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CONTINUOUS MARS HABITATION WITH A LIMITED NUMBER OF CYCLER VEHICLES

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This paper explores efficient ways to sustain a sizable colony on Mars. Various combinations of newly and previously discovered cycler and semi-cycler trajectories transport crews from Earth to a Mars base and back. It is assumed that the Mars base should never be abandoned and that the cycler vehicles safely and comfortably transport twelve people at a time. Since these cycler vehicles involve a significant investment, as few as possible should be built. The key trades are between the number of vehicles, the trajectory ΔV, and the crew mission duration. The trajectory ΔV drives propulsion system requirements and the mission duration affects the crew's health. One-, two-, and three-vehicle scenarios are presented for the colonization of Mars.

Keywords: Human Space Exploration, Mars Colonization Mission

1. INTRODUCTION

The appeal of travelling to Mars in a safe, comfortable, and (consequently) massive interplanetary transfer vehicle has produced much interest in cycler and semi-cycler trajectories. These trajectories replace propulsive manoeuvres at Earth, Mars, or both with gravity assists, thereby transferring the ΔV requirements of the transfer vehicle to a smaller taxi vehicle. Thus as the ratio of transfer vehicle to taxi mass increases, cyclers and semi-cyclers could become less expensive than traditional missions (i.e. architectures without gravity assists).

Assuming that the crew transits between Earth and Mars are short (at most one year) and that Mars is to be continuously inhabited, significant trades develop between the number of transfer vehicles, the duration the crew is away from Earth, and the trajectory ΔV requirements. In previous mission studies, it is assumed that the crew stays on Mars for approximately 1.5 years before returning to Earth, and that Mars is uninhabited for several months before the next crew arrives [1–12]. On the other hand, it may be prudent to construct a permanent base on Mars and continue exploration and development of Mars without interruption. In this case, the crew remains on Mars for two to four years, significantly increasing the time they are away from Earth. Also, transportation architectures have previously involved two [5,7], three [6,10], or four [11] cycler vehicles. Four different cycler and semi-cycler architectures are examined: 1) one outbound cycler vehicle with one inbound cycler, 2) two outbound cyclers with one inbound cycler, 3) one outbound cycler with two inbound cyclers, and 4) a single semi-cycler vehicle.

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2. MODELLING ASSUMPTIONS

The semi-cycler and cycler trajectories are modelled as conics in a point-mass gravity field. All gravity assists are modelled as instantaneous rotations of the V_∞ vector, and the minimum flyby altitude is 300 km above the planet's surface. Single-vehicle semi-cyclers are constrained to have a total time of flight (TOF) of less than one synodic period (780 days). The ΔV is minimized in all cases.

Earth taxis include a single upper stage to depart LEO and rendezvous with the cycler vehicle. Mars taxis include three stages: 1) a descent stage for landing, 2) an ascent stage to launch from the surface to low-Mars orbit, and 3) an upper stage to depart LMO and rendezvous with the cycler. The rendezvous ΔV is approximated as

$$\Delta V_{rendezvous} = \Delta B / \Delta T \qquad (1)$$

where ΔT is the rendezvous time (from circular orbit departure to docking) and B is the hyperbolic asymptote (or miss distance)

$$B = r_p \sqrt{1 + \frac{2\mu}{r_p V_\infty^2}} \qquad (2)$$

and μ is the gravitational parameter and r_p is the radius of periapsis.

Vehicle parameters are provided in Table 1, and the other mission assumptions are presented in Table 2. The Mars taxi and Mars surface consumables are sent to Mars on a minimum-energy (Hohmann-like) trajectory.

TABLE 1: *Vehicle Masses and Propulsion Systems [13,14].*

Parameter	Cycler	Earth Taxi	Mars Taxi
Cabin mass, t	100	20	20
Propulsion system	NTR[a]	NTR	LH2/LOX[b]
Specific impulse, s	900	900	450
$m_{inert}/m_{propellant}$	0.8	0.6	0.2

[a] Nuclear thermal rockets.
[b] Liquid hydrogen and liquid oxygen.

TABLE 2: *Mission Parameters.*

Parameter	Value
Crew size	12 people
Rendezvous time	3 days
Parking orbit period	3 days
Circular orbit altitude	200 km
Heatshield mass	15% of landed mass
Mars descent ΔV	0.500 km/s
Cargo	0 t
Cycler rebuilt every	15 synodic periods
Consumables	5 kg/person/day

3. RESULTS

3.1 One Outbound Vehicle and One Inbound Vehicle

The outbound (Earth-Mars) transfer is achieved by the one-synodic period cycler shown in Fig. 1 (the Aldrin cycler) [5]. Because this cycler repeats every synodic period, only one outbound vehicle is required. This cycler is based on a 2:1 Earth:spacecraft resonant transfer that is extended from 2 years to 2.14 years TOF. (This cycler orbit retains the two-year period of the 2:1 resonant trajectory.) A deep space manoeuvre (DSM) of 0.11 km/s near apoapsis is required each synodic period to maintain the Aldrin cycler trajectory in a circular coplanar solar-system model. Increasing this DSM to 0.92 km/s would lower the Mars V_∞ to 6.9 km/s and lower the Earth V_∞ to 5.1 km/s. Three deep-space manoeuvres of between 0.3 and 1.1 km/s are required every seven synodic periods to maintain the cycler in a more realistic model of the solar-system. The realistic solar-system model requires 15-year itineraries because Earth-Mars trajectories approximately repeat every seven synodic periods.

There is an inbound version of the Aldrin cycler, but the departure V_∞ at Mars is relatively large (i.e. 9.3 km/s in Fig. 1), which leads to prohibitive taxi masses. One solution (to reduce taxi mass) is to replace the inbound cycler with a Mars-Earth semi-cycler, which departs Mars, flies by Earth, then returns to Mars. There is potential for the V_∞ to decrease significantly because the Mars encounters are no longer constrained to be flybys and the TOF is no longer constrained to one synodic period. In order to minimize the number of vehicles, the semi-cycler TOF should be less than 780 days (26 months) so the same inbound vehicle can be used every opportunity. (Semi-cyclers with TOF longer than 780 days exist, but require more vehicles and less ΔV.)

A trajectory that has the same period as Mars (687 days) and a periapsis equal to Earth's orbit radius provides a good initial guess for a Mars-Earth semi-cycler. Because the spacecraft and Mars share the same orbital period, the spacecraft will encounter Mars after one revolution as long as Earth does not perturb the orbit. However, judicious use of Earth's gravity will lower the ΔV required from the spacecraft. The total ΔV for this trajectory comprises the departure manoeuvre from Mars orbit, any DSMs, and the arrival manoeuvre into a parking orbit for reuse. The optimised trajectory is presented in Fig. 2, where the Earth flyby altitude is 300 km and the total TOF is 780 days. With aerocapture, the DSM can be removed with an increase in arrival V_∞ to 7.9 km/s.

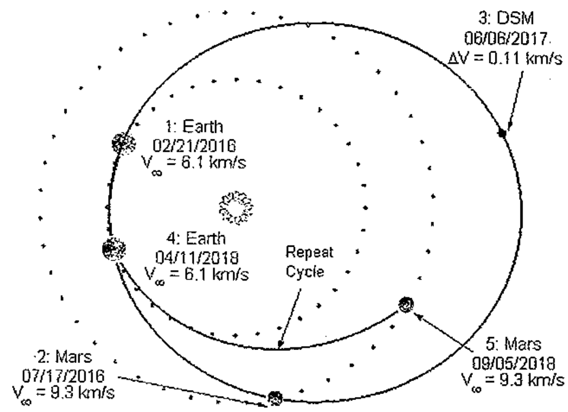

Fig. 1 Outbound Aldrin cycler with transit TOF of 147 days.

Because the TOF is one synodic period and the Mars-arrival and departure V_∞ are similar in Fig. 2, this semi-cycler can be molded into a cycler trajectory. The resulting cycler is presented in Fig. 3 (for the circular coplanar model) and in Table 3 (with integrated planetary ephemeredes), where the ΔV includes the cycler DSM and the taxi departure manoeuvre at Mars. This one-synodic-period cycler is fundamentally different than the Aldrin cycler as it is based on a 1:1 resonance with Mars while the Aldrin cycler is based on a 2:1 resonance with Earth. In fact, the local minimum of the DSM ΔV for the cycler in Fig. 3 is 1.5 km/s while the local minimum for the Aldrin cycler is 0.11 km/s. Because the taxi V_∞ in Fig. 3 is acceptable and the ΔV for the cycler is less than that of the semi-cycler, this new cycler is used for the inbound crew transfers.

The mission timeline is provided with the radial distance plot in Fig. 4. The crew departs Earth on February 21, 2016 and arrives at Mars 147 days later. Because Mars is to be continuously inhabited, the crew skips the return opportunity on April 19, 2018 and stays on Mars an extra 780 days until June 7, 2020, when they board the inbound cycler for a 173 day trip to Earth. The total mission duration (for the crew) is 4.8 years (58 months) with 3.9 years (47 months) on Mars. With the assumption that twelve people arrive at and depart from Mars each mission, there are 24 people on Mars for 641 days and 12 people for 139 days every synodic period.

3.2 Two Outbound Vehicles and One Inbound Vehicle

The scenario with two outbound cyclers is similar to the single cycler case, except the repeat time on the cycler trajectory is two synodic periods, requiring an extra transfer vehicle to complete an Earth-Mars transfer during every opportunity. This two-synodic period cycler is based on a 3:2 Earth:spacecraft resonant trajectory (1.5 year period) followed by a near 1.5 year Earth-Earth transfer (as in Fig. 5). The trajectory shifts

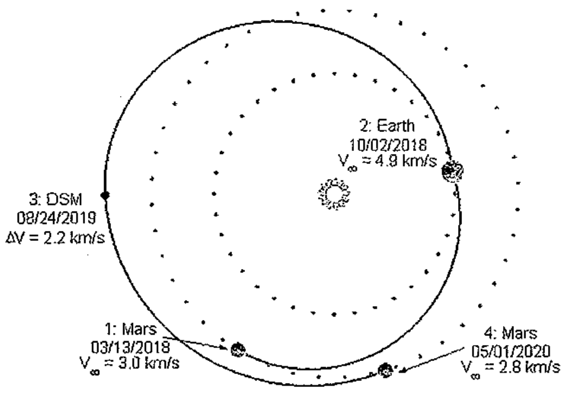

Fig. 2 Inbound Mars-Earth semi-cycler with transit TOF of 203 days.

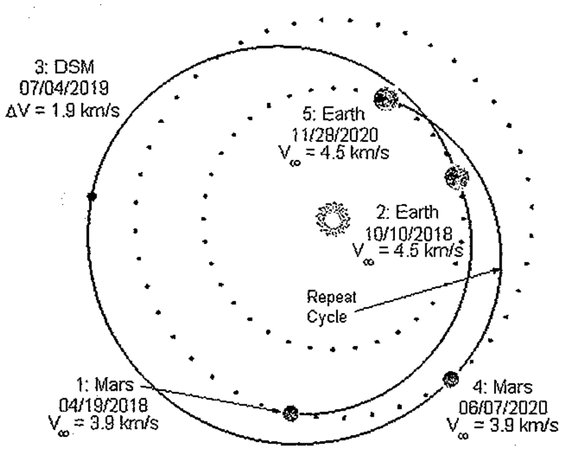

Fig. 3 New inbound cycler trajectory with transit TOF of 173 days and one-synodic period repeat time.

between the 3:2 and 1.5:1.5 resonances via Earth gravity assists. This sequence requires zero deterministic ΔV (even in the more accurate elliptical-inclined solar system as provided in Ref. 11) and is thus a ballistic cycler.

The return (Mars-Earth) crew transfer is achieved by the single inbound cycler vehicle (Fig. 3). The mission sequence is therefore 150 days to Mars, 1,366 days (45 months) on Mars, then 173 days back to Earth. The total trip time is 4.6 years with 3.7 years on Mars. This sequence is provided in more detail in Fig. 6. Again, assuming a crew of twelve for each mission, there are 24 people on Mars for 582 days and 12 people for 198 days every synodic period.

3.3 One Outbound Vehicle and Two Inbound Vehicles

In this scenario, the outbound trajectory is the traditional Aldrin cycler, and the inbound trajectory follows the ballistic cycler in Ref. 11. This inbound cycler is similar to the trajectory in Fig. 5, except the Mars encounter is phased to provide a 150-day Mars-Earth transfer. Because the inbound cycler is ballistic, no significant propulsion systems are required on these vehicles. (Propulsion is still required for attitude control and to target planetary flybys.) A propulsion system is required on the outbound cycler for deep-space manoeuvres during three missions in a seven mission cycle. (Earth-Mars trajectories approximately repeat every seven synodic periods.)

TABLE 3: *Itinerary for New Inbound Cycler.*

Encounter	Date mm/dd/yyyy	V_∞ or ΔV km/s	Altitude km	TOF Days
E-1	04/15/2010	4.824	5,700	
Manoeuvre	02/06/2011	2.263		
M-2	11/07/2011	4.769	300	571
E-3	05/24/2012	4.729	13,100	200
Manoeuvre	03/13/2013	2.017		
M-4	12/09/2013	4.051	1500	564
E-5	07/01/2014	4.647	32,400	203
Manoeuvre	04/25/2015	1.639		
M-6	01/31/2016	3.345	2600	579
E-7	08/04/2016	4.595	34,200	186
Manoeuvre	06/02/2017	1.478		
M-8	04/03/2018	2.689	300	607
E-9	09/28/2018	3.715	63,600	178
Manoeuvre	03/01/2019	2.289		
M-10	08/07/2020	5.730	300	679
E-11	12/17/2020	3.640	45,200	131
Manoeuvre	05/29/2021	2.096		
M-12	10/03/2022	7.977	300	655
E-13	02/16/2023	4.250	26,000	136
Manoeuvre	10/11/2023	1.775		
M-14	10/25/2024	7.297	300	617
E-15	03/31/2025	4.708	7600	157

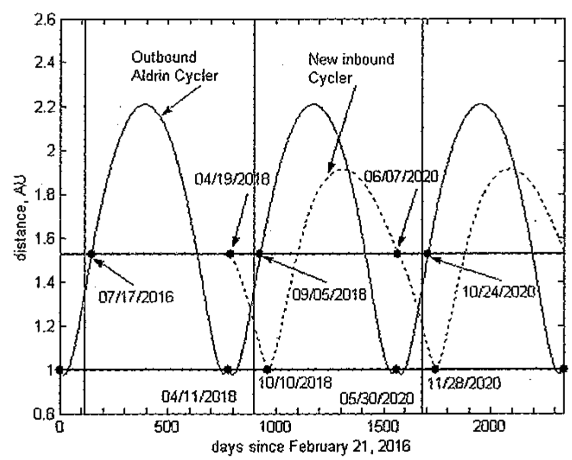

Fig. 4 Radial distances of outbound and inbound cyclers. Closed circles denote planetary encounters and the vertical lines denote dates of opposition.

3.4 One Outbound and Inbound Vehicle

It is noted that in Fig. 4 and Fig. 6, the outbound vehicle arrives at Mars a few months after opposition, while the inbound vehicle departs Mars a few months before opposition. As a result, the population on Mars is lower for several months each synodic period between the times that one crew departs and another one arrives. A possible solution is to "squeeze" the Mars departure and arrival dates together so that the new crew

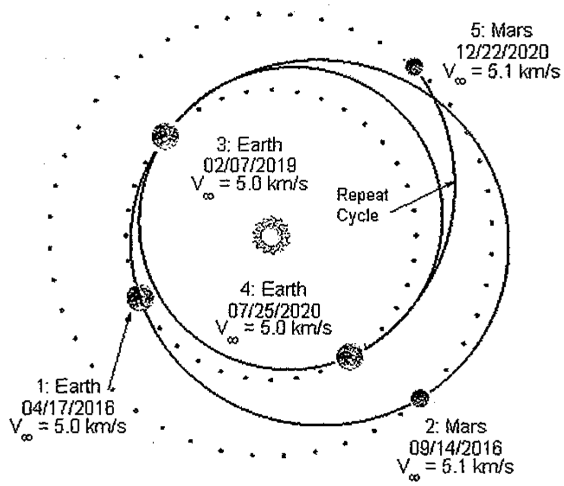

Fig. 5 Outbound cycler trajectory with two-synodic period repeat time.

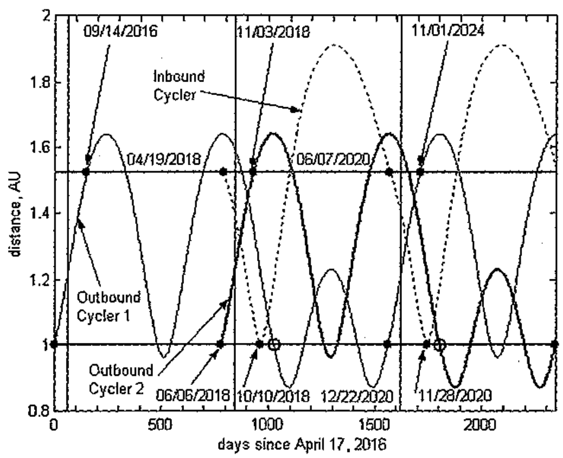

Fig. 6 Radial distances for two outbound cyclers and one inbound cycler. Closed circles denote arrival or departure flybys, open circles denote gravity assists, and vertical lines denote dates of opposition.

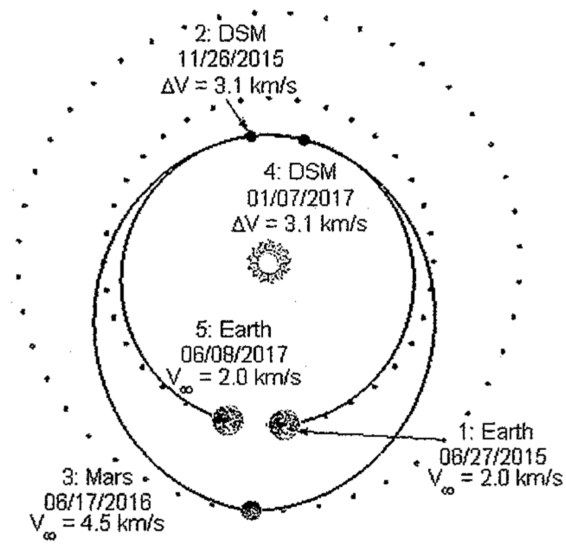

Fig. 7 Earth-Mars semi-cycler trajectory with one-synodic-period repeat time and 356-day transits between Earth and Mars.

arrives shortly before the previous crew departs. In this scenario, only one vehicle is required because the outbound and inbound transits may be performed by the same vehicle. Moreover, if the Mars arrival and departure occur on the same day, there is a possibility to replace a parking orbit at Mars with a gravity assist that sends the transfer vehicle back to Earth. Such trajectories that depart Earth, flyby Mars, then arrive back at Earth are called Earth-Mars semi-cyclers, as opposed to Mars-Earth semi-cyclers, which have a Mars-Earth-Mars sequence.

The trajectory in Fig. 7 begins at Earth (say in a parking orbit) takes 356 days to reach Mars, then returns to Earth 356 days after a Mars flyby. Because the total TOF is less than one synodic period, a single transfer vehicle may be reused to provide trips to Mars every synodic opportunity. This trajectory is reminiscent of a bi-elliptic transfer, where the vehicle follows a Hohmann transfer to a perihelion of about 0.8 AU, then a DSM pushes the aphelion to just above the orbit of Mars. A Mars gravity-assist rotates the line of apsides of this second ellipse, and the transfer vehicle again drops to a perihelion of 0.8 AU before a second DSM lowers aphelion back to 1 AU. This trajectory was optimised to minimize the sum of the departure manoeuvre at Earth, any DSMs, and the injection manoeuvre into a parking orbit. The Mars flyby occurs at an altitude of 1,040 km in the circular coplanar model. An itinerary for this trajectory with integrated planetary ephemeredes is presented in Table 4.

In Fig. 8 the Mars arrival and departure date occurs at opposition. The crew sequence begins on June 27, 2016 with a 356-day transfer to Mars. The crew remains on Mars for 780 days from June 7, 2016 until August 6, 2018. Then the crew departs Mars for another 356-day transfer to arrive at Earth on July 28, 2019. Here the total duration is 4.1 years with 2.1 years on Mars. The transfer TOF can be reduced from 356 days to 300 days with an additional 0.3 km/s of ΔV, or reduced from 356 days to 265 days for an extra 1.5 km/s ΔV. It may be possible to decrease the ΔV by applying a Venus flyby near perihelion [15]. Several other Earth-Mars trajectories with the Mars encounter centred at opposition and short transfer TOF are discussed by Wertz [16]. This trade in transfer TOF reduces the total mission duration, but the Mars stay time remains constant at 2.1 years. The transfer TOF in Table 4 is constrained to 300 days. Because the same number of people arrive at and depart Mars near the same time, the population on Mars is nearly constant. Assuming the cycler vehicle transports a crew of twelve, the number of people on Mars is only twelve as opposed to the cycling scenarios, where the population fluctuates between 24 and 12 people.

The transfer TOF could be extended to 390 days, placing the trajectory flight time at 780 days, or one synodic period. If the Earth departure and arrival manoeuvres are replaced with gravity assists, then the semi-cycler becomes a cycler with 390-day Earth-Mars transits. Though this transit TOF is relatively long, only one cycler vehicle is required. Comparatively, if only one vehicle travels along the trajectory in Fig. 1 or Fig. 3, then either the inbound or outbound TOF would exceed 600

TABLE 4: *Itinerary for One-Vehicle Earth-Mars Semi-Cycler.*

Encounter	Date mm/dd/yyyy	V_∞ or ΔV km/s	Altitude km	TOF Days
E-1	03/08/2009	6.402		
Manoeuvre	06/14/2009	2.982		
M-2	01/02/2010	4.667	300	300
Manoeuvre	08/15/2010	2.113		
E-3	10/29/2010	7.319		300
E-4	05/24/2011	7.248		207
Manoeuvre	08/11/2011	2.438		
M-5	03/19/2012	4.656	300	300
Manoeuvre	10/16/2012	2.908		
E-6	01/13/2013	6.706		300
E-7	10/07/2013	5.791		267
M-8	07/12/2014	4.440	300	278
Manoeuvre	12/07/2014	3.564		
E-9	05/08/2015	7.315		300
E-10	11/02/2015	6.141		178
M-11	07/24/2016	4.860	300	265
Manoeuvre	01/06/2017	2.330		
E-12	05/20/2017	4.872		300
E-13	12/21/2017	6.341		216
M-14	08/23/2018	4.882	300	244
Manoeuvre	02/20/2019	1.751		
E-15	06/19/2019	4.318		300
E-16	11/07/2019	4.303		141
Manoeuvre	03/07/2020	1.943		
M-17	09/02/2020	4.868	300	300
E-18	05/08/2021	5.998		249
E-19	12/02/2021	5.382		208
Manoeuvre	04/19/2022	2.647		
M-20	09/28/2022	4.759	300	300
E-21	06/24/2023	6.065		269

days. This cycler is not investigated further because the transfer times exceed one year and the ΔV is much greater than the DSMs of the other cyclers.

The injected mass to low-Earth orbit (IMLEO) using the vehicle characteristics in Table 1 and Table 2 and the trajectory data in Ref. 5, Table 3, Ref. 11, and Table 4 is provided in Table 5. Seven consecutive missions are examined to capture the approximate range of IMLEO values into the far future.

4. DISCUSSION

A preliminary comparison of these four scenarios, including the IMLEO, flight time, and number of vehicles required by each is given in Table 6. The one outbound vehicle with one inbound vehicle scenario only requires two transfer vehicles and is very similar to the Aldrin cycler. By starting with a different inbound "seed" trajectory, the undesirable launch V_∞ of 9.3 km/s with the inbound Aldrin cycler is reduced to 3.9 km/s with an extra 1.8 km/s of DSM ΔV required from the transfer vehicle each synodic period. While the DSM for the inbound cycler is relatively large, the ΔV is still less than that of Mars-Earth semi-cyclers. For the inbound cycler one complex (i.e. not "off the shelf") transfer vehicle and one complex propulsion system must be developed and maintained. (It is plausible that building and maintaining the propulsion systems could be just as expensive as the transfer vehicles.) Because the outbound cycler requires periodic adjustments (DSMs) to maintain its orbit and perhaps to mollify the extreme taxi entry speeds, a complex propulsion system is required for the outbound transfer vehicle part of the time (during three missions out of a seven mission cycle). Thus, the one outbound and one inbound vehicle scenario requires two reusable transfer vehicles and at least one, sometimes two, reusable propulsion systems. It is noted that using the new inbound cycler instead of the Aldrin cycler for the two-vehicle scenario reduced the IMLEO by about 40%.

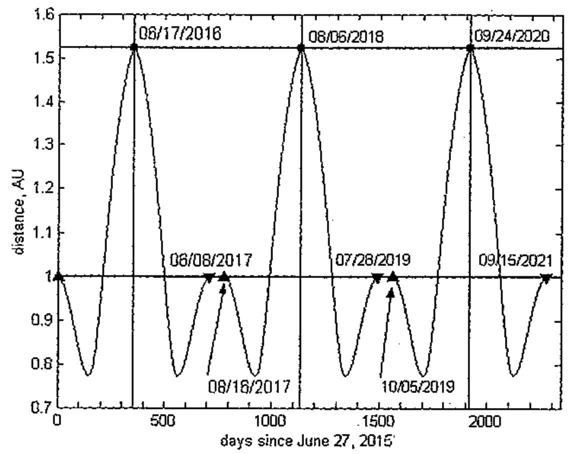

Fig. 8 Radial distance plot of the Earth-Mars semi-cycler in Fig. 7. ▲ denotes departure, ▼ denotes arrival, and • denotes flyby. Vertical lines are dates of opposition.

Another option is to replace one transfer vehicle and one propulsion system with two transfer vehicles and no (complex) propulsion systems. (An off-the-shelf system would perform small flyby targeting manoeuvres.) There are two options in this case: 1) two outbound vehicles and one inbound vehicle or 2) one outbound vehicle with two inbound vehicles. The one inbound vehicle option requires a propulsion system for every mission whereas the one-outbound vehicle option only requires a propulsion system for three of seven missions in a synodic cycle. As a result, the IMLEO is slightly less for the one outbound vehicle scenario, but the Mars entry speeds are higher than with two outbound cyclers. The mission timeline is very close to that of the one outbound and one inbound vehicle scenario, so there is little difference in the time that the crew is away from Earth.

The single inbound and outbound vehicle concept is a shift from the other cycling scenarios. The key benefit is that only one transfer vehicle and propulsion system must be built and maintained. Also, the total time a crew is away from Earth is only 3.6 to 4.1 years compared to 4.6 to 4.8 years with the cyclers. However, in this scenario the ΔV far exceeds that of the cycler trajectories. The reduction in number of vehicles and mission duration must be balanced against the additional ΔV (with larger propulsion systems and more propellant mass) necessary to transport a crew to Mars and back each synodic opportunity.

The single outbound and inbound vehicle scenario requires the most IMLEO and the population on Mars is usually lower than with the other architectures; however, only one transfer vehicle is required and the mission duration is about one year shorter. The one outbound and two inbound vehicle scenario has the lowest IMLEO and only requires a propulsion system

TABLE 5: *IMLEO for Different Mars Transportation Scenarios.*

Mission Year	One outbound[a] One inbound[a]	One outbound[a] One inbound[b]	Two outbound[c] One inbound[b]	One outbound[a] Two inbound[c]	One outbound and inbound
2009	1,950	1,060	1,110	910	2,670
2011	1,410	940	990	760	2,880
2014	1,430	840	880	730	1,990
2016	1,260	820	790	890	1,430
2018	2,050	1,210	1,170	1,520	1,320
2020	3,960	2,270	2,220	1,950	1,350
2022	3,050	1,730	1,730	1,330	1,570
Average	**2,158**	**1,270**	**1,270**	**1,160**	**1,890**

a. The Aldrin cycler [5].
b. The new inbound cycler.
c. The two-synodic period cycler [11].

TABLE 6: *Mission Characteristics for Four Different Scenarios.*

Mission Parameter	One outbound[a] One inbound[a]	One outbound[a] One inbound[b]	Two outbound[c] One inbound[b]	One outbound[a] Two inbound[c]	One outbound and inbound
Vehicles	2	2	3	3	1
Propulsion systems	0[d]	1[e]	1	0[d]	1
Average IMLEO, t	2,158	1,270	1,270	1,160	1,890
Mars population	24 people 82% 12 people 18%	24 people 82% 12 people 18%	24 people 75% 12 people 25%	24 people 75% 12 people 25%	12 people 100% of the time
Mission duration, yr	4.8	4.8	4.6	4.6	3.8

a. The Aldrin cycler [5].
b. The new inbound cycler.
c. The two-synodic period cycler [11].
d. One propulsion system is required on three of the seven missions in a synodic cycle.
e. Two propulsion systems are required on three of the seven missions in a synodic cycle.

for three missions in a seven mission cycle, but the arrival V_∞ at Mars can exceed 11 km/s. The one outbound and one inbound vehicle scenario with the new inbound cycler has about half the IMLEO as the original Aldrin cycler. The two outbound and one inbound vehicle scenario require the most vehicles and propulsion systems of the scenarios examined. However, this architecture has moderate IMLEO, it can sustain a sizable population on Mars, and the arrival V_∞ never exceeds 5 km/s at Earth or 8 km/s at Mars.

5. CONCLUSIONS

A large population on Mars may be sustained with the construction of between one and three reusable cycler vehicles and only one reusable cycler propulsion system. A single crew must remain on Mars for between 2.1 and 3.9 years to ensure that the infrastructure on Mars is never abandoned and to maintain full-time exploration. Assuming that nuclear thermal rockets are available, it is possible to sustain up to two dozen explorers on Mars for around 1,200 t in low-Earth orbit every synodic period.

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