48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico
ICES-2018-239

Mass-Optimal Transit Time for Acceptable Effective Radiation Dose on Manned Deep Space Exploration Missions

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As future deep space exploration missions venture beyond Earth's protective magnetosphere, astronauts will be exposed to higher ambient radiation doses than ever before. Radiation mitigation that provides sufficient protection for astronauts while also keeping total mission mass and cost within budget presents a significant engineering challenge. To meet established constraints on total allowable mission effective dose, mission planners can either use fast orbital transfers with little radiation shielding or slow transfers with heavy radiation shielding. The objective of this study is to determine the optimal transit time that minimizes the initial mass in low-Earth orbit (IMLEO) required to deliver a vehicle to Mars with enough radiation shielding to not exceed the maximum allowable mission effective dose. Lambert's problem is solved for a range of Earth-Mars transfers to determine the total delta-V required as a function of transit time. For a given transit time, the radiation shielding mass required to meet effective dose constraints is determined. Then, the IMLEO required to deliver a transit habitat with the added radiation shielding and consumables mass is computed using the delta-V corresponding to that transit time. The sensitivity of IMLEO to transit time is reported and the minimum IMLEO is identified. The minimum IMLEO is shown to be obtained at a faster-than-Hohmann transfer because reducing the transit time down to the optimal point reduces the shielding mass more than the loss in payload capacity. The mass and time savings of the optimal transit relative to a standard minimum-energy transfer is reported and discussed. Even when the mission is optimized solely for radiation mitigation, the fastest transfer is clearly not always favored. The sensitivity of these results to the radiation shielding model used and allowable exposure limits is explored along with the potential for using existing ECLSS water as the shielding material.

Nomenclature

DRA	=	Design Reference Architecture
ECLSS	=	environmental control and life support system
EMC	=	Evolvable Mars Campaign
GCR	=	galactic cosmic ray
IMLEO	=	initial mass in low-Earth orbit
LEO	=	low-Earth orbit
NCRP	=	National Council on Radiation Protection and Measurement
REID	=	risk of exposure induced death
SPE	=	solar particle event
Sv	=	Sievert

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α	=	areal density of radiation shield
$C3$	=	characteristic energy
g_0	=	standard gravity
I_{sp}	=	specific impulse
m_0	=	initial mass in low-Earth orbit
m_f	=	final payload mass
m_{food}	=	mass of food consumables
m_{hab}	=	mass of transit habitat (excluding radiation shield and food)
m_{shield}	=	mass of radiation shield
n_{crew}	=	number of crew members
Q_{limit}	=	allowable mission effective dose
$\dot{Q}_{\text{surface}}$	=	effective dose rate on the surface of Mars
$\dot{Q}_{\text{transit}}$	=	effective dose rate during transit
r_{food}	=	mass of food consumed per crew member per day
S	=	surface area of transit habitat
$t_{mars,orbit}$	=	time spent in Mars orbit
$t_{mission}$	=	total mission duration
$t_{surface}$	=	time spent on the surface of Mars
$t_{transit,in}$	=	transit time on the inbound leg of mission (Mars to Earth)
$t_{transit,out}$	=	transit time on the outbound leg of mission (Earth to Mars)
Δv	=	delta-V for orbital maneuvers

I. Introduction

AS future long-duration deep space exploration missions venture beyond Earth's protective magnetosphere, astronauts will be exposed to higher ambient radiation doses of galactic cosmic rays (GCRs) and solar particle events (SPEs) than ever before. While operations on Mir and the International Space Station resulted in long-duration flight experience in low-Earth orbit (LEO), the longest manned mission beyond the Van Allen belts was Apollo 17, which lasted a mere 12.5 days. With Mars mission plans often citing durations of around 1,000 days, the risk surrounding radiation exposure and the resulting need for radiation mitigation strategies becomes apparent.[1,2]

For future Mars missions, NASA has adopted a permissible exposure limit standard for space radiation of ≤ 3% Risk of Exposure Induced Death (REID) with a 95% confidence interval. Current practice determines the allowable deep space exposure limits based on the National Council on Radiation Protection and Measurement (NCRP) LEO limits outlined in NCRP-132 as shown in Table I and Table II below.[1,3] Because blood-forming organs yield the most stringent limit, they will be used throughout the subsequent analysis.

Table I
RECOMMENDED ORGAN DOSE EQUIVALENT LIMITS FOR ALL AGES [REPRODUCED FROM REF. 3]

Exposure Interval	Blood-Forming Organs Dose Equivalent (cGy-Eq)	Ocular Lens Dose Equivalent (cGy-Eq)	Skin Dose Equivalent (cGy-Eq)
30-day	25	100	150
Annual	50	200	300
Career	See Table II	400	600

Table II
LEO CAREER WHOLE BODY EFFECTIVE DOSE LIMITS (Sv) [REPRODUCED FROM REF. 3]

Age	25	35	45	55
Male	0.7	1.0	1.5	2.9
Female	0.4	0.6	0.9	1.6

Satisfying radiation exposure limits has proven to be a major hurdle for manned Mars missions, which current literature suggests will require mitigation strategies. Passive radiation shielding, such as aluminum, water, or polyethylene walls, is the primary means of reducing the effective dose received by astronauts and will be the focus of this study.[1,4,5] Depending on the shielding material and maximum acceptable effective dose rate, the areal density (or thickness) of shielding required during transit can be determined as shown in Figure 1. Thus, the amount of shielding needed directly drives the mass of the spacecraft. Previous work has identified that, while passive shielding can in theory be used to achieve acceptable effective doses, an excessive amount of mass would need to be launched.[1,2] While on the surface of Mars, the background radiation is reduced to about 22 cSv/yr during solar minimum because some of the incident radiation is attenuated in the atmosphere and blocked by the planet itself.[1]

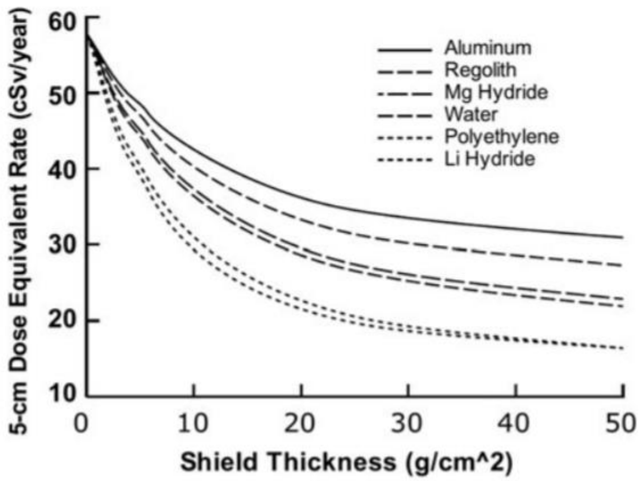


Figure 1. Dose equivalent rate from GCR at solar minimum as a function of shield thickness for various shielding materials. *The plotted data is taken from Simonsen 1997 (see Ref.* 1*). The plot shows how increasing shield thickness decreases received effective dose with diminishing returns. It also shows that materials such as water and polyethylene provide more shielding than aluminum.*

Radiation mitigation that provides sufficient protection for astronauts while also keeping total mission mass and cost within budget presents a significant engineering challenge. To meet established constraints on total allowable mission effective dose using passive shielding, mission planners can either use fast transfers with little radiation shielding or slow transfers with heavy radiation shielding. This tradeoff stems from fundamental constraints of astrodynamics whereby faster impulsive transfers require more delta-V, which translates through the rocket equation into reduced payload mass fraction. A commonly cited radiation mitigation strategy to meet effective dose limits is to use fast transits, which allow for higher acceptable effective dose rates, and, hence, minimal shielding mass. For example, the mission architecture detailed in NASA Design Reference Architecture (DRA) 5.0, which uses a 174 day transit time, identifies that "interplanetary transit times are reduced to minimize the exposure of the crew to harmful solar and galactic cosmic radiation."[6] As another example, one of SpaceX's proposed BFR missions to Mars uses a 100 day transit, with all proposed transits ranging from 80 to 150 days.[7] This extremely fast transit is likely selected for architectural reasons other than just radiation mitigation, such as frequent reuse, reduced consumables mass, and reduced microgravity exposure. Interestingly, the Evolvable Mars Campaign (EMC) hybrid SEP-chemical architecture is actually targeting slower 300 to 400 day transfers using 20-40 g/cm^2 of radiation protection.[8,9] These mission concepts present the wide range of potential transit time selections.

II. Motivation

One of the major shortcomings of current mission proposals is an emphasis on reducing the exposure time and required radiation shielding mass instead of reducing the overall mass of the Mars transit vehicle. These Mars mission concepts often consider sending crew on what they perceive as a non-optimal, in terms of propellant mass, fast transfer because of the perceived need to reduce the exposure time to deep space radiation. These faster transit times result in increased propellant mass for a fixed transit habitat mass. However, the amount of radiation shielding mass required to ensure a given total mission effective dose decreases with decreasing transit time. This has the effect of reducing the transit habitat mass for faster transfers, which can reduce the propellant required as long as the delta-V penalty for the faster transfer is not larger than the radiation shielding mass saved by going faster. Thus, an optimal transit time can be found that minimizes the amount of mass that must be initially launched into orbit to deliver a Mars transit habitat on a roundtrip Mars mission.

This paper proposes that a Mars transit vehicle should be optimized by varying the transit time to minimize the initial mass in low-Earth orbit (IMLEO) while carrying enough passive radiation shielding to meet a constraint on allowable effective dose. Transit time was selected as the free parameter for optimization because transit time directly drives the orbit transfer, radiation exposure time, and propellant required to reach Mars. This work will also consider the sensitivity to the radiation shielding model used and the allowable mission effective dose limit, which is dependent on career limit standards, as well as the age, gender, and flight experience of astronauts on the mission. In particular, this work focuses on roundtrip Mars missions, but the process can be replicated for other deep space destinations.

III. Methodology

The goal of this work is to determine the mass-optimal transit time that meets allowable effective radiation dose constraints for manned deep space exploration missions. In order to perform this optimization, we must first define an objective function. The cost function (objective function to be minimized) used in this analysis is the initial mass in low-Earth orbit (IMLEO). This is a commonly used metric that indicates the total mass that needs to be placed into LEO at the start of a mission. Minimizing this mass serves to optimize our mission architecture by reducing the number of launches required and the size of our spacecraft. The IMLEO, m_0, is computed from the ideal rocket equation using the final payload mass after all thruster firings are completed, m_f, the delta-V, Δv, the specific impulse, I_{sp}, and the standard gravity, g_0. The final payload mass is computed from three contributions, the mass of the food consumables for the duration of the mission, m_{food}, the mass of the radiation shielding required, m_{shield}, and the mass of the rest of the habitat that is assumed to be insensitive to radiation levels and transit time, m_{hab}.

$$m_0 = m_f \exp\left(\frac{\Delta v}{I_{sp} g_0}\right) = \left(m_{hab} + m_{shield} + m_{food}\right) \exp\left(\frac{\Delta v}{I_{sp} g_0}\right) \tag{1}$$

In order to perform the desired optimization of finding the transit time that minimizes IMLEO, we must be able to compute the following quantities as a function of transit time: Δv, m_{shield}, and m_{food}. Then, the IMLEO can be computed over a range of transit times and the minimum identified.

First, let's consider the calculation of Δv as a function of transit time. A standard technique in astrodynamics for planning Mars mission trajectories is to solve Lambert's problem (see Ref. 10), which can be iteratively solved to find the trajectory that carries a spacecraft from one position vector to another position vector in a specified amount of time. By comparing the velocity on this trajectory to the velocity in the initial and final orbits, the delta-V can be found for each burn. The first step in this process is to obtain planetary ephemerides for Mars and Earth. With the position and velocity vectors for each planet known over the time period of interest, one can loop through numerous departure dates and transit time combinations to produce a so-called "porkchop" plot. Although typical porkchop plots only report the characteristic energy (C3) for departure from Earth, the delta-V for each launch opportunity can be computed by assuming an initial parking orbit and desired final orbit around Mars. In this way, the delta-V can be found for any given value of transit time.

Now, we compute the mass of radiation shielding required to meet effective dose limits, which includes 30-day, annual, and career limits, as a function of transit time. For GCRs, the NCRP specified 30-day and annual dose equivalent limit (see Table I) can be satisfied by targeting a dose equivalent rate without regard for transit time and mission duration. However, the NCRP specified career effective dose limit (see Table II) would likely be exceeded on long-duration manned Mars missions even when yearly limits are satisfied. Thus, the transit time and total mission duration must be considered to size shielding for NCRP-specified career limits. The allowable average effective dose rate during transit, $\dot{Q}_{transit}$, can be computed from the allowable mission effective dose, Q_{limit}, the effective dose rate on the surface of Mars, $\dot{Q}_{surface}$, the time spent on the surface, $t_{surface}$, the transit time on the outbound leg of mission, $t_{transit,out}$, the time spent in Mars orbit, $t_{mars,orbit}$, and the transit time on the inbound leg of the mission, $t_{transit,in}$. To model the worst case scenario for radiation exposure, this analysis assumes that instead of descending to the surface where effective dose rates are lower, the crew spends 500 days in Mars orbit waiting for the return launch window, which is based on the synodic period of Earth and Mars. This situation models contingency operations for a scrubbed Mars landing, or an early manned Mars orbital mission. It should be noted that the allowable mission effective dose used would only be equal to the career limit if the crew is made up of first-time astronauts.

$$\dot{Q}_{transit} = \frac{Q_{limit} - \dot{Q}_{surface} t_{surface}}{\left(t_{transit,out} + t_{mars,orbit} + t_{transit,in}\right)} \tag{2}$$

Once this allowable effective dose rate is determined, the areal density, α, of shielding required to satisfy the effective dose limit constraint can be computed. In this study, water was nominally assumed to serve as the radiation shield with the hopes of using existing onboard ECLSS water as shielding. However, alternative shield materials can be analyzed with this framework. Two primary shielding models, given by Simonsen (Ref. 4) and Cucinotta (Ref. 5), can be used to determine required shielding thickness. Using the data presented in Figure 2, the areal density of a particular shielding material that corresponds to the allowable effective dose rate can be selected for either shielding model, as well as an exponential fit model to the Cucinotta data. The subsequent analysis nominally uses the exponential fit model. The sensitivity of results to model selection will be discussed.

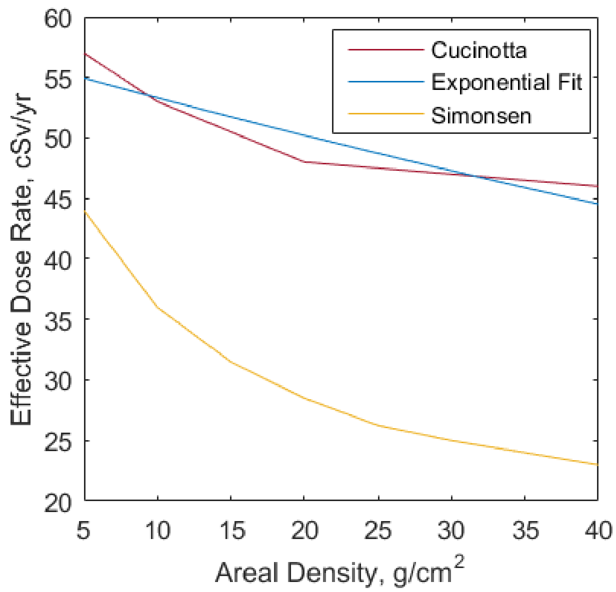


Figure 2. Effective dose rate from GCR at solar minimum as a function of areal density of a water radiation shield for three different models. *The Cucinotta data set from 2012 (Ref. 5) predicts much higher effective dose rates than the Simonsen data from 1997 (Ref. 4). The exponential fit model was developed to follow the Cucinotta data while forcing the transmitted effective dose to zero as radiation shield thickness grows beyond the available data.*

By assuming a transit habitat surface area, S, the mass of radiation shielding, m_{shield}, can be directly computed as $m_{shield} = \alpha S$. For simplicity in computing the surface area, a spherical radiation shield was assumed to surround a habitat with a net habitable volume of 25 m^3/person.[11] With four crew members, this leads to a habitat volume of 100 m^3.

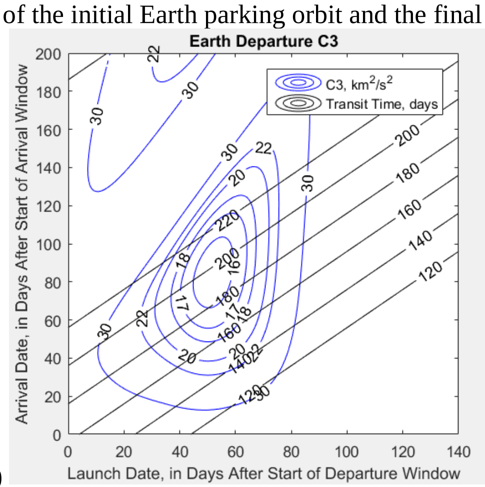
The mass of food consumables was included as another factor that may skew the selection of an optimal transit time compared to if radiation shielding were considered alone. The mass of food required was computed from a known consumption rate, r_{food} [in kg/crew-day]. We know that the total mission duration is given by: $t_{mission} = t_{transit,out} + t_{mars,orbit} + t_{surface} + t_{transit,in}$. Then, the total mass of food becomes: $m_{food} = r_{food} n_{crew} t_{mission}$. Some other factors that could also be considered as having masses dependent on transit time are: other consumables, spare parts, and attitude control thruster propellant. For simplicity, these factors were not explicitly considered in this analysis. However, they could be incorporated in much the same way as the food consumables mass.

IV. Results

The methodology described above was applied for a Mars mission subject to a constraint on allowable mission effective radiation dose. First, the relationship between delta-V and transit time was computed. Then, the dependence of IMLEO on transit time is presented and the minimum IMLEO point is identified. The set of parameter values used in this analysis are reported in Table III in the Appendix. Lastly, the sensitivity of the results to shielding models and allowable mission effective dose is explored.

A. Delta-V vs. Transit Time

First, porckchop plots were generated by solving Lambert's problem given the planetary ephemerides for Earth and Mars. This resulted in the contour plots shown in Figure 3, which gives various potential launch and arrival dates, along with their associated characteristic energy and transit time. The characteristic energy required for a transfer is independent of the initial Earth parking orbit and the final Mars science orbit.

a) 

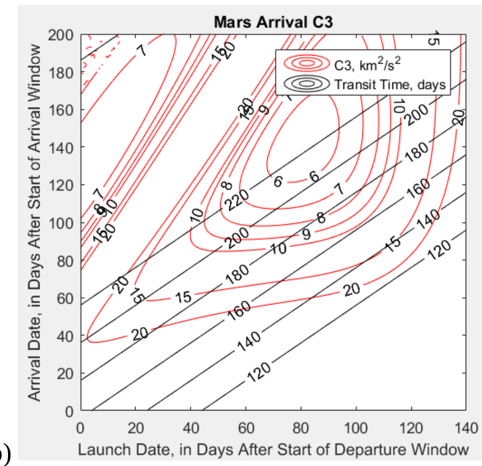
b) 

Figure 3. Characteristic energy (C3) and transit time for various launch and arrival dates. *The reported C3 value provides a measure of the amount of energy needed to complete a journey to Mars. Note that the trajectory with departure and arrival dates yielding the minimum departure C3 (see Figure 2a) does not have the minimum arrival C3 (see Figure 2b). Thus, when the trajectory as a whole is considered, we will find an intermediate departure date and arrival date are preferred. Note that a similar plot of Mars departure C3 is also used for analysis of the return trip. The data shown is for the 2005 launch window, which was taken as a representative case.*

To obtain a value for the total mission delta-V (which will be used to compute the IMLEO), orbits around Earth and Mars must be assumed. For this analysis, the Earth parking orbit was assumed to be circular at 300 km altitude. The science orbit around Mars was assumed to have a perigee of 250 km and a period of 5 sols. The delta-V required to transfer between these orbits and the interplanetary trajectories in the porkchop plot was then computed. This consisted of orbital maneuvers for trans-Mars injection, Mars orbit insertion, and trans-Earth injection. This process was repeated for each combination of launch and arrival dates to produce Figure 4.

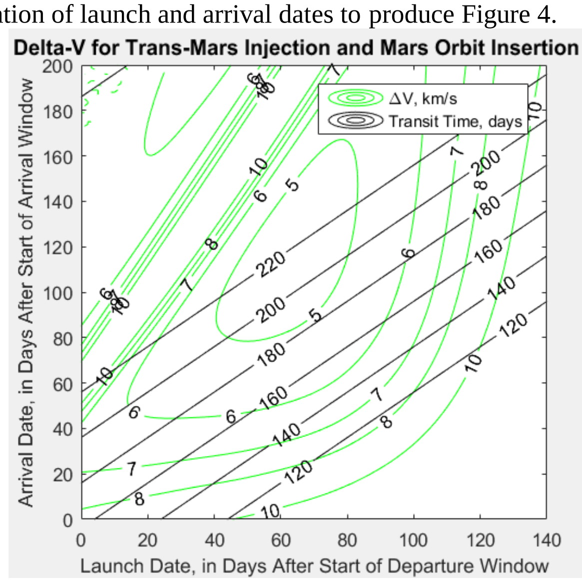


Figure 4. Delta-V and transit time for various launch and arrival dates. *This figure shows the delta-V required for the outbound leg (from Earth to Mars) of a roundtrip Mars mission as a function of the launch and arrival dates selected. These dates uniquely drive the transit time. A similar plot has been generated for the mission's inbound leg (from Mars to Earth), which consists solely of trans-Earth injection, to determine the total round-trip delta-V.*

On the delta-V plot in Figure 4, it is clear that a given transit time can be achieved using various departure dates, and most importantly, varying amounts of delta-V. However, the minimum delta-V point for each transit time can be determined from the plot. This would be the trajectory that would nominally be chosen for a mission with a desired transit time. Thus, a unique delta-V can be assigned to achieve a desired transit time as shown in Figure 5. The ability to relate these quantities is key in solving for the mass-optimal transit time.

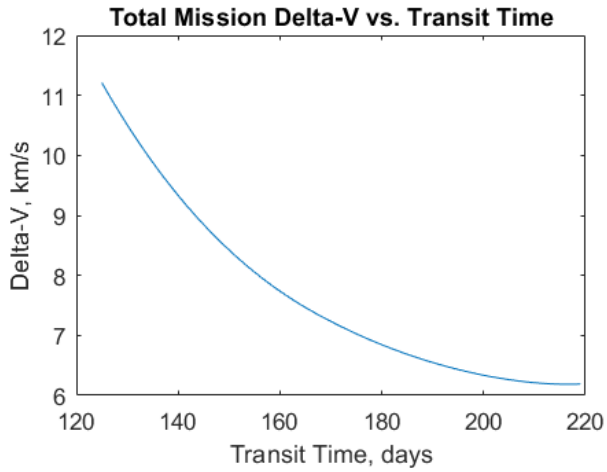


Figure 5. Delta-V as a function of transit time. *This figure depicts the tradeoff between reducing transit time and increasing delta-V required to complete the mission. The delta-V is the total required for trans-Mars injection, Mars orbit insertion, and trans-Earth injection. The transit time shown is the one-way transit time, either outbound or inbound, which are assumed to be equal for the mission concept considered. It is clear that initial reductions in transit time can be accomplished with minimal delta-V penalty, but the delta-V quickly rises with further reduction in transit time.*

B. IMLEO vs. Transit Time

To find the optimal transit time that minimizes IMLEO, we must iterate through all transit times considered and compute the IMLEO required in each case using Eqn. 1. Evaluating this equation involves computing the shielding mass and food mass at each transit time considered as described in the methodology section. We will also use the results reported in Figure 5 to determine the delta-V for each transit time. Following this process, Figure 6 was produced showing the impact of transit time on IMLEO.

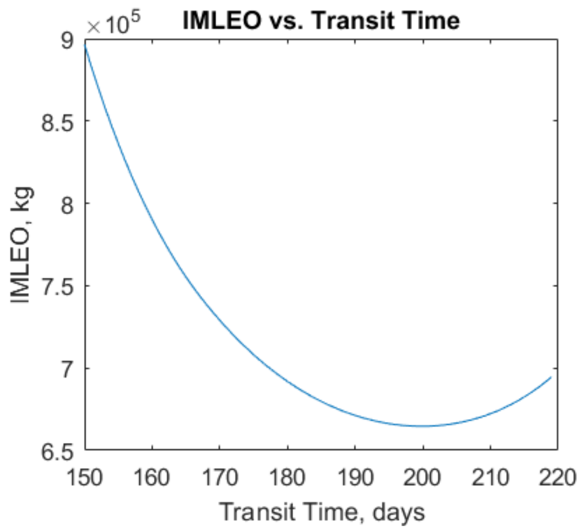


Figure 6. IMLEO as a function of transit time. *The presence of a minimum IMLEO indicates that, even when a Mars mission is designed solely to meet radiation mitigation constraints, the solution is not simply to add more shielding or travel faster. There exists a point beyond which using a faster transit to reduce exposure time will result in a negative overall effect by reducing the amount of shielding you can carry.*

It is interesting to see that, when radiation effects are considered explicitly, the favored transit time is neither the fastest nor the slowest. The result in Figure 6 shows that, under the mission concept presented in this analysis, the optimal transit time is 19 days faster than the minimum delta-V transfer and saves 29.9 mT of IMLEO. The existence of a minimum IMLEO shows that a "faster is better" approach to transit times for proposed Mars mission architectures cannot be justified on the basis of radiation mitigation or food consumable mass reduction. Other considerations that may lead a mission to favor a faster transit time are the risks of microgravity exposure and component failure. Another interesting result is that the transit time can be reduced by as much as 40 days relative to the minimum delta-V (slowest transfer in Figure 6) without increasing the IMLEO.

C. Sensitivity to Shielding Effectiveness

One key finding from this analysis is that the results are highly sensitive to the radiation shielding model used. As radiation shielding models have developed over time, changes have occurred in the predicted effective dose rate behind a radiation shield. For example, the recent models presented by Cucinotta in 2012 (Ref. 5) predict significantly higher effective dose rates than Simonsen in 1997 (Ref. 4). To analyze the effect of these changes, the optimal transit time analysis for IMLEO vs. transit time was repeated using three different radiation shielding models (see Figure 2) as shown in Figure 7. The results of this sensitivity analysis provide strong evidence that further research into the effective dose received behind radiation shielding must be conducted to aid Mars mission planning. Changes in radiation shielding models after a mission has been designed can lead to large deviations from the desired transit time.

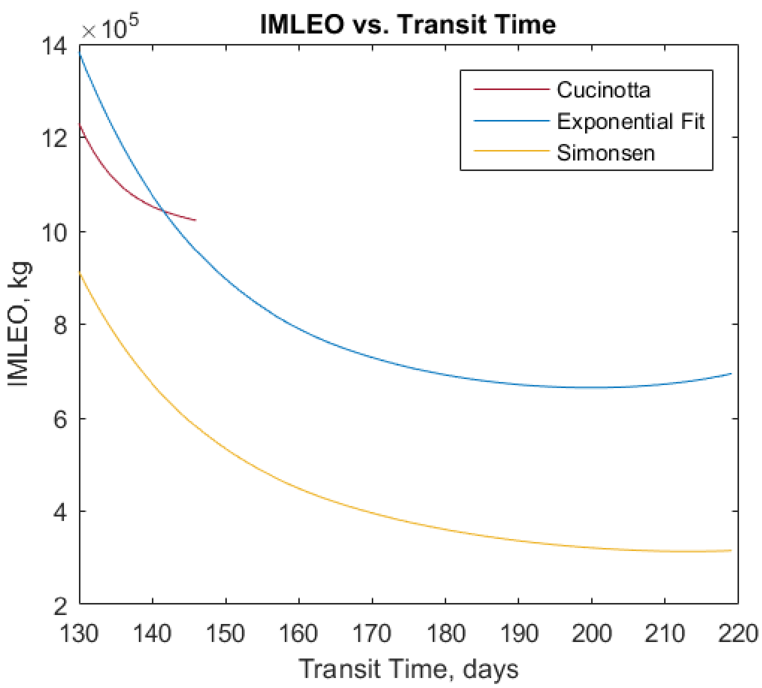


Figure 7. IMLEO as a function of transit time for three different radiation shielding models. *This plot shows the strong sensitivity of the radiation shielding model used to the optimal transit time and resulting IMLEO. For example, the effective dose rates achieved by the shielding depths presented by Cucinotta (Ref. 5) require Mars missions with transits less than about 146 days.*

As another indication of the sensitivity of the results to the radiation shielding model, the mass of radiation shielding required using each of the three different models was computed. These results, shown in Figure 8, are important for determining whether shielding materials already present on the spacecraft, such as ECLSS water, can provide sufficient shielding. Here it should be noted that intelligent positioning of the water onboard the spacecraft can achieve better shielding than the spherical shell assumed in this analysis. In addition, the propellant onboard can also provide a dual benefit as radiation shielding, but this has not been considered in this analysis.

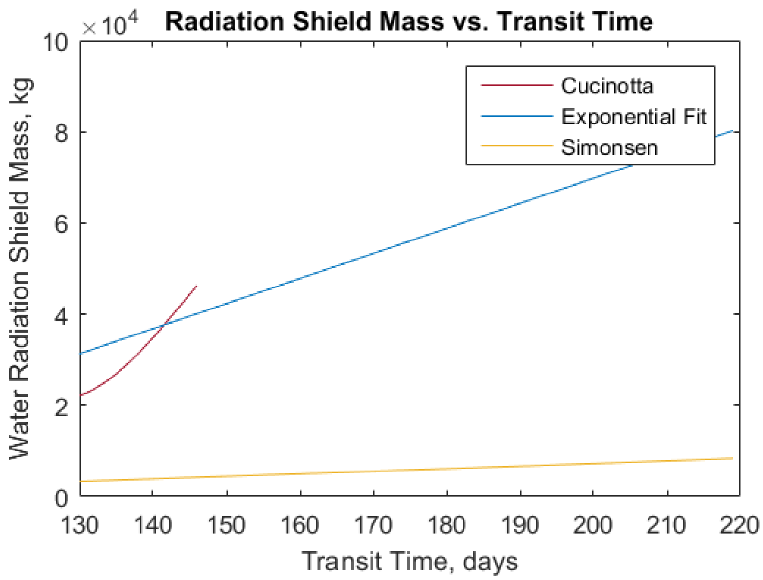


Figure 8. Water radiation shield mass as a function of transit time for three different radiation shielding models.. *Under the Simonsen (Ref. 4) shielding assumptions, the ability to shield a spacecraft with water already present onboard appeared much more feasible than it does with the Cucinotta (Ref. 5) data set. In addition, note that the optimal transit time, which minimizes IMLEO, does not correspond to any distinct feature on the plot of required radiation shielding mass. Instead, the amount of shielding needed simply declines with reduced transit time. Thus, if only a certain mass of shielding material is already available onboard, the transit time could be driven to a non-optimal value to meet the constraints. However, in general, net system-level benefits are achieved by operating at the mass-optimal transit time without regard for the total amount of radiation shielding mass onboard.*

D. Sensitivity to Allowable Mission Effective Dose

The analysis to this point has imposed a limit on allowable mission effective dose. Now, we will explore the sensitivity of the results to this allowable mission effective dose. This will capture the impact of changing standards as career effective dose limits for deep space exploration are developed. Another reason to explore this sensitivity is that the make-up of the flight crew can alter the allowable mission effective dose. If the crew is composed entirely of first-time astronauts of the same gender and age, then this quantity can at most be selected to be the career limit for those astronauts. However, if the crew is made up of various genders and ages, the most stringent of their career limits must be used. Furthermore, if a crew member has previous flight experience, meaning that they have already accrued radiation exposure toward their career limit, the total allowable mission effective dose will need to be reduced accordingly. The impact of this allowable mission effective dose on the result for IMLEO vs. transit time is presented in Figure 9.

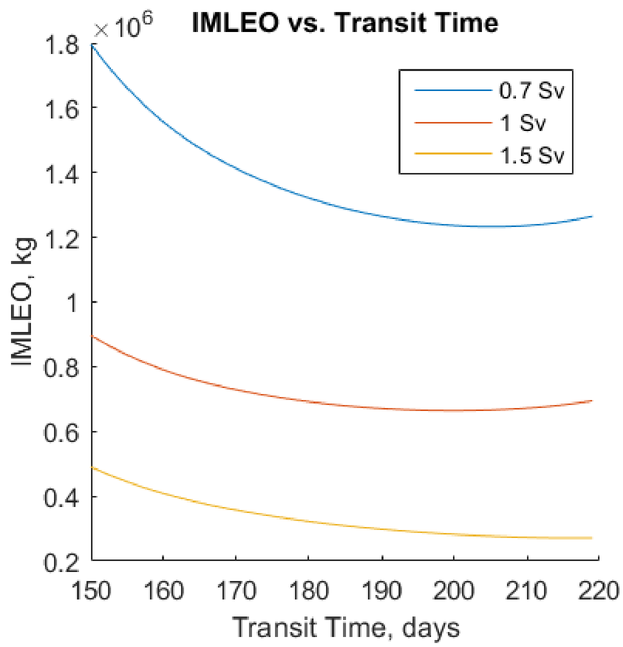


Figure 9. IMLEO as a function of transit time for various allowable mission effective doses. *This plot shows that changes in the allowable mission effective dose can significantly change IMLEO as well as the selection of transit time. Thus, the composition of the flight crew should be considered during mission planning. Based on NCRP-132 (see Table II) career limit standards, the 0.7 Sv mission corresponds to an age 25 male or an age 35 female. The 1.5 Sv mission corresponds to an age 45 male or an age 55 female. This result tends to favor older, male astronauts with no prior flight experience because they will enable selection of a mission with a high allowable mission effective dose, thus reducing IMLEO.*

The identified impact of allowable mission effective dose on IMLEO has implications on how yet-to-be-developed standards for allowable career limits in deep space will affect Mars mission planning. In addition, interesting considerations arise regarding the selection of age and gender of astronauts for Mars missions because NCRP limits depend on those factors. It's reasonable to desire that a diverse group of experienced astronauts with significant LEO flight hours would be selected for a Mars mission. However, selecting experienced astronauts will significantly reduce the allowable mission effective dose, which can have strong impacts on trajectory selection and shielding mass required, and hence IMLEO.

V. Conclusion

Future manned missions to Mars will inherently seek to mitigate radiation exposure to bring the total mission effective dose within acceptable limits. Common solutions to this problem include the use of passive radiation shields and faster transit times to reduce the required shielding mass. However, a true optimization of a Mars mission in the presence of an allowable mission effective dose constraint involves a tradeoff between transit time and shielding mass to arrive at a mission architecture with minimum IMLEO. This ensures crew safety while reducing the cost, complexity, and schedule constraints of placing large amounts of mass into orbit.

The framework presented in this paper provides a method to conduct this optimization by combining an astrodynamics solution to Lambert's problem with limits on career effective dose and models for the areal density of shielding required for a given effective dose rate. The ideal rocket equation is then used to determine the IMLEO required to transport the resulting transit habitat from Earth to Mars and back. The analysis process was carried out for a representative mission scenario, and the results showed significant IMLEO savings are possible through slightly faster transits. However, the notion that faster transits are always better from the perspective of radiation exposure was dispelled.

This analysis has computed the sensivity of results to recent changes in shielding models, which showed Mars mission planners must carefully monitor research developments in that area. In addition, exploring the sensitivity of results to the allowable mission effective dose revealed that careful selection of the age, gender, and flight experience of the crew must be considered in order to meet career limits on radiation exposure with a reasonable IMLEO. The framework presented in this paper allows for quantification of the effects of future developments in any of these driving parameters. This paper has shown that the potential for using ECLSS water as radiation shielding exists, at least under certain circumstances. In addition, intelligent positioning of available shielding materials, such as water and propellant on board the transit habitat can result in even better shielding performance (see Ref. 12).

When an allowable mission effective dose constraint is considered, the minimum IMLEO is obtained at a faster-than-Hohmann transfer because slow transfers require higher radiation shield mass. Reducing the transit time can, at least initially, reduce the shielding mass faster than the payload capacity lost through the rocket equation with a higher delta-V. The ability to utilize transit time as a free parameter to minimize IMLEO while still meeting radiation exposure constraints presents an exciting opportunity for reconciling the need for radiation mitigation with the realities of tight cost and mass budgets on Mars mission architectures.

Appendix

Table III below reports the values used in conducting the analysis presented in this paper.

Table III
VALUES USED IN ANALYSIS

Parameter	Value	Unit
Volume of transit habitat	100	m^3
Specific impulse	380	s
Number of Crew	4	#
Food consumption rate	1.8	kg/CM-day
Mass of transit habitat	50	mT
Earth parking orbit altitude	300	km
Mars parking orbit periapsis	250	km
Mars parking orbit period	5	sol
Mission allowable effective dose	1	Sv
Time spent in Mars orbit	500	days
Standard Gravity	9.8	m/s^2

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