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Tackling a Mars Cycler Design Head-on

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We approach the design of a conceptual Mars cycler that could accommodate major numbers of emigrant settlers to a Mars colony, regardless of how extreme or out-of-reach some of the required technologies might seem. It is commonly assumed that in the distant future, a significant planetary migration program might eventually take place for the establishment of a multi-planet species. Whereas some critics have questioned whether priorities for planetary colonization might be misplaced, others point out that there may only be a short window for humanity to become a space-faring civilization. Recently, Elon Musk of SpaceX has advocated for an accelerated settlement of Mars with a population of one million by the year 2050, using 1,000 Starships sent at each Earth-Mars launch opportunity. Setting aside discussions regarding the timing and appropriateness of such an ambitious endeavor, even though the numbers seem daunting there are engineering solutions that could make it work. While SpaceX has designed reusable transportation systems that could conceivably carry out the task, the sheer scale of launching, refueling, and carrying 100 persons per vessel across vast distances and durations will require significant logistical and technical considerations. We analyze the Musk targets, and realistically consider the problem from a human habitation perspective to ask what it would take to accommodate such large numbers in a transit scenario.

Acronyms and Nomenclature

AG = Artificial Gravity
AU = Astronomical Units
CAD = Computer Aided Design
ECLSS = Environmental Controll & Life-Support Systems
EVA = Extra-Vehiclular Activity
ISRU = In-Situ Resource Utilization
L1 = LaGrange Point 1
LEO = Low Earth Orbit
MEL = Mass & Equipment List
MMOD = Micro-Meteoroid and Orbital Debris shielding
SEP = Solar Electric Propulsion

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I. Introduction

THE planning and execution of an interplanetary human exploration mission will be orders of magnitude more difficult than cis-lunar missions. Getting the transportation system correct is only one of many aspects that are required to provide safe passage of any human explorers to and from the destination. Not only will there need to be infrastructure available on Earth to support launch and recovery of pressurized ascent/descent vehicles, but the same must also be well-established and functional at the target planet. Destination launch facilities will likely need to include propellant production using In-Situ Resource Utilization (ISRU) technologies. Launch of humans traveling to Mars should not even begin until the return trip is guaranteed, with full tanks ready to go (Zubrin et al 1991; Connolly et al 2017; Drake 2009). As we are grappling with the complex problems of how to send crews to Mars and back, with over 60 missions proposed since the 1960's (Crewed Mars Mission Plans 2025), some have discussed a further step of Mars colonization (Zubrin 2011; Boyle 2016; Kooser 2020; SpaceX 2024). Whereas some critics have questioned whether priorities for planetary colonization might be misplaced (Young & Docherty 2024, Maiwald et al 2024), others point out that there may only be a short window for humanity to become a space-faring civilization (Howe 2015).

Recently, Elon Musk of SpaceX has advocated for an accelerated settlement of Mars with a population of one million by the year 2050 (Boyle 2016; Kooser 2020), using 1,000 Starships sent at each Earth-Mars launch opportunity. While SpaceX has designed reusable transportation systems that could conceivably carry out the task (SpaceX 2024), the sheer scale of launching, refueling, and carrying 100 persons per vessel across vast distances and durations will require significant logistical and technical considerations. In this paper, we cannot address the very big 'elephant in the room' of Mars surface infrastructure, and assume that either such already exists or will be in progress by the time our concept is ready to fly.

Our proposed concept keeps SpaceX Starships (or their equivalent) at the heart of the transportation system for launch and eventual landing on the Mars surface but adds a Mars cycler component to the transit segment. Mars Cycler orbits have been proposed that would allow a transit vehicle to continually fly between Earth and Mars using very little propellant, and function as a regular transportation method for crews and passengers traveling back and forth between the two planets (Hollister 1969; Byrnes et al 1993; Chen et al 2012; Rogers et al 2015; Landau & Longuski 2007). We argue that 100 persons per Starship on a six-month mission duration would likely be dangerous to the psychological and physiological health of the passengers, even if they were all well-trained astronaut-explorers. For a typical non-professional clientele, we make the case that a practical cycler transit vessel would argue for more of a cruise-ship than a passenger ferry approach, which is likely what a 100-person Starship would feel like on a six-month journey. Considering the duration of each one-way trip, we advocate for an artificial gravity approach that will allow occupants to maintain muscle and bone density all the way to the destination. Using a toroidal structure that can be assembled robotically in Earth orbit, as proposed by Offworld Industries (Offworld Industries 2024), we calculate habitable volume, life-support systems, structure mass, shielding, logistics, and accommodation for a single vessel, and generate a Mass & Equipment List (MEL). We also discuss the use of Starships to launch the equipment and materials to manufacture the cycler, using a space robotic manufacturing system designed for the task, and calculate the propellant and rough trajectory for placing the cycler into the initial Earth-Mars cycle orbit based on delta-v proposed for cycler taxis (Rauwolf et al 2002). We also calculate the number of Starships needed to be available at Earth and Mars for resupply of the cycler and for shuttling passengers between the cycler and planet surface.

II. Back Up a Bit: Large-scale Space Construction

Before we start on a discussion of Earth-Mars transit vessels, we need to lay the groundwork for construction of very large orbital structures. Offworld Industries has proposed a robotic constructor that will be capable of assembling large pressurized structures in orbit.

The Offworld Industries 'Sargon' system (Figure 1) will require Earth-to-orbit launch transportation systems to deliver a variety of construction vehicles and materials to the construction site. Contrary to terrestrial construction projects, all materials, equipment, and construction machines must nominally be connected mechanically to each other, because every isolated body will have its own orbit. Even on large, sprawling connected sites, different parts of the structure will have their own center of mass and create strain in connected elements that must be dealt with. Proximate orbits though seemingly parallel, could eventually diverge and risk collisions head on at twice the orbital velocity. The construction system would allow for temporary separation for the purpose of material handling, but in general, most material handling and assembly should occur within the mechanically connected whole.

The Sargon system uses a series of cassette assemblers that can be linked together in rings. Each cassette can handle a stack of 2.5m x 2.5m panels (or fraction thereof), and linked together in a ring will be able to weld together panels into straight or curved cylindrical volumes. The cylindrical volume is variable for each structure, with circumference dimension driving the radius and diameter. For example, eight assembly cassettes linked into a ring will be able to weld together eight 2.5m panels such that the circumference becomes 20m, and 12 cassettes linked in a ring can create a circumference of 30m and so on (Figure 2). Because of the nature of the assembly, curved cylindrical volumes can also be constructed where the longest segment is 2.5m long, such that the curved volume comes around to meet itself in the form of a torus.

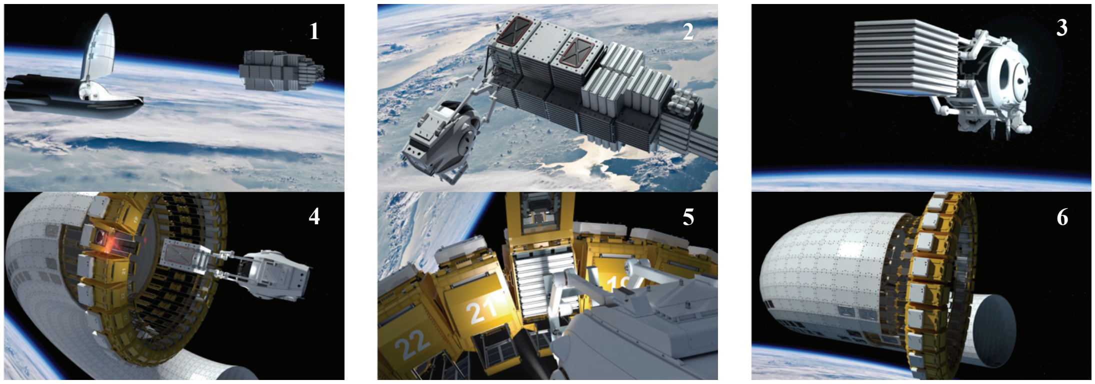


Figure 1: Sargon system material handling: (1) materials 'tree' delivered via Starship (or other contractor); (2) small robotic or crewed manipulator craft retrieving panel stack from materials 'tree'; (3) manipulator craft carrying panel stack; (4) approaching panel cassette at construction site; (5) insertion of panel stack into cassette; (6) assembly of panel into torus structure.

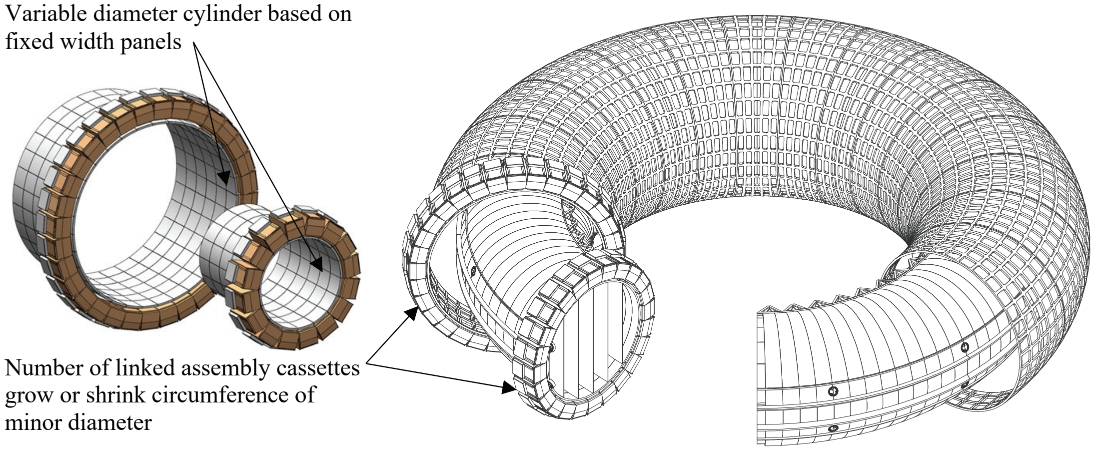


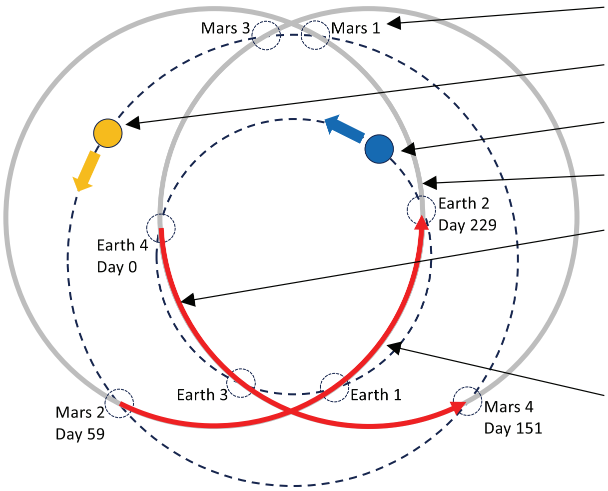
Figure 2: Sargon construction system is based on maximum panel sizes of 2.5m. Eight assembly cassettes linked together can assemble a cylinder of 20m circumference, 12 cassettes assemble a cylinder of 30m and so on.

One of the greatest challenges for the assembly of such a large structure will be tolerance control. Not only do the minor circumference panels need to come together in great precision, but getting a torus to close properly will be a major undertaking. Laser surveying and feducials will be employed to continually monitor the construction, and earth-based factories will be able to modify the panel curvature and interfaces during manufacture to address assembly needs in real time. Also, there are various fall-back alternatives for assembly, that might include guide rings, or constructing the torus in quarters and using adjustable, inflatable gap fillers for the final structure. For the scope of this paper, we will not go into the details of attitude control or maneuvering large quarter toroids in proximity to each other (with each respective center of mass on its own orbit), but assume that such a task will be possible without exotic solutions.

Though out of scope for this study, we have considered deployable thermal control with Micro-Meteoroid and Orbital Debris (MMOD) shielding spring-loaded from the welded hull panel, as well as robotically placed secondary and tertiary structure that could complete the outer torus once it has been fully welded together. Similarly, scarring for attachments, hatches, and windows would be manufactured into the center of the 2.5m panels to facilitate robotic orbital assembly of the main pressure vessel. Once the main toroidal volumes are completed, a known internal navigation system can be implemented for mobile robotic systems. A discussion of Offworld Industries' methods or details for the robotic assembly of modular interior secondary structures, utilities, flooring, partitions, crew systems, lighting, air-handling, and logistics stowage are out of scope for this study, and have multiple non-exotic solutions available. We also assume that some minor assembly and handling of logistics would be done manually by passengers and crew during transit.

III. Earth-Mars Transit: A Mars Cycler

In this study, what we are interested in is the transit portion of an Earth-Mars mission. Assuming that the first few human missions to Mars may follow the Conjunction Class (long-stay 496-day surface duration) or Opposition Class (short stay 30-day surface duration) missions as outlined by Drake (2009) and others (Connolly et al 2017; Zubrin et al 1991), a regular transit between the two worlds could be established once some surface infrastructure has been established on Mars. A Mars Cycler as proposed by Aldrin and others (Byrnes, Longuski & Aldrin 1993; Hollister 1969; Chen at al 2012; Landau & Longuski 2007; Rogers et al 2015) can be launched on mostly passive trajectories around both worlds with very little boost needed to maintain the trajectory indefinitely. Rauwolf, et al (2002) suggest that a 1,500 m/s boost every 15 years to maintain the cycler orbit could be accomplished with high-powered Solar Electric Propulsion (SEP) with a specific impulse of 5,000s, where propellant could regularly be refueled at each rendezvous. In particular Rauwolf, Friedlander, and Nock (2002) elaborate on 'up and down escalators' where two cyclers with mirroring trajectories allow for periodic transits for less than 180 days (six months). The 'up escalator' cycler, on which human crews would ride from Earth to Mars, would complete the transit in less than 180 days, but would continue on past Mars for a longer period until it comes back around for another human boarding encounter. Similarly, the mirrored 'down escalator' would allow for six-month Mars-Earth return transits (Figure 3).



Mars encounter points

Mars orbit (orange)

Earth orbit (blue)

Mars Cycler orbits (gray)

In this example, up escalator starts at Earth on Day 1, arriving at Mars on Day 151 for a total duration of 151 days. After the Mars encounter (Mars 4), the up escalator Cycler journey takes longer than 6 months to return to a useful encounter

In the same scenario, down escalator Cycler starts on Day 59 and arrives at Earth on Day 229, for a total duration of 170 days

Figure 3: Mars Cycler Up/Down escalator trajectories (Rauwolf, Friedlander, Nock 2002)

Our concept will make use of the Mars Cycler up and down escalator trajectories. In the context of this study we have not designed the SEP propulsion system for trajectory maintenance, but have made general calculations for how much propellant would be needed for departure to initially place the cycler in its perpetual orbit. Rauwolf et al (2002) assume the vehicle would start at Earth-Moon LaGrange Point 1 (L1) with a delta-v of 2,500 m/s to get onto the cycler trjectory, but since we are constructing the cycler at Low Earth Orbit (LEO) we calculate departure delta-v to be a little less than 5,000 m/s as per the following equation:

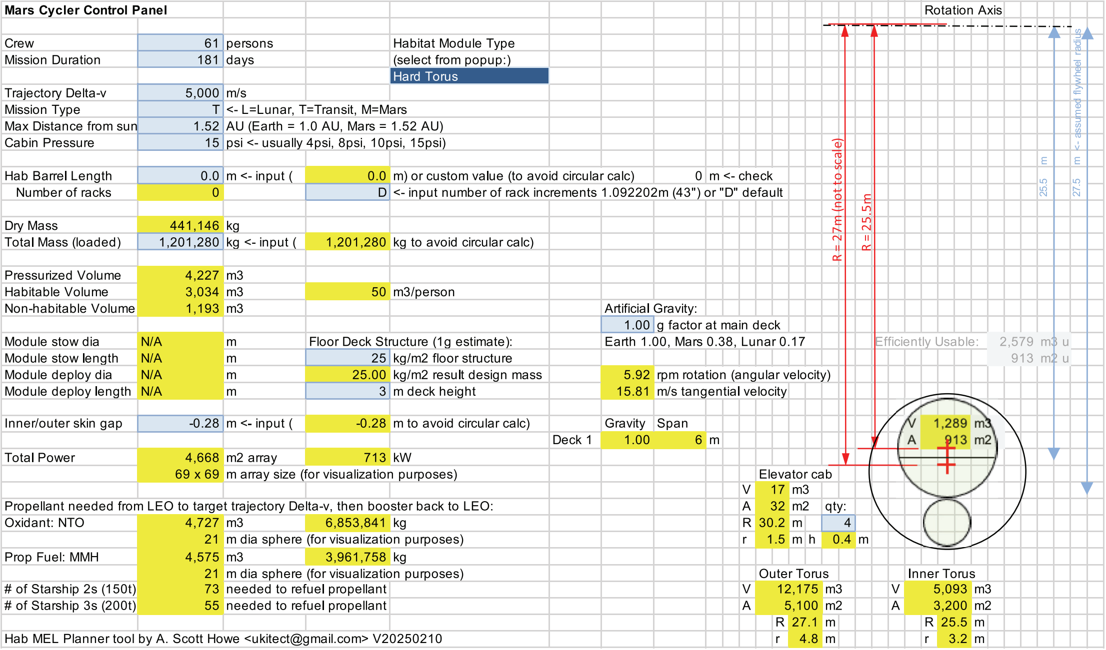
$$\Delta v = \sqrt{{v_{inf}}^2 + \frac{2GM}{r}} - \sqrt{\frac{GM}{r}} = 4{,}739 \text{ m/s}$$

Assumes that v-infinity = 6,000 m/s (Rauwolf, et al 2002), Earth GM = 3.986×10^{14} m^3s^2, Earth radius = 6,378,000 m, and LEO construction orbit altitude is 300,000 m.

IV. Minimal-sized Artificial Gravity Mars Cycler

For long-duration missions, there is still controversy on whether microgravity effects can be mitigated without resorting to artificial gravity (AG), which it was assumed would require complex centrifuges (Caiozzo et al 2009; Cardus 1994; Cramer 1985; Merz 1986; Mader et al 2011). Several authors discuss possible difficulties and complexities applying artificial gravity to spacecraft (Griffin 1978; Hall 2009; Hill & Schnitzer 1962; Joosten 2007) and possible workarounds (Landau 2008, Howe & Hall et al 2019). These include economic spin-up / spin-down, accommodation of multiple visiting vehicles that want to dock on the exact center of rotation, procedures for docking under spin, orientation of solar panels / radiators, spin / counterspin interfaces, Extra-Vehicular Activity (EVA) under spin, and ergonomics of activities to be performed by crew in a rotating environment, among others. Unfortunately, government contracts continue to avoid the inevitability of the need for an artifial gravity testbed (Howe & Hall 2019).

We believe that the Sargon space construction system provides a novel way of solving various problems with construction and operation of artificial gravity incorporated space platforms. We start with a flywheel approach. The use of a flywheel to cancel angular momentum and use electrical power for spin-up / spin-down rather than consume propellant was proposed by Sullivan (2002). Wheeled platforms linked around the inside of a toroidal volume have been proposed for motor-driven spin-up / spin-down including concepts described in science fiction (Hogan 1987, Howe 2023). Ruzicka (2024) goes into detail about how structural decoupling of large rotating structures from support frames can allow for significantly larger artificial gravity structures.


Mars Cycler Control Panel

Crew 61 persons
Mission Duration 181 days
Habitat Module Type
(select from popup:)
Hard Torus

Trajectory Delta-v 5,000 m/s
Mission Type T <- L=Lunar, T=Transit, M=Mars
Max Distance from sun 1.52 AU (Earth = 1.0 AU, Mars = 1.52 AU)
Cabin Pressure 15 psi <- usually 4psi, 8psi, 10psi, 15psi)

Hab Barrel Length 0.0 m <- input (0.0 m) or custom value (to avoid circular calc) 0 m <- check
Number of racks 0 D <- input number of rack increments 1.092202m (43") or "D" default

Dry Mass 441,146 kg
Total Mass (loaded) 1,201,280 kg <- input (1,201,280 kg to avoid circular calc)

Pressurized Volume 4,227 m3
Habitable Volume 3,034 m3 50 m3/person
Non-habitable Volume 1,193 m3

Artificial Gravity:
1.00 g factor at main deck
Earth 1.00, Mars 0.38, Lunar 0.17

Module stow dia N/A m
Module stow length N/A m
Module deploy dia N/A m
Module deploy length N/A m

Floor Deck Structure (1g estimate):
25 kg/m2 floor structure
25.00 kg/m2 result design mass
3 m deck height

5.92 rpm rotation (angular velocity)
15.81 m/s tangential velocity

Efficiently Usable: 2,579 m3 u
913 m2 u

Inner/outer skin gap -0.28 m <- input (-0.28 m to avoid circular calc)

Gravity Span
Deck 1 1.00 6 m

Total Power 4,668 m2 array 713 kW
69 x 69 m array size (for visualization purposes)

Elevator cab
V 17 m3
A 32 m2 qty:
R 30.2 m 4
r 1.5 m h 0.4 m

Propellant needed from LEO to target trajectory Delta-v, then booster back to LEO:
Oxidant: NTO 4,727 m3 6,853,841 kg
21 m dia sphere (for visualization purposes)
Prop Fuel: MMH 4,575 m3 3,961,758 kg
21 m dia sphere (for visualization purposes)
# of Starship 2s (150t) 73 needed to refuel propellant
# of Starship 3s (200t) 55 needed to refuel propellant

Outer Torus
V 12,175 m3
A 5,100 m2
R 27.1 m
r 4.8 m

Inner Torus
V 5,093 m3
A 3,200 m2
R 25.5 m
r 3.2 m

V 1,289 m3
A 913 m2

Hab MEL Planner tool by A. Scott Howe <ukitect@gmail.com> V20250210

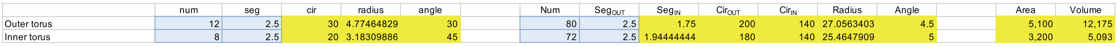
Figure 4: Minimal-sized Mars Cycler mission parameter control panel

We propose a stationary, non-rotating torus that can accommodate visiting vehicles docked to as many ports around the perimeter as needed, with a second smaller diameter pressurized torus inside, decoupled and rotating using a figure-eight-shaped null-flux coil suspension system. In addition to the inner rotating torus, a counter-rotating flywheel structure will share the center of mass and will cancel overall net angular momentum of the system. Finally, a series of linked elevator cabins will also be free to rotate as a system on its own flux coil suspension rails, to continually spin up to meet the inner torus, or de-spin to dock with the non-rotating outer torus to allow transfer of crew from visiting vehicles to the spinning inner torus. The elevator cabins will have enough volume to function as short-term refuges for all passengers on board, in case the inner torus needs to be evacuated for repairs. Decouplling the artificial gravity centrifuge from the outer non-rotating torus allows a variety of options for distributed docking ports for multiple visiting vehicles, mounting of fixed radiators and solar arrays without the need of gimbals or motorized mounts, and transfer of crew and cargo without spin-up or spin-down.

Mission parameters for the minimal-sized Mars Cycler are shown in Figure 4.

A. Mars Cycler Configuration

Since we have chosen the Offworld Industries Sargon construction system to assemble the cycler transit spacecraft, our first step is to determine the smallest sized torus that the system can construct. Using a simple tool 'SpinCalc' (Hall 2000) to understand various theories on how human crews might react to centrifuge radii, we determine that the minimal radius for comfortable 1g artificial gravity (as far as is known) will be 25 meters. Using that minimal radius as the driving factor, Sargon can construct the thinnest torus 'tube' using an eight cassette assembler ring (20 meter circumference) with 72 panels around the major torus circumference (180 meters). The resulting pressurized volume is 5,093 m^3 (Figure 5) with a habitable volume of 3,034m^3 that, divided by 50m^3 per person, results in a crew of 52-61 persons. Published sources (Eckart et al 1999, p438; Hanford 2004, p9) suggest medium duration missions of 28-180 days would need 30m^3 habitat +8m^3 laboratory volume per person, but since the cycler mission duration is close to the 181 day boundary, we assume 50m^3 +10m^3 per crew member.

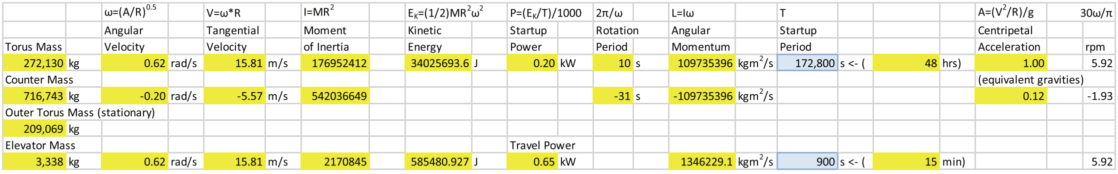


	num	seg	cir	radius	angle		Num	Seg_{OUT}	Seg_{IN}	Cir_{OUT}	Cir_{IN}	Radius	Angle		Area	Volume
Outer torus	12	2.5	30	4.77464829	30		80	2.5	1.75	200	140	27.0563403	4.5		5,100	12,175
Inner torus	8	2.5	20	3.18309886	45		72	2.5	1.94444444	180	140	25.4647909	5		3,200	5,093

Figure 5: Minimal-sized Cycler double torus construction parameters: outer non-rotating torus 'tube' has a circumference of twelve 2.5m panels = 30m, with a toroidal major circumference of 200m, consisting of eighty 2.5m panels; similarly, the pressurized inner torus has a minor circumference of 20m (eight panels), and major circumference of 180m (seventy-two panels)

The pressurized inner torus will be the rotating structure that simulates artificial gravity. Around this torus will be an outer torus that will remain stationary, or non-rotating, with figure-eight-shaped null-flux coils in a suspension system for the rotating inner torus and counter-rotating flywheel mass. The right side of Figure 4 shows a schematic of a scaled cross-section of the cycler inner torus with rotation axis, which determine the artificial gravity parameters (Figure 6), with outer torus and spin-up/spin-down elevator/airlock capsules.

On the control panel (Figure 4) we calculate that the cycler will have a total mass of 1,201,280kg, as tallied by the Mass & Equipment List (MEL) shown on the following pages (Figure 8, Figure 9, Figure 10, Figure 11). It would take nine Starship 2 launches (150 ton capacity each), or seven Starship 3 launches (200 ton capacity each) to deliver all the materials for the minimal-sized cycler to the orbital construction site, plus more flights for the assembly equipment which would remain in orbit.



		$\omega=(A/R)^{0.5}$		$V=\omega*R$		$I=MR^2$		$E_K=(1/2)MR^2\omega^2$		$P=(E_K/T)/1000$		$2\pi/\omega$		$L=I\omega$		T				$A=(V^2/R)/g$		$30\omega/\pi$
		Angular		Tangential		Moment		Kinetic		Startup		Rotation		Angular		Startup				Centripetal		
Torus Mass		Velocity		Velocity		of Inertia		Energy		Power		Period		Momentum		Period				Acceleration		rpm
272,130	kg	0.62	rad/s	15.81	m/s	176952412		34025693.6	J	0.20	kW	10	s	109735396	kgm^2/s	172,800	s <- (	48	hrs)	1.00		5.92
Counter Mass																				(equivalent gravities)		
716,743	kg	-0.20	rad/s	-5.57	m/s	542036649						-31	s	-109735396	kgm^2/s					0.12		-1.93
Outer Torus Mass (stationary)																						
209,069	kg																					
Elevator Mass										Travel Power												
3,338	kg	0.62	rad/s	15.81	m/s	2170845		585480.927	J	0.65	kW			1346229.1	kgm^2/s	900	s <- (	15	min)			5.92

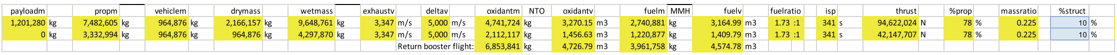
Figure 6: Minimal-sized Cycler artificial gravity parameters

B. Artificial Gravity Design

The minimal-sized Mars Cycler will rotate at 0.62 radians/second, or 5.92 revolutions per minute, which we consider to be the extreme upper end of the range for human comfort. Tangential velocity will be 15.81 m/s. The counter-rotating flywheel mass which would share the center of mass with the inner torus, in order to cancel out angular momentum to keep the outer torus non-rotating, will need to rotate at 1.93 rpm in the opposite direction.

C. Chemical Propulsion System

In order to thrust the vehicle 5,000 m/s delta-v needed to achieve the cycler orbit, a pair of massive propellant tanks each 21m in diameter will be required (similar to Figure 14, left). Offworld Industries has designed a system using linked panel-stack cassette assemblers that will be able to assemble arbitrarily large-scale hemispherical structures in orbit that would form the basis of these large propellant tanks. Since they are not launched from the surface, these tanks would need to be refilled in orbit, by multiple Starship launches. Because the propellant will be sitting in the tanks for long periods of time until they are filled, we chose a more stable fuel that would have diminished tendency for evaporation loss.



payloadm		propm		vehiclem		drymass		wetmass		exhaustv		deltav		oxidantm	NTO	oxidantv		fuelm	MMH	fuelv		fuelratio		isp		thrust		%prop		massratio		%struct	
1,201,280	kg	7,482,605	kg	964,876	kg	2,166,157	kg	9,648,761	kg	3,347	m/s	5,000	m/s	4,741,724	kg	3,270.15	m3	2,740,881	kg	3,164.99	m3	1.73 :1		341	s	94,622,024	N	78	%	0.225		10	%
0	kg	3,332,994	kg	964,876	kg	964,876	kg	4,297,870	kg	3,347	m/s	5,000	m/s	2,112,117	kg	1,456.63	m3	1,220,877	kg	1,409.79	m3	1.73 :1		341	s	42,147,707	N	78	%	0.225		10	%
													Return booster flight:	6,853,841	kg	4,726.79	m3	3,961,758	kg	4,574.78	m3												

Figure 7: Minimal-sized Cycler delta-v and propellant requirements to insert into cycler orbit, and allow for booster to decelerate and return to Earth orbit for reuse

The oxidizer we chose in our study is Nitrogen Tetroxide N_2O_4, with Monomethyl Hydrazine CH_3NHNH_2 fuel. According to our calculations, this would require seventy-three Starship 2 launches, or fifty-five Starship 3 launches to completely refuel the behemoth booster with both oxidant and fuel (Figure 7). Our choice of stable MMH/N2O4 as a departure propellant was purely for this study only, and for safety purposes would need to be revisited for actual systems of this scale. In reality, 50-70 Starship launches carrying toxic propellant may pose a significant environmental risk.

D. Mission Profile

The mission profile would begin in LEO using the large orbit-built booster to achieve 5,000m/s delta-v for insertion into the cycler orbit. Once the cycler vehicle is in that orbit, only minor adjustments would be needed to perpetually keep the trajectory, so the booster stage would simply be carried along on its way to Mars. In this study, we have not designed any attitude control or thruster system for maintaining the cycler orbit, but we assume this could be accomplished with electric propulsion ion thrusters using current technology. When the crew departs at Mars, the cycler vehicle will continue on the cycler orbit in a long elliptical trajectory beyond the 1.52 Astronomical Units (AU) of Mars orbit until the next Earth encounter. This leg of the trip beyond Mars would exceed the 181 day mission duration for human crews, and would also exceed recommended yearly exposure limits to Galactic Cosmic Rays (GCR) radiation. Since the cycler is only stocked for the shorter Earth-Mars mission leg, an entire crew would not be able to make the complete multi-year round trip back to Earth, but it is recommended that the leg beyond Mars would be crewless, using automated means for maintaining the habitat and onboard systems. During this entire outbound leg of the initial trip, the booster stage would still be hitching a ride on the passive cycler orbit. Finally, when the cycler approaches one complete loop for the next Earth encounter, we have calculated enough propellant to remain in the booster for it do undock and decelerate back into LEO to refuel and reuse for a second cycler insertion.

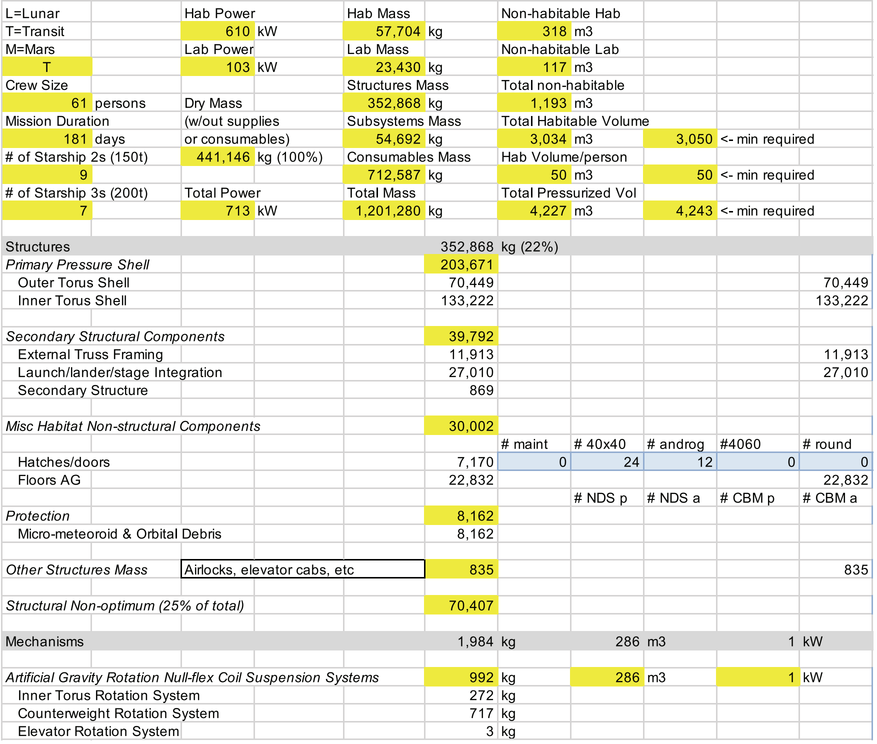
E. Mass & Equipment List (MEL)

The Mass & Equipment List (MEL) is driven by the number of crew and mission duration, as listed in the control panel in Figure 4, as well as unique geometries that can be obtained from an accurate Computer Aided Design (CAD) model. Our MEL for a minimal-sized Mars Cycler is divided into a breakdown structure shown in Figure 8, Figure 9, Figure 10, and Figure 11, which should all be considered together rather than individually. In other words, the habitat MEL (Figure 10) does not contain any structure elements, which are bookkept in the Figure 8 portion of the MEL.

The MEL, starting with Structures in Figure 8, was calculated based on several published sources. Mass estimates for the outer and inner torus shell structure and external truss framing, which will be welded panels assembled by the Offworld Industries cassette assembler rings, and also AG floors and elevator cabs were calculated using CAD models and area masses based on the surface area of toroidal geometries. The AG null-flex coil suspension system for levitating the inner torus within the outer torus will consist of thin superconducting elements.

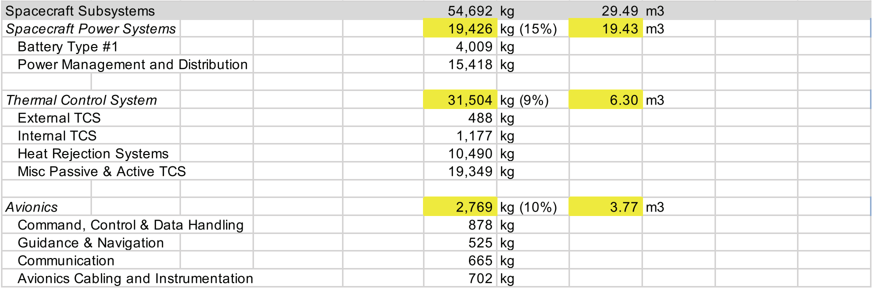
The levitation system mass was difficult to estimate due to the lack of published sources, but we assumed 1/1,000th of the mass to be levitated for both the inner torus and counter-rotating flywheel. Structure for the levitation system is bookkept elsewhere, so the stated mass accounts only for the superconducting elements. These mass numbers can be adjusted later when more detailed system information becomes available.

The Spacecraft MEL (Figure 9) began with a percentage rule of thumb for spacecraft systems suggested in Petro (1999, p410). Power, thermal, and avionics system figures were multiplied per every 10 persons in the crew.



L=Lunar		Hab Power		Hab Mass		Non-habitable Hab				
T=Transit		610	kW	57,704	kg	318	m3			
M=Mars		Lab Power		Lab Mass		Non-habitable Lab				
T		103	kW	23,430	kg	117	m3			
Crew Size				Structures Mass		Total non-habitable				
61	persons	Dry Mass		352,868	kg	1,193	m3			
Mission Duration		(w/out supplies		Subsystems Mass		Total Habitable Volume				
181	days	or consumables)		54,692	kg	3,034	m3	3,050	<- min required	
# of Starship 2s (150t)		441,146	kg (100%)	Consumables Mass		Hab Volume/person				
9				712,587	kg	50	m3	50	<- min required	
# of Starship 3s (200t)		Total Power		Total Mass		Total Pressurized Vol				
7		713	kW	1,201,280	kg	4,227	m3	4,243	<- min required	
Structures					352,868	kg (22%)				
Primary Pressure Shell					203,671					
Outer Torus Shell					70,449					70,449
Inner Torus Shell					133,222					133,222
Secondary Structural Components					39,792					
External Truss Framing					11,913					11,913
Launch/lander/stage Integration					27,010					27,010
Secondary Structure					869					
Misc Habitat Non-structural Components					30,002					
						# maint	# 40x40	# androg	#4060	# round
Hatches/doors					7,170	0	24	12	0	0
Floors AG					22,832					22,832
							# NDS p	# NDS a	# CBM p	# CBM a
Protection					8,162					
Micro-meteoroid & Orbital Debris					8,162					
Other Structures Mass		Airlocks, elevator cabs, etc			835					835
Structural Non-optimum (25% of total)					70,407					
Mechanisms					1,984	kg	286	m3	1	kW
Artificial Gravity Rotation Null-flex Coil Suspension Systems					992	kg	286	m3	1	kW
Inner Torus Rotation System					272	kg				
Counterweight Rotation System					717	kg				
Elevator Rotation System					3	kg				

Figure 8: Minimal-sized Cycler MEL Mass & Equipment List (structures & mechanisms)

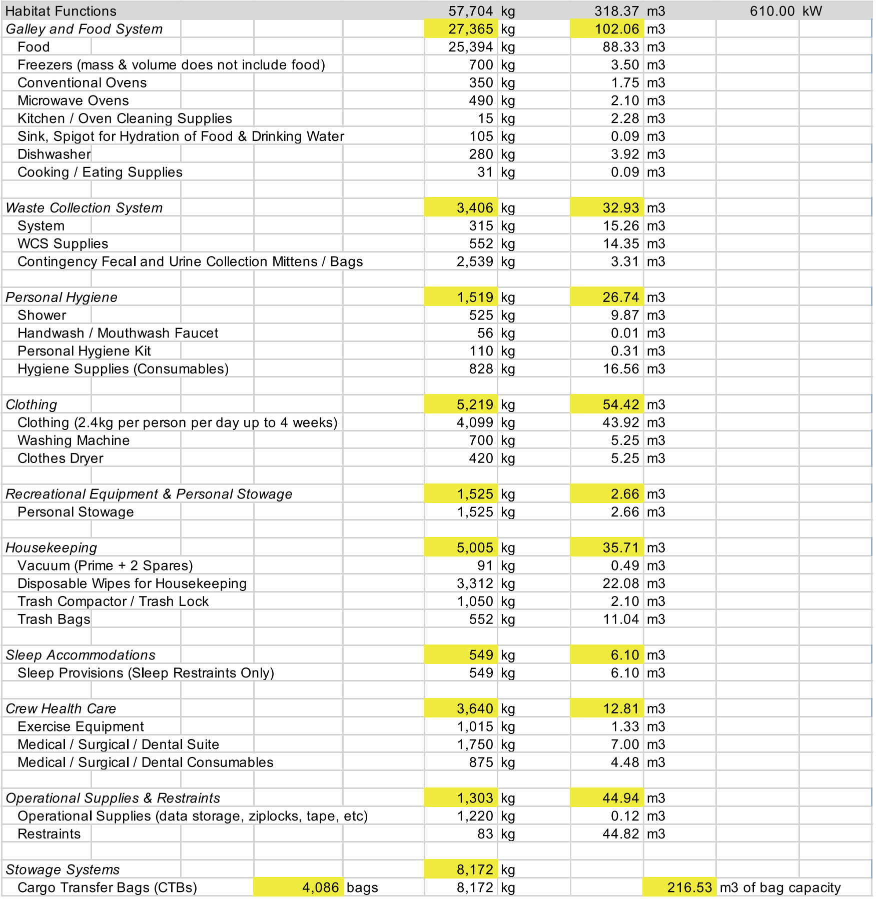


Spacecraft Subsystems				54,692	kg	29.49	m3	
Spacecraft Power Systems				19,426	kg (15%)	19.43	m3	
Battery Type #1				4,009	kg			
Power Management and Distribution				15,418	kg			
Thermal Control System				31,504	kg (9%)	6.30	m3	
External TCS				488	kg			
Internal TCS				1,177	kg			
Heat Rejection Systems				10,490	kg			
Misc Passive & Active TCS				19,349	kg			
Avionics				2,769	kg (10%)	3.77	m3	
Command, Control & Data Handling				878	kg			
Guidance & Navigation				525	kg			
Communication				665	kg			
Avionics Cabling and Instrumentation				702	kg			

Figure 9: Minimal-sized Cycler MEL (spacecraft)

Habitat MEL numbers (Figure 10) are based off of published recommendations per person per day of mission duration (Stilwell et al 1999, p596). Again it must be stressed that our MEL should be understood to be a formulation-level estimate that can be adjusted in later cycles of the design process, but we have performed all calculations based on the published sources. For example, it was our inclination to remove all exercise equipment from the MEL, understanding that such might be optional in a 1-g artificial gravity environment that does not require all crew and passengers to perform two hours of rigorous equipment-enabled exercize per day, but we decided to include it to maintain the line item suggested by published sources. Any adjustments up or down can easily be performed in later iterations of the design cycles.

Laboratory MEL numbers (Figure 11) are also partly based on Stilwell et al (1999), with physio-chemical Environmental Control and Life-Support Systems (ECLSS) as recommended by Doll et al (1999, p554, p558). Extra-Vehicular Activity (EVA) suit, tools & equipment, and airlock masses are also from published sources (Griffin et al 1999, p709). Assuming that a Mars Cycler would consist of both crew members and possibly non-working passengers, the laboratory and EVA mass calculations have been multiplied per every 100 persons onboard.



Habitat Functions			57,704	kg	318.37	m3	610.00	kW
Galley and Food System			27,365	kg	102.06	m3		
Food			25,394	kg	88.33	m3		
Freezers (mass & volume does not include food)			700	kg	3.50	m3		
Conventional Ovens			350	kg	1.75	m3		
Microwave Ovens			490	kg	2.10	m3		
Kitchen / Oven Cleaning Supplies			15	kg	2.28	m3		
Sink, Spigot for Hydration of Food & Drinking Water			105	kg	0.09	m3		
Dishwasher			280	kg	3.92	m3		
Cooking / Eating Supplies			31	kg	0.09	m3		
Waste Collection System			3,406	kg	32.93	m3		
System			315	kg	15.26	m3		
WCS Supplies			552	kg	14.35	m3		
Contingency Fecal and Urine Collection Mittens / Bags			2,539	kg	3.31	m3		
Personal Hygiene			1,519	kg	26.74	m3		
Shower			525	kg	9.87	m3		
Handwash / Mouthwash Faucet			56	kg	0.01	m3		
Personal Hygiene Kit			110	kg	0.31	m3		
Hygiene Supplies (Consumables)			828	kg	16.56	m3		
Clothing			5,219	kg	54.42	m3		
Clothing (2.4kg per person per day up to 4 weeks)			4,099	kg	43.92	m3		
Washing Machine			700	kg	5.25	m3		
Clothes Dryer			420	kg	5.25	m3		
Recreational Equipment & Personal Stowage			1,525	kg	2.66	m3		
Personal Stowage			1,525	kg	2.66	m3		
Housekeeping			5,005	kg	35.71	m3		
Vacuum (Prime + 2 Spares)			91	kg	0.49	m3		
Disposable Wipes for Housekeeping			3,312	kg	22.08	m3		
Trash Compactor / Trash Lock			1,050	kg	2.10	m3		
Trash Bags			552	kg	11.04	m3		
Sleep Accommodations			549	kg	6.10	m3		
Sleep Provisions (Sleep Restraints Only)			549	kg	6.10	m3		
Crew Health Care			3,640	kg	12.81	m3		
Exercise Equipment			1,015	kg	1.33	m3		
Medical / Surgical / Dental Suite			1,750	kg	7.00	m3		
Medical / Surgical / Dental Consumables			875	kg	4.48	m3		
Operational Supplies & Restraints			1,303	kg	44.94	m3		
Operational Supplies (data storage, ziplocks, tape, etc)			1,220	kg	0.12	m3		
Restraints			83	kg	44.82	m3		
Stowage Systems			8,172	kg				
Cargo Transfer Bags (CTBs)	4,086	bags	8,172	kg		216.53	m3 of bag capacity	

Figure 10: Minimal-sized Cycler MEL (habitat)

Power needs for both the habitat and laboratory were calculated on a per-capita basis from Eckart et al (1999), and null-flex coil levitation / suspension system startup and maintenance power requirements were calculated from the total masses of the inner torus, flywheel, and elevator operation.

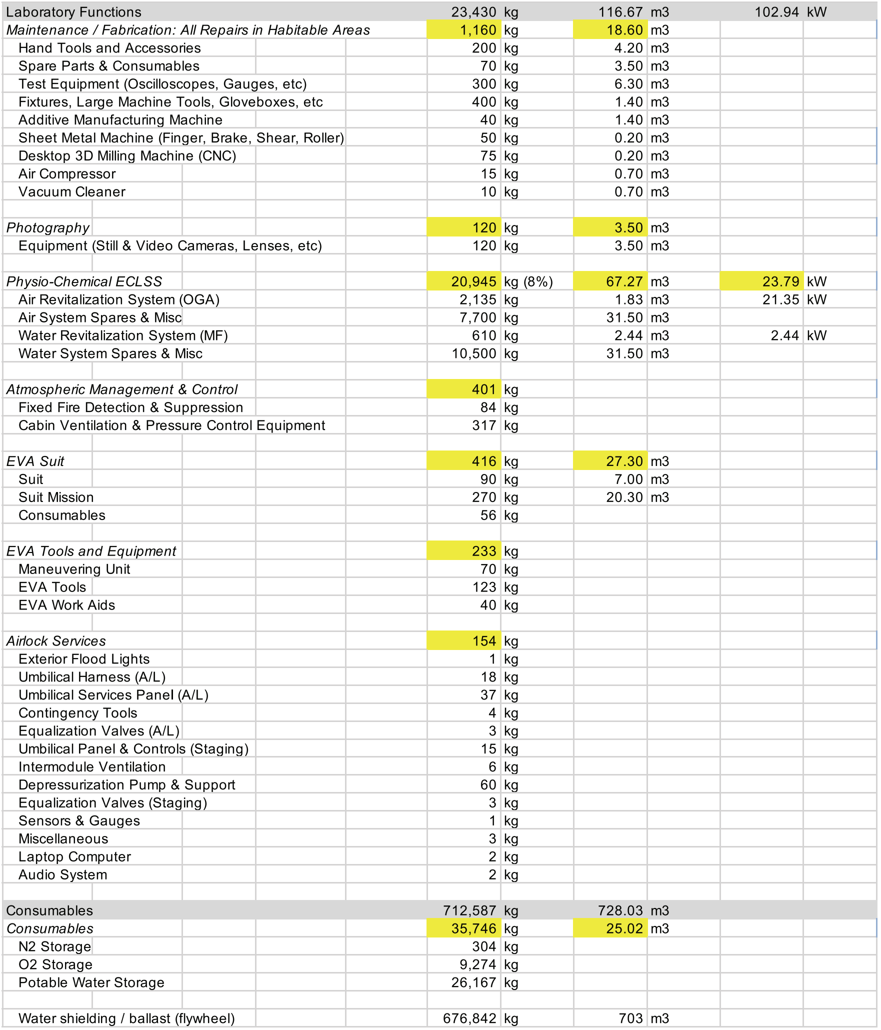
Lastly, the Consumables section of the MEL is based off of published sources (Grenouilleau 1999, p930; Reed & Coulter 1999, p122, p125).

We also account for 0.26m thickness water shield around the inner torus for radiation shielding (located in the flywheel), which would be required for a long-duraton mission in interplanetary space to keep the yearly dose limits of the crew and passengers within recommended levels. These numbers are based on recommended shielding as per the literature (Dobynde & Shprits 2020; Dobynde et al 2021).

F. Minimal-sized Mars Cycler Summary

Final masses tallied up from the MEL are divided into Inner Torus mass 272,130kg, Counter-rotating Flywheel mass 716,743kg, Outer Torus non-rotating mass 209,069kg, and Elevator mass 3,338kg. The propellant and mission profile are described for a fully loaded (not including crew and passengers) minimal-sized artificial gravity Mars Cycler. In this quick study, the four categories of masses have 'borrowed' some systems, logistics, and equipment from the MEL to populate the counter-rotating flywheel mass. Crews could access stowage and logistics stored in the flywheel by entering the elevator cabs, slowing down the elevator spin to zero matching the outer torus, then counterspinning until the flywheel rotation rate is matched. At that point any needed stowage could be transferred to the elevator, or trash, garbage, refuse placed in the flywheel as needed. However, in reality masses would be distributed based on various complex balances, centers of gravity, and according to whether an interface would be needed to pass material between rotating segments.

The problem with rotational interfaces has not been discussed in the context of this paper, and may prove to be challenging to solve. We have some concepts for transferring power, control, information, and even liquids between rotating segments, but more work needs to be done on these challenges.



Laboratory Functions	23,430	kg	116.67	m3	102.94	kW
Maintenance / Fabrication: All Repairs in Habitable Areas	1,160	kg	18.60	m3		
Hand Tools and Accessories	200	kg	4.20	m3		
Spare Parts & Consumables	70	kg	3.50	m3		
Test Equipment (Oscilloscopes, Gauges, etc)	300	kg	6.30	m3		
Fixtures, Large Machine Tools, Gloveboxes, etc	400	kg	1.40	m3		
Additive Manufacturing Machine	40	kg	1.40	m3		
Sheet Metal Machine (Finger, Brake, Shear, Roller)	50	kg	0.20	m3		
Desktop 3D Milling Machine (CNC)	75	kg	0.20	m3		
Air Compressor	15	kg	0.70	m3		
Vacuum Cleaner	10	kg	0.70	m3		
Photography	120	kg	3.50	m3		
Equipment (Still & Video Cameras, Lenses, etc)	120	kg	3.50	m3		
Physio-Chemical ECLSS	20,945	kg (8%)	67.27	m3	23.79	kW
Air Revitalization System (OGA)	2,135	kg	1.83	m3	21.35	kW
Air System Spares & Misc	7,700	kg	31.50	m3		
Water Revitalization System (MF)	610	kg	2.44	m3	2.44	kW
Water System Spares & Misc	10,500	kg	31.50	m3		
Atmospheric Management & Control	401	kg				
Fixed Fire Detection & Suppression	84	kg				
Cabin Ventilation & Pressure Control Equipment	317	kg				
EVA Suit	416	kg	27.30	m3		
Suit	90	kg	7.00	m3		
Suit Mission	270	kg	20.30	m3		
Consumables	56	kg				
EVA Tools and Equipment	233	kg				
Maneuvering Unit	70	kg				
EVA Tools	123	kg				
EVA Work Aids	40	kg				
Airlock Services	154	kg				
Exterior Flood Lights	1	kg				
Umbilical Harness (A/L)	18	kg				
Umbilical Services Panel (A/L)	37	kg				
Contingency Tools	4	kg				
Equalization Valves (A/L)	3	kg				
Umbilical Panel & Controls (Staging)	15	kg				
Intermodule Ventilation	6	kg				
Depressurization Pump & Support	60	kg				
Equalization Valves (Staging)	3	kg				
Sensors & Gauges	1	kg				
Miscellaneous	3	kg				
Laptop Computer	2	kg				
Audio System	2	kg				
Consumables	712,587	kg	728.03	m3		
Consumables	35,746	kg	25.02	m3		
N2 Storage	304	kg				
O2 Storage	9,274	kg				
Potable Water Storage	26,167	kg				
Water shielding / ballast (flywheel)	676,842	kg	703	m3		

Figure 11: Minimal-sized Cycler MEL (laboratory)

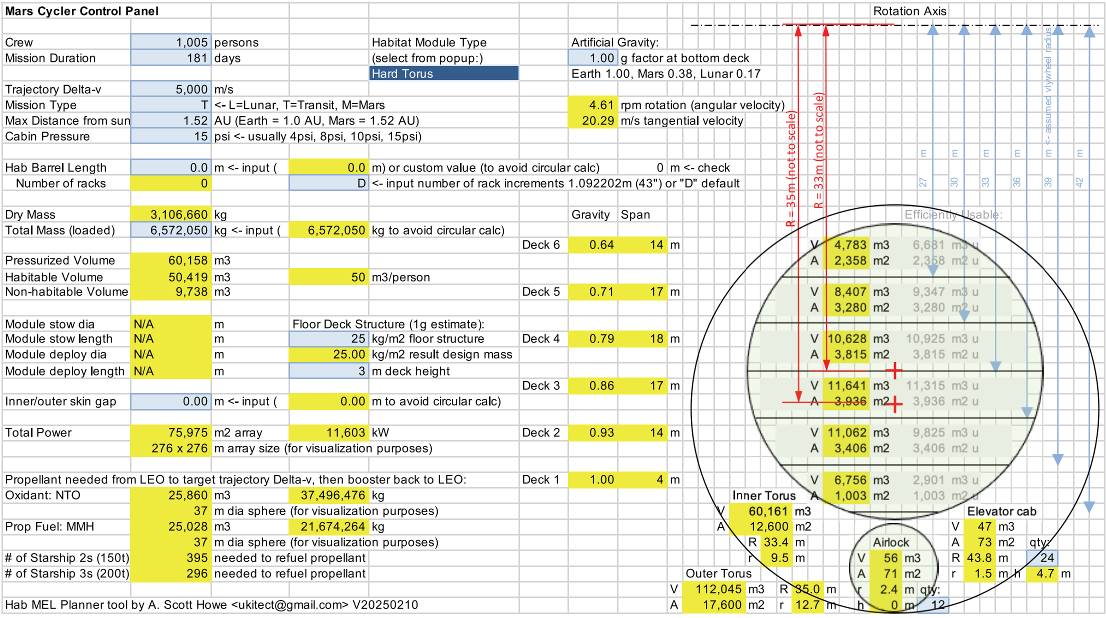
Water radiation shielding or ballast could be stored in the flywheel in a manner that allows for pumping or minor redistribution around the perimeter to help flatten out the effects of distributed masses in order to maintain the common center of mass. In the same way, logistics and consumables stored in the inner torus would also need to be on a redistribution system (pumped liquids, logistics on rails, etc) that encircles the habitat for the purpose of balancing out dynamic moving masses (such as passengers and crew on the move).

We have designed the outer torus to be a pressure vessel, but the presence of atmosphere within the outer torus may create resistance to the rotating elements inside and thus cause the rotation to degrade over time, increasing the amount of power needed to keep the rotation. Therefore we have allowed for the possibility that the interior of the outer torus could be kept at vacuum or pressurized as options.

On a final note, with larger and larger transit vessels and artificial gravity, it will be possible to use alternative ECLSS systems such as plant growth systems (Doll & Eckart 1999, p561; Drysdale et al 2008) and even small animals (Tako et al 2010).

V. Scaling Up: A Cruise Ship-sized Mars Cycler

To get to the numbers suggested by the SpaceX plan to colonize Mars, a much larger Mars Cycler would be needed. We have gone through the numbers for how much mass and propellant would be needed for a cruise ship-sized Mars Cycler that could accommodate ~1,000 persons. Using the same process for designing the minimal-sized vehicle, we have designed a 6,572 ton transit vehicle that would require 37m diameter oxidant and fuel propellant tanks for the booster (Figure 12). The inner torus would have six decks, and would be constructable using a 24-cassette assembler ring for the inner torus, and a 32-cassette assembler ring for the outer torus.



Mars Cycler Control Panel

Crew 1,005 persons
Mission Duration 181 days
Habitat Module Type (select from popup:) Hard Torus
Artificial Gravity: 1.00 g factor at bottom deck
Earth 1.00, Mars 0.38, Lunar 0.17
Trajectory Delta-v 5,000 m/s
Mission Type T <- L=Lunar, T=Transit, M=Mars
Max Distance from sun 1.52 AU (Earth = 1.0 AU, Mars = 1.52 AU)
Cabin Pressure 15 psi <- usually 4psi, 8psi, 10psi, 15psi)
4.61 rpm rotation (angular velocity)
20.29 m/s tangential velocity

Hab Barrel Length 0.0 m <- input (0.0 m) or custom value (to avoid circular calc) 0 m <- check
Number of racks 0 D <- input number of rack increments 1.092202m (43") or "D" default

Dry Mass 3,106,660 kg
Total Mass (loaded) 6,572,050 kg <- input (6,572,050 kg to avoid circular calc)

Pressurized Volume 60,158 m3
Habitable Volume 50,419 m3 50 m3/person
Non-habitable Volume 9,738 m3

Module stow dia N/A m
Module stow length N/A m
Module deploy dia N/A m
Module deploy length N/A m
Floor Deck Structure (1g estimate):
25 kg/m2 floor structure
25.00 kg/m2 result design mass
3 m deck height

Inner/outer skin gap 0.00 m <- input (0.00 m to avoid circular calc)

Total Power 75,975 m2 array 11,603 kW
276 x 276 m array size (for visualization purposes)

Propellant needed from LEO to target trajectory Delta-v, then booster back to LEO:
Oxidant: NTO 25,860 m3 37,496,476 kg
37 m dia sphere (for visualization purposes)
Prop Fuel: MMH 25,028 m3 21,674,264 kg
37 m dia sphere (for visualization purposes)
# of Starship 2s (150t) 395 needed to refuel propellant
# of Starship 3s (200t) 296 needed to refuel propellant

	Gravity	Span		V		A		Efficiently Usable: V		A	
Deck 6	0.64	14	m	4,783	m3	2,358	m2	6,681	m3 u	2,358	m2 u
Deck 5	0.71	17	m	8,407	m3	3,280	m2	9,347	m3 u	3,280	m2 u
Deck 4	0.79	18	m	10,628	m3	3,815	m2	10,925	m3 u	3,815	m2 u
Deck 3	0.86	17	m	11,641	m3	3,936	m2	11,315	m3 u	3,936	m2 u
Deck 2	0.93	14	m	11,062	m3	3,406	m2	9,825	m3 u	3,406	m2 u
Deck 1	1.00	4	m	6,756	m3	1,003	m2	2,901	m3 u	1,003	m2 u

Inner Torus
V 60,161 m3
A 12,600 m2
R 33.4 m
r 9.5 m

Outer Torus
V 112,045 m3
A 17,600 m2
R 35.0 m
r 12.7 m

Airlock
V 56 m3
A 71 m2
r 2.4 m
h 0 m
qty: 12

Elevator cab
V 47 m3
A 73 m2
R 43.8 m
r 1.5 m
h 4.7 m
qty: 24

Hab MEL Planner tool by A. Scott Howe <ukitect@gmail.com> V20250210

Figure 12: Cruise ship-sized Mars Cycler

The cruise ship-sized Mars Cycler would have 12 docking ports around the perimeter of the fixed, non-rotating outer torus (Figure 14, right), sandwiched between pairs of elevators (Figure 13). The elevator cab volumes would be enough to provide short-term refuge for all passenger and crew in case the main inner torus needed to be evacuated.

As with the miminal-sized vessel, the booster would be mated with the main outer torus via an interface in the ‘donut hole’, and would be needed only once to get the vehicle on the target cycler orbit (Figure 14, left). A section (Figure 15) shows how the spherical fixed (non-rotating) airlocks attached to the outer torus interface with pressure hatches on the elevators, which in turn would spin up to match the pressure hatches in the wall of the inner torus for crew transfer back and forth. We assume that the elevators would perhaps have a regular schedule for moving between the rotating 1g artificial environment and the zero-g airlock which could also be used for recreation. Stowage retrieval or trash/refuse depositing in the flywheel could also be performed by the elevators.

The counter-rotating flywheel for the cruise ship-sized Cycler would nominally spin at 5.79 rpm, neutralizing the angular momentum of the inner torus rotating at 4.62 rpm.

So far the numbers we have presented represent the resources needed to insert a fully-loaded ‘wet mass’ vehicle into the target cycler orbit. Alternatively, we can reduce the number of one-time launch resources by spreading the outfitting out over time. For example, boosting a ‘dry mass’ only vehicle 3,000 tons would reduce the amount of initial propellant expended to 18,000 tons, using dual oxidizer/fuel 25m dia spherical tanks, and require only 97 Starship 3 launches to refuel. However, this reduced-mass alternatives would only postpone the remaining outfitting and resupply of the cycler, where supply ships would need to catch up to the cycler at each encounter, and transfer required logistics during the encounter window.

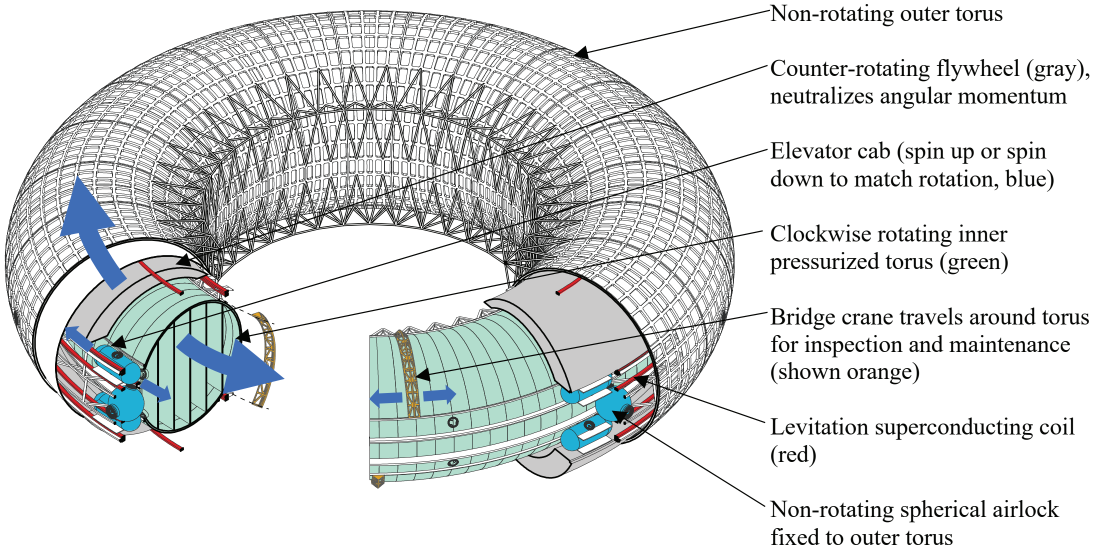


Figure 13: Mars Cycler exploded section

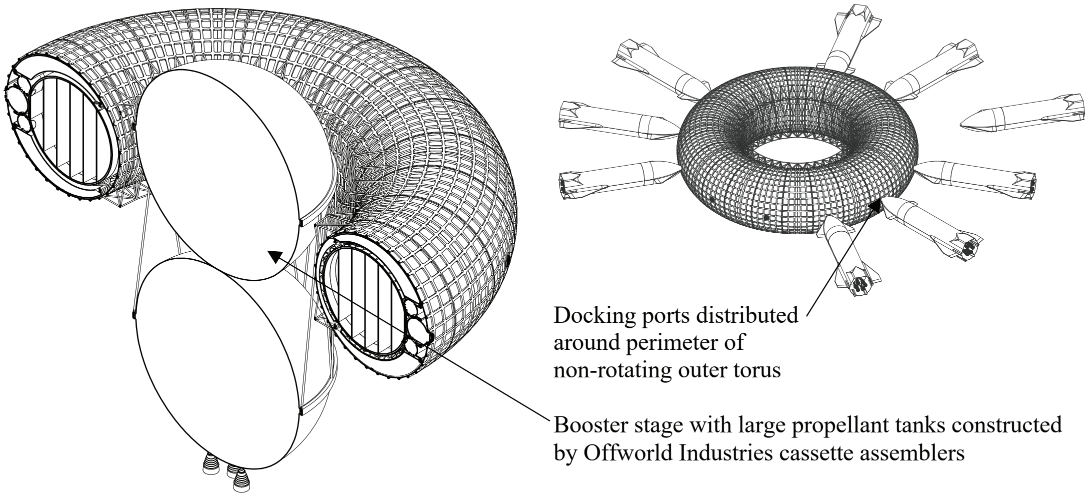


Figure 14: Cruise ship-sized Mars Cycler booster (left) and docking configuration (right)

Similarly, a third alternative would be if only the outer and inner torus structures are launched onto the cycler orbit, 15,000 tons of propellant would be needed with 24m dia spherical tanks, using 83 Starship 3 launches to refuel. This last alternative would be much more complex because the continued construction and remaining outfitting of the vehicle would occur underway, requiring supply and construction launches to catch up at encounters, and coordinate material handing and robotic assembly tasks remotely with communication latencies in play. While a cycler vehicle construction in LEO could have human oversight, a construction project underway would need to be fully automated, and thus likely less practical.

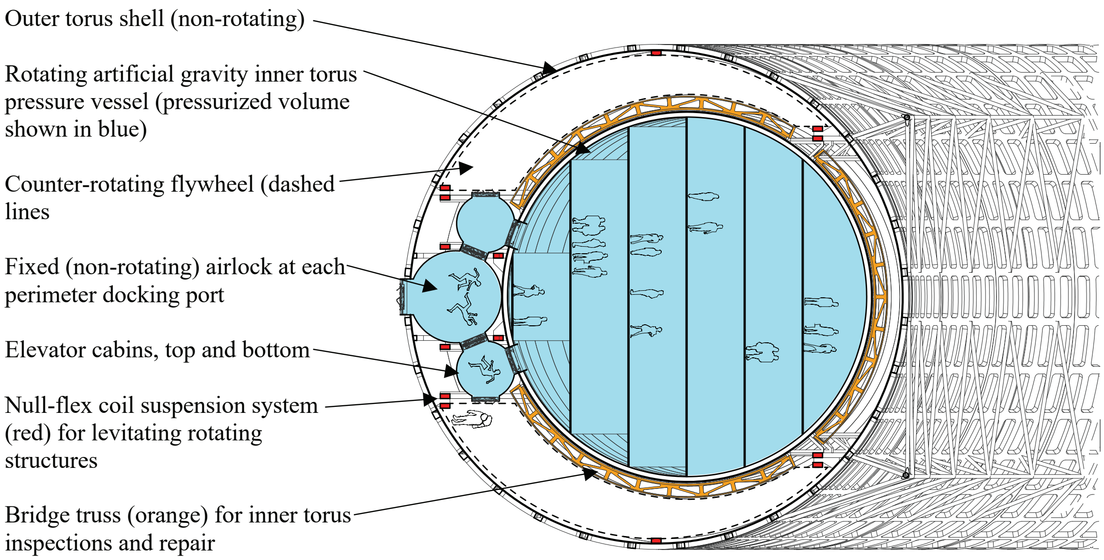


Figure 15: Cruise ship-sized Mars Cycler section

The Cruise ship-sized Mars Cycler is decidedly a project that might bust national economies. However, even with the scale that we are suggesting, we have shown how such a large-scale engineering project could be accomplished using current-day technologies.

VI. Conclusion

Early Mars missions may use smaller capsules and transit habitats, crewed by well-trained explorers. However, it will not be practical to assume large numbers of passengers could be transported to Mars strapped to seats like commercial air flights. Allowing for some volume for passengers to move around and live six months-worth of their lives will require larger personal volumes and, in our opinion, artificial gravity. Practical artificial gravity solutions could be accomplished by rotating beams or trusses balanced with habitat or propulsion systems on both ends, or even more simple, extremely low-mass tethers. It might also be possible to create simple pressurized tunnels between Starships mounted in a rotating frame configuration and spun for artificial gravity. We believe these simple solutions will have a place in the progression of larger and larger-scale transit vessels. However, coupled rotating systems (Ruzicka 2024) will always be fraught with problems such as rotation during acceleration, docking at the center of rotation, EVAs during rotation, economical spin up and spin down, etc. Ultimately we believe decoupled toroidal artificial gravity vehicles will become more affordable for the demand of large passenger transport. The Offworld Industries cassette assembler ring technology provides a logical means for constructing these large vehicles in orbit.

A minimal-sized artificial gravity Mars Cycler for ~60 passengers and crew would require nine Starship 2 launches for the materials and supplies used in the construction of the vehicle plus another seventy-three Starship 2 launches to refuel the propellant tanks for its initial acceleration into the cycler orbit, giving a total of 82 Starship 2 launches. Using the higher capacity Starship 3, seven launches will be required for construction of the vehicle plus fifty-five for the propellant, totalling 62 Starship 3 launches. Once the Mars Cycler has been placed in its cycler orbit, it will continue the trajectory indefinitely with very little propulsive boost required. We believe it is reasonable to assume that such a minimal-sized 60-person artificial gravity Mars Cycler could be on the horizon, and the numbers of Starship launches, though excessive by today's standards will be routine in a few years.

However, to accommodate the number of settlers SpaceX is aiming for will require a much larger Mars Cycler vehicle. Our purpose for this study was to actually run the numbers of what it would take to accomplish such an ambitious endeavor. A larger cruise ship-sized Mars Cycler for ~1,000 passengers and crew would need 44 Starship 2s for construction plus 395 Starship 2s for propellant. Alternatively Starship 3 launches would be 33 for construction and 296 launches for propellant. These numbers are significant, but still within the range of engineering possibility for large space construction projects in the decades to come. It is not our goal that this paper be considered a design proposal as much as a vehicle for discussion on realistic numbers for ambitious spaceflight requirements that the industry will be faced with in the near future.

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