Space Shuttle Family: Shuttle II, Mini Shuttle, and Micro Shuttles

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Introduction

THE Space Shuttle or Space Transportation System (STS) is the culmination of years of intensive development by NASA, Rockwell International, and other contractors. NASA designed the Shuttle to carry large, heavy payloads into low Earth orbit on crewed missions with a high degree of safety and reliability. But it was initially miscast in its role as a do-it-all launch vehicle that could be used to provide cheap, quick, and easy access to space. The truth is that the Shuttle is a huge workhorse, which is costly to operate and requires a longer turnaround time than originally anticipated. However, it has proven to be the safest and most reliable system yet devised for crewed missions and the launching of large, heavy payloads into orbit.[1] Rather than discard this highly successful system in favor of a totally different and unproven one, such as that of the Lockheed Martin X-33/VentureStar,[2] it makes sense to first consider redesigning the basic system to improve it and simplify its operation so as to become more cost effective. This idea has been enunciated in the Shuttle II concept[3] and that of the kerosene-fueled Mini Shuttle.[4]

The Shuttle II is a reconstituted Space Shuttle with essentially the same external tank (ET) and solid rocket boosters (SRBs) but having an Orbiter upgraded with the latest technology and an improved thermal protection system.[5] The Mini Shuttle is a downsized version of the Space Shuttle using the same SRBs but having a $\frac{3}{4}$-size Orbiter and ET. In converting from liquid hydrogen to kerosene (RP-1) for fuel, there is a reduction of about 62% in the required volume of the ET and a reduction of about 58% in its inert mass, along with a reduction of about 23% in specific impulse of the liquid rocket propulsion system. This translates into a smaller fraction of liftoff mass being able to be placed in orbit. It has been found that the Mini Shuttle can place in orbit only about 61% of the total mass of the Shuttle Orbiter plus its payload. However, by downsizing the Orbiter 25% while increasing its average density slightly to keep the same planform loading, the Mini Shuttle has a payload capability about 84% of that for the Shuttle. From all indications it appears that the new Russian RD-180 engine,[6] soon to be produced in the United States, would be an ideal liquid rocket engine for the downsized Orbiter. It operates at high pressure and oxygen rich and so runs cooler than U.S. high-performance engines. Moreover, it can be throttled from 37 to 100% of its rated output of 933,000 lb of thrust while remaining fixed in specific impulse.

The purpose of this Note is to show how the Mini Shuttle concept can be extended to obtain smaller crewed or uncrewed versions of the Mini Shuttle, which are similar in function and shape but differ greatly in size and weight. These Micro Shuttles have a payload capability that is proportional to their liftoff weight and that is the same fraction of liftoff weight as that for the Mini Shuttle. Together with the Shuttle II and Mini Shuttle, they comprise the Space Shuttle family. In addition to being able to efficiently launch small- to medium-size payloads (2000–14,000 lb) into orbit with a semireusable two-stage vehicle, such as the X-34, which NASA is developing to be a small, low-cost rocket launcher,[7] there are other possible applications for the Micro Shuttles. The smaller of these vehicles could be used by the Air Force in a crewed or uncrewed mode to develop the operational capability in space it has long sought.[8] To this end, an experimental uncrewed space maneuver vehicle (SMV) is currently undergoing preliminary development by Boeing Space Systems for the Air Force.[9] This SMV is about the size of the smallest ($\frac{1}{5}$-size) Micro Orbiter but weighs only about $\frac{1}{3}$ as much. Because of its low planform loading, it has high sensitivity to winds and gusts, as well as to timing of the landing flare. This would not be a problem with the smallest Micro Orbiter, which, like the other Micro Orbiters, has the same planform loading (about 65 lb/ft^2) as the Space Shuttle Orbiter and the Mini Orbiter. The potential value of a larger military spaceplane or space operations vehicle (SOV) for crewed or uncrewed use by the Air Force has also come under consideration.[10–12] It would appear that either of the middle-sized Micro Shuttles (having $\frac{1}{4}$- and $\frac{1}{3}$-size Orbiters) is ideally suited to being an SOV with a stringent set of requirements. Among these are the ability to launch on short notice, economy of operation, relatively easy maintenance, and reusability.

Another suitable utilization of the middle-sized Micro Shuttles would be for emergency or rescue operations, where, here also, the capability of launch on short notice may be required. NASA has recently begun development of the X-38 lifting body as a possible new crew return vehicle (CRV) for the International Space Station (ISS).[13] This CRV is about the size and weight of the next to smallest ($\frac{1}{4}$-size) Micro Orbiter. Because of its high planform loading and low lift-to-drag ratio, the X-38 has a landing speed that is considered too high for safety, and so a parafoil is used for final descent and landing. The $\frac{1}{4}$-size Micro Orbiter would not require such a risky type of landing technique and already has a reliable means of delivery to orbit. The $\frac{1}{3}$-size Micro Orbiter would also be suitable for use as a CRV in a situation where the full seven-person complement of the ISS has to be evacuated.

Scaling Rationale

The basis for scaling the smaller vehicles (Micro Shuttles) in the Space Shuttle family is threefold. 1) The fractions of total liftoff weight for each of their four components (Orbiter, payload, SRBs, and ET) are the same as the component fractions for the Mini Shuttle. 2) The planform loading is the same for all of the Orbiters in the family (including the Shuttle II and Mini Shuttle) so that the Orbiter weight or mass m is proportional to the square of its size or scale factor (SF) with $m_2/m_1 = (\mathrm{SF})^2$. 3) The cubic scaling law is used to determine the separate and distinct SFs for sizing the SRBs and ET of each vehicle. The cubic scaling law infers that the mass ratio of similarly shaped vehicle components of the same average density (such as the SRBs and ET) is given by the cube of the SF. If m is the component mass, then $m_2/m_1 = (\mathrm{SF})^3$. Another way of saying this is that in shrinking the size of a vehicle component (SRB or ET) so that all dimensions are reduced by the SF (with the average density held fixed), the mass of the smaller component is equal to the mass of the larger component times the SF cubed. Conversely, to determine the SF required to achieve a desired mass ratio, it is necessary to find the cube root of the mass ratio, so that $\mathrm{SF} = (m_2/m_1)^{1/3}$.

In arbitrarily stipulating the sizes or SFs of the various Micro Orbiters ($\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$), it is a simple matter to determine their weights according to the second basis and the given weight of the Mini Orbiter. In downsizing the Shuttle Orbiter, it is desirable to increase its average density so as to maintain about the same value of planform loading and ensure similar aerodynamic characteristics. This is in conformity with the natural tendency of aircraft or spacecraft to increase slightly in average density when reduced in size. Then, according to the first basis for scaling, the payload weight in each case is in the same proportion as that for the Mini Shuttle, as are also the propellant weights and the inert weights of the SRBs and the ET. The final step in the sizing process, after obtaining the various component weights, is to determine the separate SFs for the SRBs and ET in each case, according to the cubic scaling law. With these SFs, the dimensions of the SRBs and ETs are readily obtained.

Size and Weight Results

An appreciation of the relative size of vehicles in the Space Shuttle family may be gained from the drawings to scale presented in Figs. 1 and 2. The overall dimensions of each vehicle, along with the SFs and dimensions of its components, are listed in Table 1. It was assumed that the dimensions of the Shuttle II would be the

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Table 1 Component dimensions (in feet) and weights (in pounds) along with thrust requirements (in pounds) for vehicles in the Space Shuttle family

			Micro Shuttles			
Component	Shuttle II full-size Orbiter	Mini Shuttle $\frac{3}{4}$-size Orbiter	$\frac{1}{2}$-size Orbiter	$\frac{1}{3}$-size Orbiter	$\frac{1}{4}$-size Orbiter	$\frac{1}{5}$-size Orbiter
Orbiter (SF)		(0.7500)	(0.5000)	(0.3333)	(0.2500)	(0.2000)
Total length	122.0	91.5	61.0	40.7	30.5	24.4
Wing span	78.1	58.6	39.1	26.0	19.5	15.6
Payload bay	15 × 60	11.25 × 45	7.5 × 30	5 × 20	3.75 × 15	3 × 12
External tank (SF)		(0.7500)	(0.5747)	(0.4386)	(0.3621)	(0.3120)
Length	154.2	115.7	88.6	67.6	55.8	48.1
Diameter	27.5	20.6	15.8	12.1	10.0	8.6
SRBs (SF)		(1.0000)	(0.7633)	(0.5848)	(0.4827)	(0.4160)
Length	149.2	149.2	114.3	87.3	72.0	62.1
Diameter	12.2	12.2	9.3	7.1	5.9	5.1
Whole vehicle						
Overall length	184.2	149.2	114.3	87.3	72.0	62.1
Overall width	78.1	58.6	39.1	26.0	19.5	15.6
Orbiter liftoff weight	180,000	100,000	45,000	20,000	11,250	7,200
Payload weight	42,196	35,321	15,874	7,064	3,974	2,543
SRBs (inert) weight	365,430	365,430	164,444	73,086	41,111	26,311
Solid propellant weight	2,220,580	2,220,580	999,261	444,116	249,815	159,882
ET (inert) weight	73,860	31,160	14,022	6,232	3,506	2,244
Liquid oxygen weight	1,332,000	1,230,470	553,712	246,094	138,428	88,594
Fuel weight	224,000[a]	455,105[b]	204,797[b]	91,021[b]	51,199[b]	32,768[b]
Total liftoff weight	4,438,066	4,438,066	1,997,130	887,613	499,282	319,541
Orbiter main engines						
Sea level thrust	1,125,000	932,000	419,400	186,400	104,850	67,104
Vacuum thrust	1,410,000	1,170,000	526,500	234,000	131,625	84,240
SRBs						
Liftoff thrust	5,800,000	5,800,000	2,610,000	1,160,000	652,500	417,600
Average thrust	4,600,000	4,600,000	2,070,000	920,000	517,500	331,200
Whole vehicle at liftoff						
Total thrust	6,925,000	6,732,000	3,029,400	1,346,400	757,350	484,704
Thrust-to-weight ratio	1.56	1.52	1.52	1.52	1.52	1.52

[a]Liquid hydrogen. [b]RP-1.

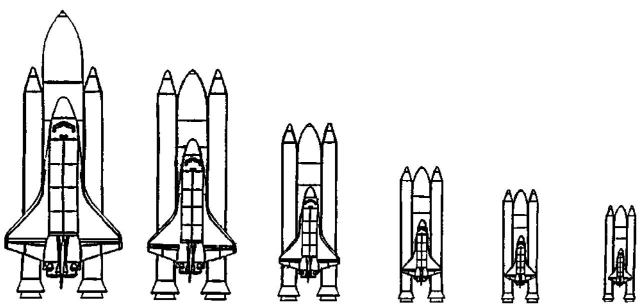

Fig. 1 Space Shuttle family (left to right): Shuttle II full-size Orbiter, Mini Shuttle $\frac{3}{4}$-size Orbiter, Micro Shuttle $\frac{1}{2}$-size Orbiter, Micro Shuttle $\frac{1}{3}$-size Orbiter, Micro Shuttle $\frac{1}{4}$-size Orbiter, and Micro Shuttle $\frac{1}{5}$-size Orbiter.

same as those for the Space Shuttle, which were used to obtain the dimensions of the Mini Shuttle. Apart from size, the only difference in design of vehicles in the Space Shuttle family is that the Shuttle II uses liquid hydrogen for fuel rather than kerosene. But, for the Micro Shuttles, the size of the Orbiter decreases to a greater degree than the sizes of the SRBs and ET due to the constraint of keeping the value of planform loading the same for each Orbiter.

In addition to specifying the overall dimensions of each vehicle and its components, the weights of the various masses of components and propellants at liftoff are listed in Table 1. It is indicated that the rather arbitrary sizing of the various Micro Shuttles is such as to produce a family of semireusable launch vehicles with a payload capability varying from small (2543 lb) to medium (15,143 lb). Furthermore, beginning with the Mini Shuttle, there is a reduction in vehicle weight and payload weight by roughly one-half in going to the next smaller vehicle. This provides a reasonable gradation in launch capability whereby the size and weight of payload are closely tailored to the size and weight of the launch vehicle. This matching of payload and vehicle size and weight, along with use of the cheapest possible fuel and reusable Orbiters, suggests that the Space Shuttle family could provide a truly cost-effective STS for all types of missions and sizes of payload.

Thrust Requirements

In the launching of any rocket-propelled vehicle into orbit, the controlling parameter is the overall thrust-to-weight ratio. In general, the variation of this ratio along the flight path determines the ascent trajectory. In the case of the Mini and Micro Shuttles (also Shuttle II), it is assumed that the ascent trajectory (and vehicle thrust-to-weight ratio) would be similar to that in a typical Space Shuttle launch with separation of the SRBs and ET in similar fashion. After vertical liftoff, the vehicle executes a gravity turn to an altitude above the sensible atmosphere, where final acceleration to orbital speed takes place. The SRBs are jettisoned after burnout at about 120 s after liftoff, and the ET is jettisoned after shutdown of the liquid rocket engines upon attainment of orbital speed at about 480 s. It would be desirable to recover all of the SRBs for reuse, but it may not be cost effective to do so for the smaller vehicles because the replacement cost of the smaller SRB casings is probably less than the cost of recovery and refurbishment. In contrast, all of the ETs must be considered expendable, but their greatly reduced size for the Mini and Micro Shuttles means that their replacement costs would be considerably less than that of the Shuttle ET. Even with the additional loss of the smaller SRB casings, the cost per pound of placing small-size satellites in orbit with the Micro Shuttles should be substantially less than is presently the case using expendable launch vehicles because the most expensive component of the launch vehicle by far is reused.

Nominal thrust requirements for all of the vehicles in the Space Shuttle family are presented in the lower part of Table 1. It has been assumed that the hydrogen-fueled Shuttle II uses three of the same liquid rocket engines as the Space Shuttle and that the kerosene-fueled Mini Shuttle uses a single Russian RD-180 engine or several

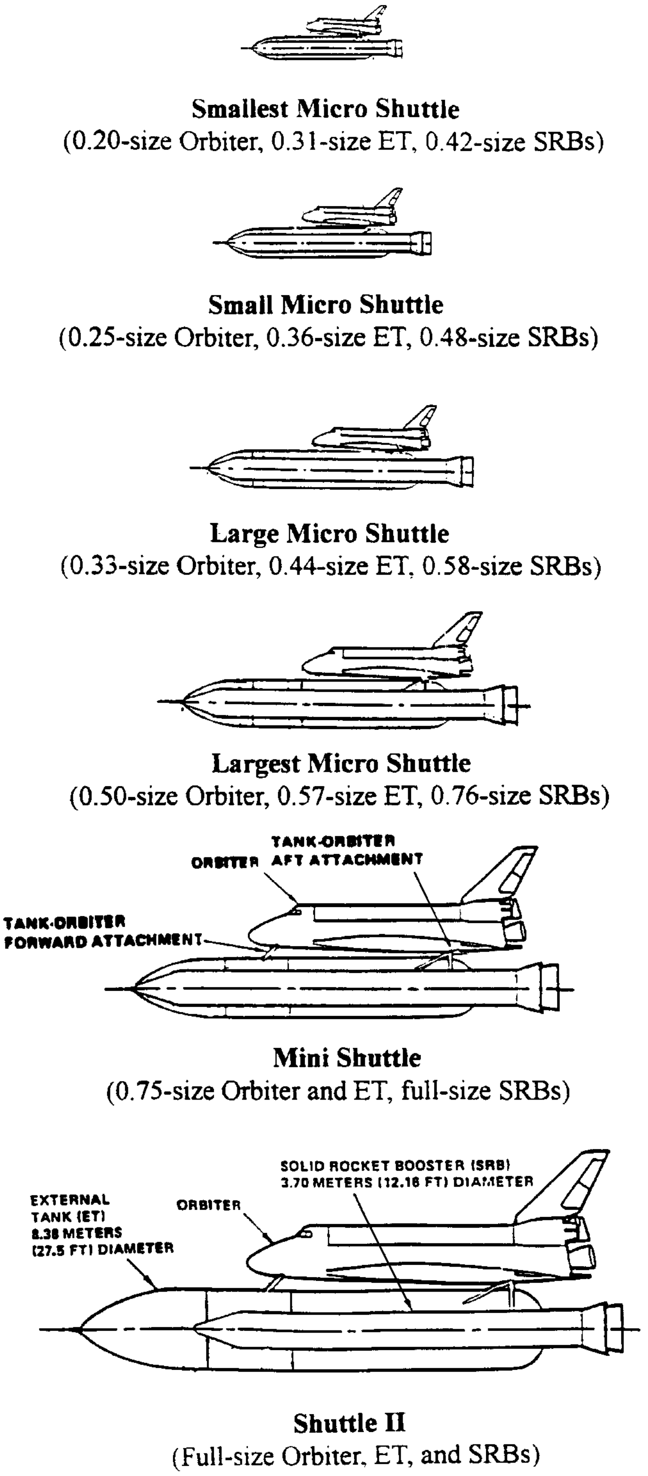

Fig. 2 Relative sizes of semireusable launch vehicles in the Space Shuttle family.

smaller liquid rocket engines with nearly the same value of specific impulse. These include the Russian NK-33 and Nk-43 engines, which are currently being considered for use with the Kistler K-1 semireusable launch vehicle.[14] Such engines, used singly, would probably be ideal for the kerosene-fueled Micro Shuttles. The thrust levels required for these engines and the various-size SRBs are simply scaled down for each vehicle so as to maintain roughly the same value of thrust-to-weight ratio at liftoff as the Shuttle. In scaling the Micro Shuttles, by simply downsizing the SRBs and ET of the Mini Shuttle and keeping the Orbiter weight also in the same proportion, the same fraction of liftoff weight for propellant is maintained. Thus, there is assurance that each different-size vehicle will have sufficient liquid and solid propellant to attain orbital speed.

Aerodynamics and Thermal Protection

In using the same shape of Orbiter for all vehicles in the Space Shuttle family, there is a great saving in wind-tunnel development time and expense. Because the design of the Shuttle Orbiter evolved out of a concerted effort to produce an efficient and durable spacecraft for entering the atmosphere at orbital speed, it is undoubtedly near the optimum shape for such a vehicle. The only differences in the aerodynamic characteristics of the various-size Orbiters in the family should be in some relatively minor, Reynolds number or scale effects. These effects would not be likely to produce any significant control or stability changes throughout the entire Mach number range during descent in the atmosphere. With essentially the same planform loading for all Orbiters, the landing flare and speed at touchdown should be nearly the same as that for the Shuttle Orbiter in all cases.

The thermal protection system used on the Shuttle Orbiter was designed to last for at least 100 missions.[15] It consists of four types of reusable insulation material to cover the aluminum airframe. The nose of the Orbiter and leading edge of the wings, which receive the greatest amount of aerodynamic heating during atmosphere entry, are covered with a reinforced carbon material. Then there are flexible sheets of nylon felt coated with silicon and tiles or blocks of silica fiber to protect the aluminum skin. Finally, there is a high-temperature variation of the tiles to protect both the bottom of the spacecraft and the leading edges of the tailplane. Although this kind of thermal protection seems to have worked very well for all of the Orbiters in the Shuttle fleet, there are undoubtedly some new materials that may provide even greater thermal protection for Orbiters in the Space Shuttle family.[5]

Crewed/Uncrewed Operation

It is reasonable to assume that any or all of the vehicles in the Space Shuttle family could be operated in either a crewed or an uncrewed mode, depending on their role in the space program and the particular type of mission being served. In general, if there were no need for an onboard crew, any vehicle could be configured for fully automatic operation with all changes to a preplanned flight program transmitted from the ground to onboard computers. That is close to the way the Shuttle is presently operated, with the flight crew having the capability of manual override in case of equipment malfunction or some other type of emergency. The one exception to this is in the Orbiter landing phase, where the flight crew takes over manual control during final descent to begin approach to the runway, followed by the landing flare and touchdown. There is no reason why this final phase of landing a crewed or uncrewed Orbiter in the Space Shuttle family could not be readily conducted by remote control on the ground. This would provide even greater utility to the Micro Shuttle spacecraft in that it would then not be necessary to have a flight-rated pilot among the personnel returning from space in an emergency situation. However, the greatest advantage to having fully automatic control is that the uncrewed vehicles could be used to launch satellites or other payloads into orbit at low cost without risk to human life. Such an uncrewed vehicle, controlled from the ground with quick-launch capability, could also be used as a military spaceplane by the Air Force and as a CRV or an astronaut rescue vehicle by NASA.

Conclusions

The Mini Shuttle concept of downsizing the Space Shuttle and replacing liquid hydrogen with kerosene for fuel may be extended to a set of even smaller Micro Shuttles that could have civil, commercial, and military applications. The Mini and Micro Shuttles, together with the Shuttle II (a full-size, second-generation Space Shuttle), comprise the Space Shuttle family. A preliminary analysis indicates that a broad range of payload could be accommodated by the semireusable launch vehicles in this family. Further analysis should be conducted to evaluate the potential lowering of launch costs in using such a space transportation system.

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Critical Need for a Swingby Return Option for Early Manned Mars Missions

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Introduction

THE recent discovery of possible fossilized microbes in a Martian meteorite sample and the spectacular success of the Mars Pathfinder mission have substantially increased public interest and support for future robotic and manned exploration of Mars. NASA is currently refining a plan known as the Design Reference Mission (DRM) in which the first human landing would occur in 2014, after two cargo launches, which would place surface systems and an Earth return vehicle at Mars about two years prior to the crew's arrival.[1] At each subsequent launch opportunity (which occur approximately every 26 months), an additional Earth return vehicle, surface facility, and crew would depart for Mars, with each crew employing the systems launched during the previous opportunity. The mission design calls for a long-duration surface stay, rapid crew transits (180 days or less), in situ manufacture of the Mars ascent propellant, nuclear thermal propulsion for the trans-Mars injection (TMI) burn, and the use of aerocapture for both the cargo and crew vehicles at Mars. This architecture is largely based on the Mars Direct approach outlined by Zubrin and others in Refs. 2 and 3. The crew would travel to Mars and descend to the surface in a single vehicle and would rendezvous on the surface with the previously placed propellant production facility and ascent vehicle. At the end of the surface stay, the small ascent vehicle would carry the crew to Mars orbit, where it would rendezvous with the Earth return vehicle (ERV). A liquid oxygen/methane propulsion system would perform the trans-Earth injection burn, and upon Earth arrival, the crew would use the same capsule for re-entry that was employed for the Mars ascent.

Both the Design Reference Mission and Mars Direct call for an abort to Mars surface strategy in which the crew is committed to the entire mission profile once the TMI burn is performed.[1,4] This approach is supported because of assertions that mission designs that allow for swingby returns significantly increase total mass, subject the crew to excessive G loads upon Earth return, and result in a prolonged crew exposure to the interplanetary radiation environment. Unfortunately, this strategy requires a complete reliance on a number of complex systems for crew survival. The outbound habitat must successfully aerocapture at Mars and then perform a descent to the surface with a high-precision landing to rendezvous with the previously placed surface systems and ascent vehicle. Surface power and life support systems must function until the next launch window for Earth return, approximately 550 days after Mars arrival, and finally, the ascent stage must successfully launch and perform an orbital rendezvous with the ERV.

Discussion

We suggest that the option of performing a swingby return may be crucial to crew survival; in the DRM scenario, the failure of any of the complex systems mentioned in the preceding paragraph (Mars aerocapture, descent and precision surface rendezvous capability, surface power and life support systems, ascent and orbital rendezvous systems) will result in an almost certain loss of the crew. Moreover, the objections to a flyby abort mentioned earlier are not necessarily valid. Linking the ERV and the outbound crew vehicle would provide the propulsive capability needed to perform, if necessary, a powered swingby at Mars, followed by a minimal delta V Venus swingby and a return to Earth about 380 days after Mars arrival. If the mission goes as planned, the two vehicles would separate shortly before arrival at Mars and aerocapture independently. For the crew transit times to be minimized, this strategy would require the ERV to use a faster, higher-energy, outbound trajectory than is necessary if it is not linked to the manned vehicle. However, the combined vehicle could perform a slightly longer outbound transit than that which has been planned for the crew vehicle (184 vs 161 days) with little or no increase in the total system mass (see Table 1). The added TMI propellant needed to decrease the transit time of the ERV from a minimum energy trajectory to a 184-day leg is offset by reductions in the propellant needed for the crew vehicle (due to the slightly lengthened crew transit time) and the decreased cryogenic boiloff from the ERV resulting from the shorter loiter time in Mars orbit (about 550 days vs 4 years). In Table 1, the payload of the TMI stage for the combined vehicle is the sum of the payloads of the two separate vehicles (including the aerobrakes for Mars orbit insertions) plus the 5.5-metric-ton (MT) mass of the crew re-entry capsule for Earth return. (In the DRM architecture, the Earth re-entry capsule is sent on the cargo vehicle, which lands on Mars' surface and doubles as the crew ascent capsule.)

Contrary to previous objections, for the 2014 departure opportunity, the Earth return atmospheric entry velocity (and the resulting G load) is actually lower for the swingby return case than for the nominal mission profile. Moreover, the Earth re-entry velocity for the nominal 2014 profile listed in Table 1 (14.22 km/s) exceeds the re-entry velocities for swingby aborts of three of the four mission opportunities considered in Ref. 5 (the 2014, 2016, and 2020 Earth departures). The re-entry velocity of the swingby abort exceeds this value only for the 2018 opportunity, with an Earth entry speed of 14.68 km/s. For a more comprehensive presentation of swingby abort options for both nuclear and conventional propulsion mission architectures, see Refs. 5 and 6. Therefore, of the three objections listed in Ref. 4 to a swingby abort option [increased initial mass in low Earth orbit (IMLEO), increased Earth re-entry velocity and G loads, and crew radiation exposure], only the last is valid.

Although a Mars swingby return does expose the crew to higher radiation levels than would be experienced with an abort to the Martian surface, it provides a return mechanism for numerous failure scenarios that would otherwise result in a certain loss of the

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