for minimum IMLEO nominal missions is not very promising because there were not many mission opportunities when the nominal mission was designed for free return aborts. However, including a ΔV during the Mars encounter (swing-by) of an aborted mission could possibly increase the abort opportunities for minimum IMLEO nominal missions. In addition, Striepe and Braun[7] showed that the addition of a powered Venus swing-by during certain planetary orientations reduced the propellant requirements for nominal round-trip missions. Therefore, this concept could be applied to an abort scenario because a propellant savings may increase abort opportunities, as well as reduce the return time. Another interesting abort scenario involves the use of deep space maneuvers (DSM) during the interplanetary transfer to affect an abort trajectory back to Earth. This approach potentially would allow an abort at any point during a mission. Although this scenario shows promise, it is not included in the present analysis; however, current plans are to study the impact of DSMs on Mars mission aborts in a future investigation.

Therefore, this study examined the feasibility of giving nominal missions (minimum IMLEO, all-propulsive, round-trip piloted Mars missions) efficient abort capability through the addition of a propulsive maneuver during the Mars encounter (swing-by). That is, although some potential abort scenarios do not include a swing-by of Mars, this study addresses only those aborts that include an encounter with the planet. Note that for this scenario, the decision to abort must be made prior to Mars arrival because the Mars encounter orbital geometry would most likely be different than that for capture into the required parking orbit. This study also investigated the impact of including a powered Venus swing-by during the abort trajectory of direct transfer and outbound Venus swing-by nominal missions and removing the Venus encounter during the aborts of inbound Venus swing-by nominal missions. Note that for other nominal mission scenarios (e.g., missions using aerobraking at Mars and Earth), not only would less propellant be available for a powered Mars abort, but also the nominal mission profile (planetary encounter dates) would be significantly different from the missions included in this analysis. Thus, care should be taken not to infer conclusions about Mars powered abort possibilities for scenarios other than the one used for this study.

Received April 30, 1993; revision received Nov. 1, 1993; accepted for publication Nov. 2, 1993.

*Aerospace Engineer, Space Systems Division. Member AIAA.

Approach

Excursion class missions, one of the prime candidates for the first human expeditions to Mars, are characterized by short stay times at Mars (30–90 days) and low round-trip times (1.5–2.0 years). Optimal missions were found in the 2010–2025 time frame and were constrained to have an IMLEO of below 2 million kg and total round-trip times of less than 2 years. All trajectories were simulated with the Interplanetary Program to Optimize Simulated Trajectories (IPOST).[8] This program is capable of fast patched conic trajectory propagation and more accurate numerical integration of the governing equations of motion. In this study, all simulations utilized the patched conic propagator.

The baseline vehicle used in this study was originated by Tucker et al.,[9] and a system mass summary is shown in Table 1. A round-trip mission was initiated with the departure of the vehicle from low Earth orbit (LEO). When Mars was encountered, the vehicle was propulsively inserted into a 1 sol (i.e., 24.6 h) parking orbit for a stay time of 60 days. Prior to trans-Earth injection, the Mars excursion module (MEM) was jettisoned, and upon Earth return, the two habitation modules as well as the truss structure and support equipment (see Table 1) were propulsively captured into a 1 sol (i.e., 24 h), 500 km altitude orbit. The components that make up the 61 metric ton Earth return mass were returned so they could be re-used in future missions. Trajectory calculations were performed using models for an advanced chemical propulsion system (specific impulse I_{sp} of 480 s) and a nuclear thermal propulsion system (I_{sp} of 925 s). Also, for these all-propulsive missions, the maneuvers were considered impulsive, and the propellant tank mass was assumed to be 10% of the propellant mass. For this analysis, no propellant boil-off was assumed; however, if it were included, the only impact to this study would be an increase in the nominal mission IMLEO and additional propellant (i.e., more ΔV) available for the abort because the time allowed for the abort mission is less than or equal to the time of the nominal mission. In addition to direct transfers, nominal missions containing an outbound or inbound swing-by of Venus were also identified. Venus swing-bys could be powered or unpowered, and the lower limit on periapsis radius was set 1.1 Venusian radii (or about 6800 km) to avoid any atmospheric encounter. The various mission assumptions made in this study are summarized in Table 2.

Once these optimal missions were obtained, the possibility of an abort for each was investigated by fixing the dates of all planetary encounters prior to and including Mars arrival. That is, the abort scenario investigated in this paper assumes a nominal Earth departure with the decision to return to Earth made prior to Mars encounter. Both powered aborts and free return trajectories were searched for in this assumed mission scenario. A powered abort could represent one possible solution to some in-flight catastrophes, such as damage to the Ascent/Descent Mars surface vehicle, or a solar flare that exceeded the radiation limits. These same problems, as well as the problem of returning to Earth with an engine failure, could also be addressed by examining unpowered aborts. For a powered abort, the propellant mass was limited to the amount of onboard propellant available for the nominal mission. In such an abort scenario, a ΔV maneuver was performed at the Mars encounter, so that the return time to Earth would be minimized without the Mars and Earth return maneuvers exceeding the propellant limit. Note that in this scenario all of the remaining or available propellant was consumed in every abort. Attempts were made to increase the number of abort opportunities and decrease return times with the addition of an inbound Venus swing-by during the abort of a nominal direct or a nominal outbound Venus swing-by mission. The added Venus swing-bys could also be powered, although the combined propellant used for all maneuvers in an abort was constrained to the amount available for the nominal mission. Similarly, improvements were sought in aborted inbound Venus swing-by missions by eliminating the Venus encounter.

In addition to powered aborts, free return trajectories, which need no ΔV after the Earth departure maneuver, were searched for using the nominal mission dates. It should be noted that for free return trajectories, small midcourse corrections would still be necessary.[10] Because the free return abort applies mainly to engine-out scenarios, these aborts were simulated with a direct capture of an Apollo-type entry capsule at Earth return. For this reason, a limit of 14 km/s was placed on the Earth entry velocity at the atmospheric interface altitude of 125 km.[11] As with the powered aborts, improvements in the free return capability of nominal missions were sought by including and removing Venus swing-bys. However, these swing-bys were required to be unpowered.

Table 1 System mass summary

Vehicle component	Mass, metric tons
2 habitation modules	50
Truss structure and support equipment	11
Tank structural weight	10% of propellant mass
Mars excursion module	76
Earth return mass	61
Mass jettisoned at Mars	76

Table 2 Mission assumptions

NTP engine specific impulse	925 s
CHEM engine specific impulse	480 s
Periapsis altitude for all parking orbits	400 km
Parking orbit eccentricities for	
Initial Earth orbit	0
Mars orbit	0.807
Final Earth orbit	0.838
Stay time at Mars for nominal missions	60 days
Minimum Venus swing-by periapsis radius	6800 km
Earth atmospheric interface altitude	125 km

Results

The launch opportunities for direct nominal and aborted missions in the 2010–2025 time frame are shown in Fig. 1. These opportunities illustrate the periods in which departures are possible for missions meeting the presumed IMLEO and trip time constraints (2 million kg and 2 years, respectively). Because of the much higher specific impulse of the nuclear thermal propulsion (NTP) system as compared to the chemical propulsion (CHEM) system, the nominal NTP departure opportunities had over 13 times the number of CHEM departure opportunities; that is, over 3700 more departure days were available for the NTP system over the 16-year time frame. Specifically, eight

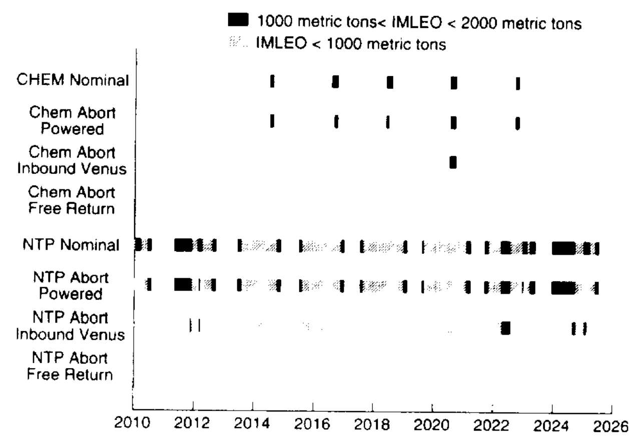

Fig. 1 Opportunities in the 2010–2025 time frame for nominal and aborted direct transfer missions.

separate NTP opportunities occurred, and each was 200–600 days in length. For the CHEM system, only five opportunities existed, and these were only 45–75 days in length. Missions with an IMLEO greater than 1 million kg are darkly shaded in Fig. 1. Thus, it is clear that nominal CHEM missions did not exist with an IMLEO less than 1 million kg. This result differed from NTP missions where 70% of the available missions had an IMLEO below 1 million kg. Another difference between the nominal NTP and chemical missions was in the total trip time. Each chemical propulsion round trip mission with a minimum IMLEO had a total trip time driven to the maximum constraint of 2 years. The duration of these optimal missions was fixed at this constraint value because unconstrained excursion class direct transfers have a global IMLEO minimum that naturally tends toward 2.5 years in duration.[12] By raising the specific impulse with NTP propulsion, larger ΔVs were possible with the same amount of propellant, thus, enabling the trip times for 40–50% of each NTP opportunity to decrease by nearly 200 days below the 2-year constraint.

The opportunities for direct mission aborts are also shown in Fig. 1. The figure shows that fixing the Earth departure and Mars arrival dates, and placing a limit on the propellant usage made it impossible to abort some of the nominal missions. This result was most clearly evident with the free return missions, which were not possible when chemical propulsion was used. The lack of free return missions was attributable to the sensitivity of these trajectories to the planetary orientation. Because the Earth departure and Mars arrival dates were fixed in a direct transfer mission abort, modification of the Earth return date was the only way to control the planetary geometry of the abort trajectory. The changes in the nominal Earth return date necessary for a free return mission were impossible to make with the assumed chemical propulsion system. Likewise, changing to NTP did little to increase the number of free returns, because an abort with an unpowered Mars swing-by was only possible in two of the eight nominal direct transfer mission opportunities (i.e., less than 3% of direct transfer missions). However, mission aborts in all eight of the nominal NTP departure opportunities were possible when a ΔV was added at the Mars encounter as a further control of the trajectory shape. This result is presented in Fig. 1 where 84% of all nominal direct transfer missions could be converted to a powered abort. A closer look at the two NTP free return opportunities revealed that the total trip time of the abort was reduced by 50–250 days if a powered abort was performed instead. Figure 2 shows trajectory plots for a nominal mission and both a free return and powered abort in the 2018 opportunity. The 570-day nominal mission could be reduced by 70 days in a free return abort and by 120 days in a powered abort, as seen in the figure. Note that the Earth departure and Mars arrival dates were the same for each scenario and that each mission would have the same IMLEO of 590,000 kg.

Further examination of Fig. 1 shows that there were gaps from 15 to 115 days in each NTP-powered abort opportunity. These missing dates indicate locations where the propellant limit or trip time constraint prevented a suitable powered abort from occurring. Figure 3 shows the variation of the total time of flight across the 2011 NTP-powered abort opportunity. The solid line indicates the total round-trip time of the NTP nominal direct transfer mission, and the bars show the total time of flight of each powered abort. The hollow bars indicate missions in which the propellant limit was exceeded; in this case, a 25-day period where the necessary abort maneuver at Mars was too large. Another 50-day period was lost because the time of flight of the abort missions exceeded the nominal trip time. Also, the figure shows that there were several sudden changes in trip time. These large changes occurred in locations where meeting the propellant constraint imposed by the nominal mission required a significant alteration of the planetary geometry by modifying the encounter dates. Figure 4 illustrates powered aborts for two nominal missions in the 2020 opportunity in which the Earth departure dates differed by only 5 days; how-

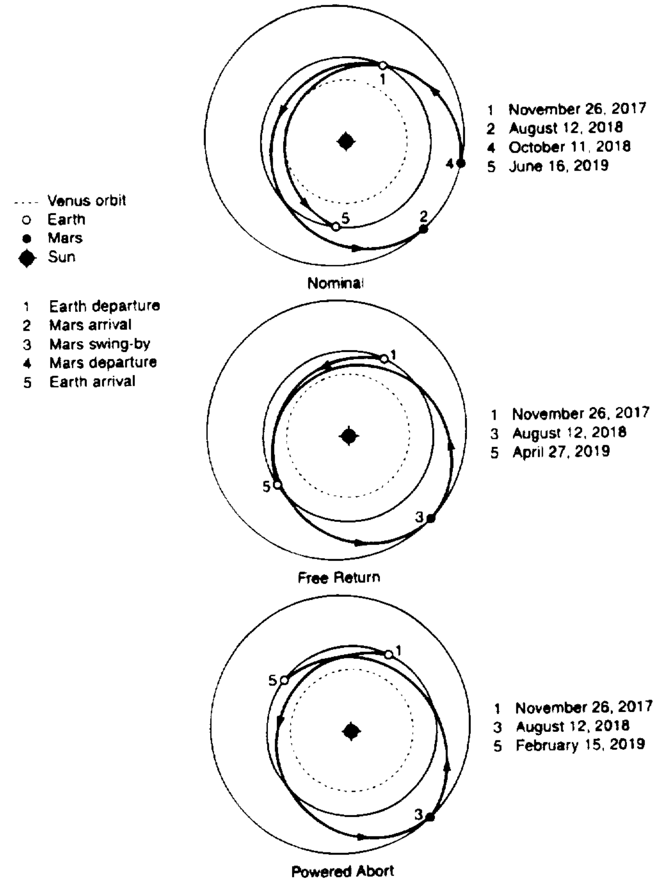

Fig. 2 2018 nominal NTP direct transfer mission trajectory and corresponding powered abort and free return trajectories.

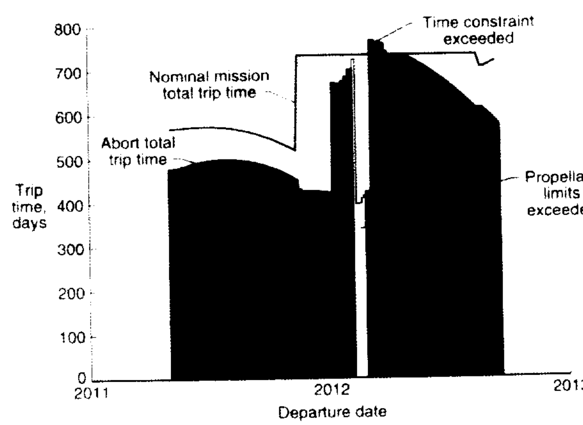

Fig. 3 Variation of trip time over the 2011 NTP direct transfer powered abort opportunity.

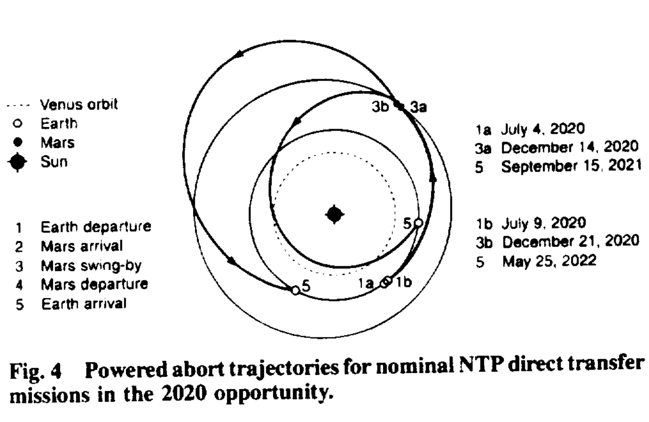

Fig. 4 Powered abort trajectories for nominal NTP direct transfer missions in the 2020 opportunity.

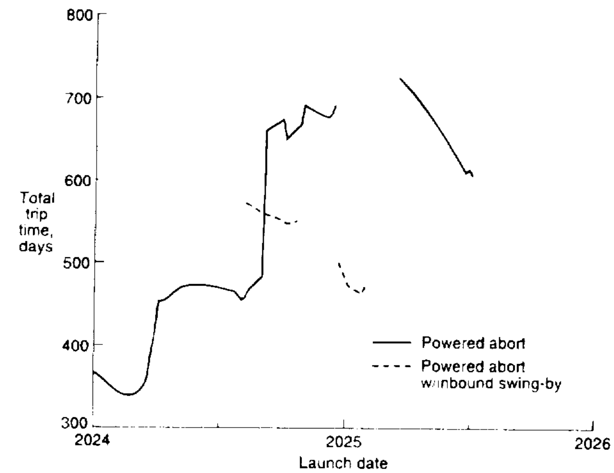

Fig. 5 Variation of trip time over the 2024 NTP direct transfer opportunity.

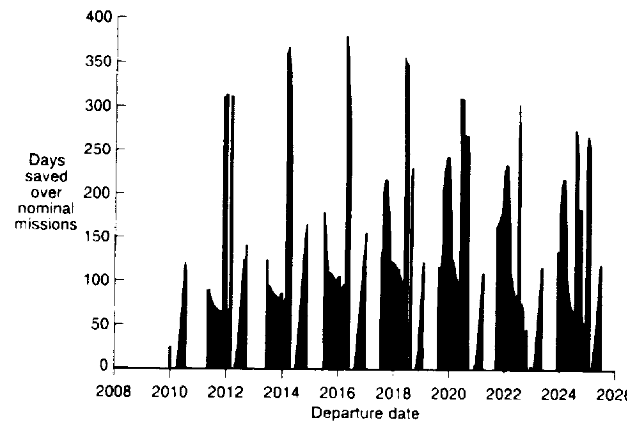

Fig. 6 Variation of trip time reduction over the nominal mission for NTP direct transfer mission aborts.

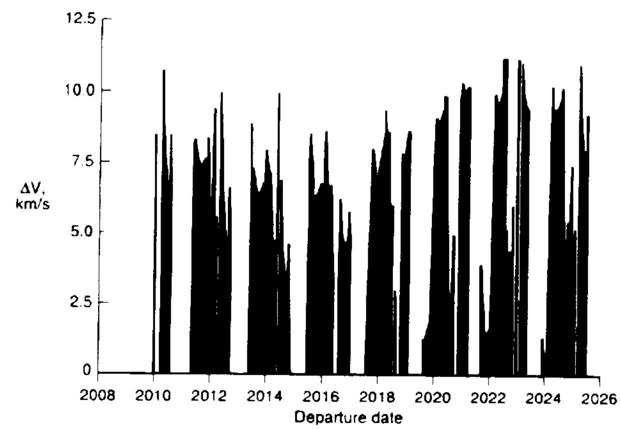

Fig. 7 Variation of powered abort maneuver ΔV magnitudes for direct transfer nominal missions.

ever, the resulting difference in total time of flight was over 250 days. This figure shows that the first leg of the mission was nearly the same for each case. However, after the Mars encounter, the first trajectory (which had the shorter abort) passed within the orbit of Venus and terminated with a large orbit capture maneuver at Earth return. The second mission, on the other hand, departed only 5 days later, and it required a longer abort because there was not a sufficient amount of propellant on board to perform the large Earth orbit capture maneuver necessary for a similarly short abort. Delaying the Earth encounter reduced the propellant required for this maneuver to an acceptable level. This result suggested that an added inbound Venus swing-by could be used as a further control to reduce the ΔV of this Earth return maneuver and improve the abort capabilities of a particular nominal mission.

Next, an attempt was made to increase the number of direct transfer abort opportunities and decrease the trip times of these aborted missions by performing an inbound Venus swing-by after the powered maneuver at Mars. This encounter was added in order to reduce either the Mars or Earth maneuvers so that the subsequent propellant savings could be applied elsewhere to further reduce the total time of flight. Figure 1 shows that inbound swing-by aborts could be performed in seven of the eight nominal NTP opportunities. Also, three of the inbound swing-by abort opportunities occurred where no powered aborts were available. Adding the inbound aborts in places where there were no direct powered aborts increased the number of nominal missions that could be aborted from 84 to 86%. Figure 5 shows the 2024 NTP abort opportunities. Both direct-powered aborts and powered aborts with an inbound Venus swing-by were possible in this opportunity. Note that it was necessary to switch between the two abort modes several times in order to minimize the trip time. Figure 6 shows the trip time savings over the nominal mission for each optimal abort across the entire 16-year period. In total, 23% of the nominal direct transfer missions shown in Fig. 1 could be aborted with an added inbound Venus swing-by. However, this additional swing-by only provided an increased trip time savings over a direct-powered abort for 8% of all nominal missions. By adding the option of performing an inbound Venus swing-by as a further control of the abort trajectory, the number of nominal missions that could be aborted with over a 100-day reduction in total trip time was increased from 38 to 44%. In some instances, the added inbound swing-by provided total trip time reductions of up to 220 days over powered aborts without the added swing-by. Figure 7 shows the variation of the magnitude of the powered abort maneuver at Mars, where over 50% of these aborts required a burn of more that 5 km/s. It is interesting to note that the addition of the inbound Venus swing-by enabled the Mars swing-by to be unpowered during some aborts. Finally, for the nominal missions utilizing CHEM, only one inbound swing-by abort opportunity was possible. These inbound swing-by aborts reduced the trip times of the direct-powered aborts by more than 200 days. Overall, 73% of the nominal CHEM missions could be aborted, with 18% of these nominal missions being aborted with an added inbound Venus swing-by. Table 3 shows the total number of nominal missions that could be aborted using the direct-powered abort and the powered abort with the inbound Venus swing-by. Additionally, because many nominal missions could be aborted using both of these abort modes, the number of nominal missions using the abort option that provides the shortest Earth return time is also shown. For NTP, 86% of the missions can be aborted using the best of either abort mode, whereas the same is true for 73% of the CHEM nominal missions. Finally, the percentage of nominal missions that can be aborted with a reduction in total trip time of more than 100 days is also listed for both of the abort modes.

Figure 8 shows the opportunities for outbound Venus swing-by missions with IMLEO below 2 million kg in the 2010–2025 time frame. There were eight NTP outbound Venus swing-by opportunities, varying from 100 to 300 days in length. The round-trip times ranged from 550 days to 2 years, and 62% of the missions had an IMLEO of less than 1 million kg (indicated by the lightly shaded regions in Fig. 8). The Venus swing-by for the NTP cases fluctuated from being unpowered to requiring ΔVs up to 10 km/s. Although this is an unrealistically high ΔV magnitude for CHEM, it may be within the range of feasibility if NTP is used. As with direct missions, substantially fewer opportunities were available when chemical propulsion was used. There were only four CHEM opportunities (of 30–80 days in length), and none of them had an IMLEO under 1 million kg.

Table 3 Direct transfer mission abort characteristics

	NTP		CHEM	
	No. of Earth departure dates	Percent of nominal missions	No. of earth departure dates	Percent of nominal missions
Nominal round trip missions	4140	—	335	—
Powered aborts	3495	84	240	72
Powered aborts with inbound swing-by	950	23	60	18
Aborts with shortest Earth return time				
Powered aborts	3250	78	185	55
Powered aborts with inbound swing-by	320	8	60	18
Total	3570	86	245	73
Aborts providing over 100 day reduction in nominal round trip time				
Powered aborts	1580	38	25	7
Powered aborts with inbound Venus swing-by	245	6	60	18
Total	1825	44 (51% of all aborts)	85	25 (35% of all aborts)

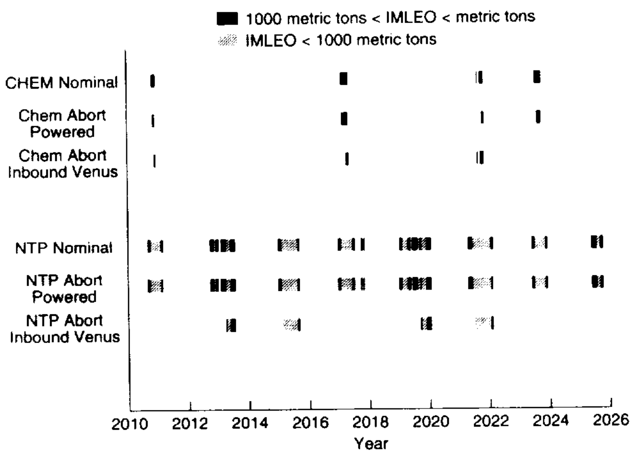

Fig. 8 Opportunities in the 2010–2025 time frame for nominal and aborted outbound Venus swing-by missions.

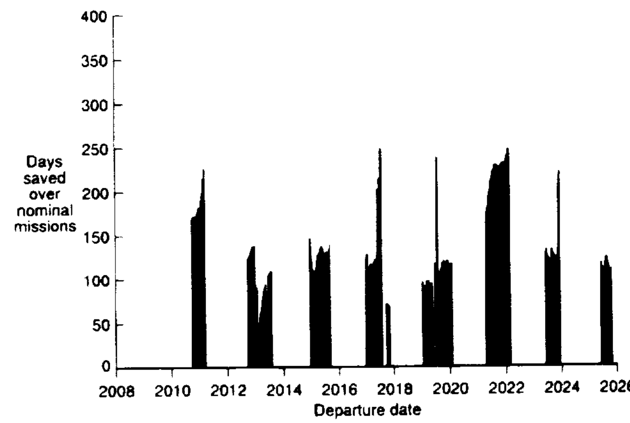

Fig. 9 Variation of trip time reduction over the nominal mission for NTP outbound Venus swing-by mission aborts.

For an outbound Venus swing-by mission abort, both the swing-by and Mars arrival dates from the nominal mission were fixed; that is, the decision to abort is made just prior to Mars arrival, as done with the direct transfer missions. No optimal outbound Venus swing-by missions provided free return aborts that met the 14 km/s Earth maximum entry velocity constraint. In fact, for both NTP and CHEM free returns, the Earth entry velocity never went below 15 km/s. Even so, Fig. 8 shows that a powered abort existed for every nominal NTP mission in every opportunity. Additionally, four powered abort opportunities also existed when an inbound Venus swing-by was added. However, these inbound aborts had longer trip times than the corresponding powered aborts and, therefore, would be of no practical use.

An outbound Venus swing-by mission abort had less flexibility than a direct transfer mission abort because the Venus swing-by for the nominal mission was chosen for a 60-day stay at Mars. Fixing this outbound swing-by date in an abort made it difficult to add another Venus swing-by on the inbound leg. Figure 9 shows the variation of trip time reduction for the abort below the nominal mission across the entire 16-year period. Although the largest reduction was less than that for direct transfer mission aborts, 84% of the NTP outbound Venus swing-by aborts trimmed over 100 days off the nominal mission. For CHEM systems, aborts were available for 81% of the nominal outbound Venus swing-by missions, and 10% of the nominal missions had aborts that utilized an inbound Venus swing-by. A summary of the abort characteristics of outbound Venus swing-by missions is listed in Table 4.

Figure 10 displays the abort opportunities for inbound Venus swing-by missions between 2010 and 2025 with an IMLEO below 2 million kg. There were seven NTP opportunities ranging from 180 to 420 days in length. The total mission times varied from 475 days to 2 years, and 70% of the missions had an IMLEO below 1 million kg (indicated by the unshaded regions in Fig. 10). Of the nominal missions, 55% of the inbound Venus swing-bys were unpowered, with the remaining missions requiring a maneuver of up to 4.5 km/s. Only CHEM opportunities with an IMLEO of less than 2 million kg existed, where the length of these opportunities varied from 40 to 200 days. The trip times were similar to the NTP missions, with 7% having an IMLEO of less than 1 million kg.

These nominal inbound Venus swing-by missions could not be aborted as free returns with either NTP or chemical propulsion systems. Unpowered Venus swing-by maneuvers could be found in an abort scenario, but a powered maneuver was always required at the Mars encounter. Powered aborts were conducted in a similar manner as the direct nominal missions because only the Earth departure and Mars arrival dates were fixed. This scenario differed from a nominal outbound mission because the inbound Venus swing-by date that was optimal for a 60-day stay at Mars did not have to be used in an abort. This inbound swing-date was moved during an abort scenario as an added control in order to reduce the total trip time. In addition, Fig. 10 shows that in some cases it was possible to abort the nominal mission without using an inbound Venus swing-by. This type of abort was similar to a direct abort where a single propulsive burn was performed at the Mars encounter. Additionally, Fig. 10 shows that many nominal missions could be aborted both if the inbound Venus swing-by is included or if it is removed. By choosing the abort option providing the fastest Earth return, 87% of the nominal inbound Venus swing-by missions could be aborted. In addition, in four of the seven NTP and one of the four CHEM opportunities, every nominal mission could be

Table 4 Outbound Venus swing-by mission about characteristics

	NTP		CHEM	
	No. of Earth departure dates	Percent of nominal missions	No. of Earth departure dates	Percent of nominal missions
Nominal round trip missions	1940	—	240	—
Powered aborts	1940	100	170	71
Powered aborts with inbound swing-by	685	35	80	33
Aborts with shortest Earth return time				
Powered aborts	1940	100	170	71
Powered aborts with inbound swing-by	0	0	25	10
Total	1940	100	195	81
Aborts providing over 100 day reduction in nominal round trip time				
Powered aborts	1620	84	100	42
Powered aborts with inbound Venus swing-by	0	0	0	0
Total	1620	84	100	42 (51% of all aborts)

Table 5 Inboard Venus swing-by mission abort characteristics

	NTP		CHEM	
	No. of Earth departure dates	Percent of nominal missions	No. of Earth departure dates	Percent of nominal missions
Nominal round trip missions	2450	—	460	—
Powered aborts	1930	79	385	84
Powered aborts with inbound swing-by	1465	60	125	27
Aborts with shortest Earth return time				
Powered aborts	840	34	340	74
Powered aborts with inbound swing-by	1290	53	45	10
Total	2130	87	385	84
Aborts providing over 100 day reduction in nominal round trip time				
Powered aborts	115	5	0	0
Powered aborts with inbound Venus swing-by	1170	48	40	9
Total	1285	53 (60% of all aborts)	40	9 (10% of all aborts)

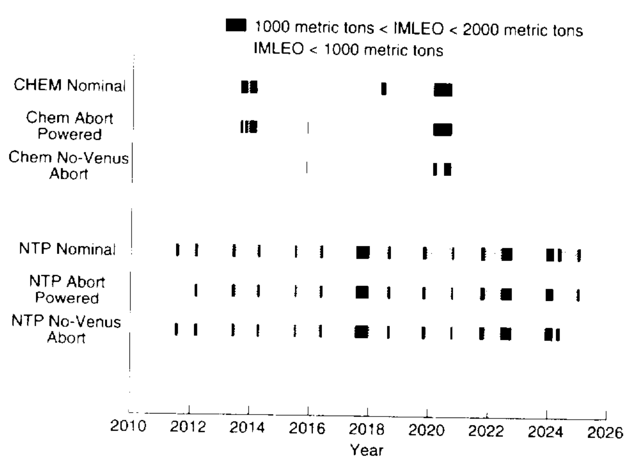

Fig. 10 Opportunities in the 2010–2025 time frame for nominal and aborted inbound Venus swing-by missions.

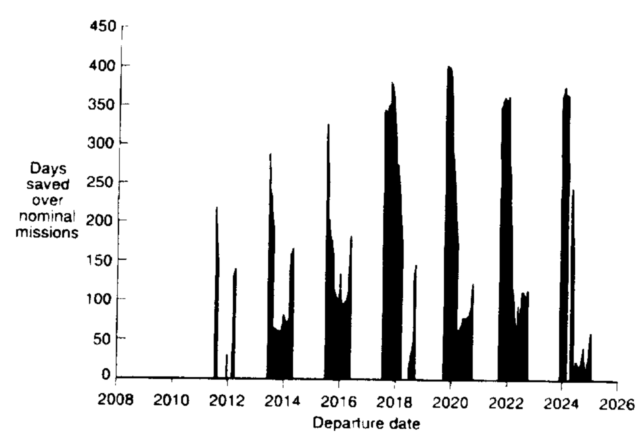

Fig. 11 Variation of trip time reduction over the nominal mission for NTP inbound Venus swing-by mission aborts.

aborted. Figure 11 shows the variation of trip time reduction for the NTP cases across the entire time period studied. Removing the inbound Venus swing-by from the aborts minimized the Earth return time for 53% of the nominal missions; sometimes reducing it as much as 380 days over powered aborts that retained the swing-by. Also, Fig. 11 shows that 60% of the aborts had reductions in trip time of over 100 days (in some instances, up to 400 days less than the nominal mission). Some type of powered abort could be applied to 84% of the nominal CHEM missions, with the inbound Venus swing-by being removed from the abort of 9% of them. The performance of the various abort techniques for nominal inbound Venus swing-by missions is shown in Table 5.

Conclusions

Many factors must be examined in determining the optimal interplanetary trajectories for human exploration of Mars. One important consideration involves the safe return of the crew to Earth in the event of an in-flight emergency. This study evaluates abort options that provide the fastest return to Earth with a minimal impact on the initial vehicle mass in LEO. Specifically, the feasibility of using free return and powered aborts in conjunction with round-trip missions to Mars that minimized IMLEO was investigated. By fixing all encounter dates up to the Mars arrival and limiting the propellant usage to that of the corresponding nominal mission, the abort capability of the minimized IMLEO nominal missions could be ascertained. In addition, the feasibility of enhancing the abort characteristics through reductions in total trip time with the addition or removal of an inbound Venus swing-by during the abort was evaluated.

The date restrictions associated with aborting optimized nominal missions severely limited the number of acceptable free returns, and only direct missions using nuclear thermal propulsion were able to be aborted in this way. The number of suitable abort opportunities, however, could be drastically increased by performing a propulsive maneuver at the Mars encounter. All nominal outbound Venus swing-by missions, as well as over 86% of direct transfer and inbound Venus swing-by missions, were able to be aborted successfully when a powered maneuver at Mars was included. Moreover, the reduction in total trip time from the nominal mission was greater for powered aborts than for free returns. In addition, the trip time for some aborts of direct transfer nominal missions could be reduced as much as 250 days with the addition of an inbound Venus swing-by. Likewise, the total trip time for some nominal inbound Venus swing-by mission aborts could be lowered by as much as 380 days with the removal of the Venus encounter. Furthermore, many additional abort opportunities, which did not exist without the addition or removal of the inbound Venus swing-by, were found for direct transfer and inbound Venus swing-by nominal missions. In summary, this study showed that by using powered aborts, and in some cases the addition or removal of a Venus swing-by, most nominal missions that minimized IMLEO could be aborted successfully.

References

[1] Braun, R. D., "The Influence of Interplanetary Trajectory Options for a Chemically Propelled Manned Mars Vehicle," *Journal of Astronautical Sciences*, Vol. 38, No. 3, 1990, pp. 289–310.

[2] Soldner, J. K., "Round-trip Mars Trajectories—New Variations on Classic Mission Profiles," AIAA Paper 90-2932, Aug. 1990.

[3] Hoffman, S. J., McAdams, J. V., and Niehoff, J. C., "Round-trip Trajectory Options for Human Exploration of Mars," American Astronomical Society, AAS Paper 89-201, April 1989.

[4] Lyne, J. E., and Braun, R. D., "Flexible Strategies for Manned Mars Missions Using Aerobraking and Nuclear Thermal Propulsion," American Astronomical Society, AAS Paper 93-171, Feb. 1993.

[5] Wolf, A. A., "Free Return Trajectories for Mars Missions," American Astronomical Society, AAS Paper 91-123, Feb. 1991.

[6] Lineberry, E. C., and Soldner, J. K., "Mission Profiles for Human Mars Missions," AAIA Paper 90-3794, Sept., 1990.

[7] Striepe, S. A., and Braun, R. D., "Effects of a Venus Swingby Periapsis Burn During an Earth–Mars Trajectory," *Journal of Astronautical Sciences*, Vol. 39, No. 3, 1991, pp. 299–312.

[8] Hong, P. E., Kent, P. D., Olson, D. W., and Vallado, C. A., "The Interplanetary Program to Optimize Simulated Trajectories (IPOST)," National Academy of Sciences, NAS1-18147, April 1992.

[9] Tucker, M., Meredith, O., and Brothers, B., "Manned Mars Missions," NASA TM-89320, May 1986.

[10] Joosten, B. K., Drake, B. G., Weaver, D. B., and Soldner, J. K., "Mission Design Strategies for the Human Exploration of Mars," International Astronautical Federation, IAF Paper 91-336, Oct. 1991.

[11] Striepe, S. A., "Influence of Interplanetary Trajectory Selection on Earth Atmospheric Entry Velocity of Mars Missions," *Journal of Spacecraft and Rockets*, Vol. 30, No. 4, 1993, pp. 420–425.

[12] Braun, R. D., Powell, R. W., and Hartung, L. C., "Effect of Interplanetary Trajectory Options on a Manned Mars Aerobrake Configuration," NASA TP-3019, Aug. 1990.