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Mars Spacesuit Mass Requirements

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The gravity on Mars is 3/8th of Earth gravity. The latest exploration Extravehicular Mobility Unit (xEMU) designed for lunar exploration is just under 400 lbm. While it would be reasonable for a crewmember to operate the xEMU on Earth's Moon with 1/6 gravity, related studies have demonstrated that this same suit would not be feasible to operate on the surface on Mars. Studies involving Martian offloading are limited and the few available have demonstrated difficulty in suit operation with current advanced suit prototypes. Furthermore, deconditioning due to a long-term journey to Mars is expected to affect the overall suit mass that a crewmember can operate. This initial study aims to provide an initial mass requirement to bound the Mars spacesuit design within a reasonable range. It is expected that detailed Mars-simulation testing will subsequently refine the estimate to support Martian mission timelines. Considerations such as crew deconditioning due to the long exposure to microgravity, pressure garment system (PGS) weight offloading, restricted mobility increasing metabolic rate, and human fitness and size are combined into an initial assessment. Based on preliminary considerations, 230 lbm is recommended as a starting maximum Mars suit mass, which will be split between the PGS and Portable Life Support System (PLSS) subsystems.

Nomenclature

AIBEL	=	Anthropometry, Injury Biomechanics, and Ergonomics Laboratory
ARGOS	=	Active Response Gravity Offload System
BTU	=	British Thermal Units
CG	=	Center of Gravity
DCU	=	Display and Control Unit
DRM	=	Design Reference Mission
EPG	=	Environmental Protection Garment
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
EVVA	=	Extra Vehicular Visor Assembly
f	=	Force
HUT	=	Hard Upper Torso
ISS	=	International Space Station
JSC	=	Johnson Space Center
MkIII	=	Mark-III Suit
MxEMU	=	Mars Exploration Extravehicular Mobility Unit
NBL	=	Neutral Buoyancy Lab
NIOSH	=	National Institute for Occupational Safety and Health
PLSS	=	Portable Life Support System
PGS	=	Pressure Garment System
RER	=	Respiratory Exchange Ratio
VO2	=	Volumetric Oxygen
VCO2	=	Volumetric Carbon Dioxide
xPGS	=	Exploration Pressure Garment System
TRL	=	Technology Readiness Level
xEMU	=	Exploration Extravehicular Mobility Unit

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I. Introduction

The Mars Exploration Extravehicular Mobility Unit (MxEMU) is currently being developed to operate on Mars, with gravity approximately 3/8th that of Earth and 2.3 times that of Earth's Moon. Up to now, suit developments have not considered this increased gravity level, and recent designs have increased the mass of the suit to meet demanding requirements for fault tolerance, re-usability, and maintainability that do not consider mass a large driver. Going forward it is expected that a mass-centric design will be crucial to support a crewmember on Mars and requirements, design, and testing will need to consider mass at the forefront of the design. To achieve an acceptable mass, some existing requirements may need to be modified or addressed through alternate solutions.

A. Historical Suit Numbers

Table 1 shows the breakdown of relative weight between the Pressure Garment System (PGS) and Portable Life Support System (PLSS) for the Apollo suit, the Extravehicular Mobility Unit (EMU) for shuttle and the International Space Station (ISS), the Russian Orlan suit, and Exploration EMU (xEMU) [1][2][5]. Historically, the average PLSS/PGS percentage is broken out with 60% PLSS and 40% PGS with only a +/– 5% maximum variation. Luna and Mars equivalents weights, 1/6th and 3/8th gravity respectively, are also shown for illustration below. Furthermore, assuming an average of 180 lbm (82kg) human, mass of the combined suit-human system is given to demonstrate overall mass on the surface of the respective celestial bodies.

It is important to note the latest xEMU suit has far exceeded previous suit design weights in part due to consideration of more regenerable elements and additional fault tolerance. If the xEMU suit was used on a Mars mission, the crewmember could be carrying more than their own Earth weight even with the reduced gravity of Mars.

Table 1. Suit Relative Weight Comparison

	Apollo, lbf (N)	EMU, lbf (N)	Orlan, lbf (N)	xEMU, lbf (N)	Avg., lbf (N)
Earth PGS*	60 (266) [1]	110 (489) [1]	88 (391) [2]	167 (742)	106 (472)
Earth PLSS	110 (489) [5]	141 (627) [5]	143 (636) [2]	209 (929)	150 (670)
Earth Total	170 (756)	251 (1116)	231 (1027)	376 (1672)	257 (1143)
Luna equivalent	28 (126)	41 (186)	38 (171)	62 (278)	42 (190)
Mars equivalent	63 (283)	94 (418)	86 (385)	141 (627)	96 (428)
Luna equivalent (with human)	58 (259)	71 (319)	68 (304)	92 (412)	72 (323)
Mars equivalent (with human)	131 (583)	161 (718)	154 (685)	208 (927)	163 (728)

*PGS mass is variable and typically depends on anthropomorphic sizing factors, especially for modular suits such as EMU and xEMU.

B. PLSS Mass Breakdown

Table 2 compares the Apollo, EMU, and xEMU masses broken out by the Oxygen Loop, Thermal Loop, Avionics, Batteries, and Packaging. Packaging includes structure, cover, Environmental Protection Garment (EPG), fasteners, tubing, manifolds, and harnesses. Apollo and EMU data were derived from more detailed tables and combined into similar systems [5]. The percentages reported in the table are percent of the component mass (not including packaging). From this table, we can see that electrical/avionics size has doubled and component masses across the board have increased from Apollo to xEMU. Packaging factors are included in this table, though discussed in detail in a later section.

The mass of the xEMU PLSS—not including the Display and Control Unit (DCU)—was indirectly measured and calculated to be approximately 209 lbm dry. This may vary slightly depending on configuration and the consumables on-board. The oxygen and water consumables add additional 16.3 lbm. The mass of the DCU that mounts on the front of the HUT is approximately 7.6 lbm.

Table 2. PLSS Suit Mass Breakdown*

	Apollo (lbm) [5]	EMU (lbm) [5]	xEMU (lbm)	Average (lbm)
Oxygen Loop	37.1 (58%)	33.6 (51%)	47.7 (46%)	39.5 (51%)
Thermal Loop	9.6 (15%)	6.5 (9%)	14.3 (13%)	10.1 (13%)
Avionics	6.7 (10%)	15 (23%)	21.6 (21%)	14.5 (18%)
Power Supply	9.5 (15%)	10 (15%)	19.2 (18%)	12.9 (16%)
Components	63.1	65.2	103.0	77.1
Packaging	47.3	75.8	105.7	76.2
Total	110.3	141.0	208.7	153.3
Packaging Factor (Total / Components)	1.7	2.2	2.0	2.0
Volume Packaging Factor	3.0	2.0	2.6	2.5

* Percentage is a percent of the component mass, not counting packaging

C. PGS Mass Breakdown

As shown in Table 1, there are significant mass differences between the pressure garments. One of the largest contributors is mobility design differences among the three suit systems.

The Apollo A7L and A7L/B suits served the function of not only lunar Extravehicular Activity (EVA) but also Earth launch and entry, including crew survival needs such as minimal mass and thermal burden when unpressurized for emergency egress. These functions, as well as the need to fit into the capsule, drove a PGS architecture that favored reduced mass and volume over pressurized mobility. This reduced mobility performance has often been noted in both crew reports and videos of EVA crewmembers during the Apollo missions.

The EMU suit was designed and optimized for microgravity EVAs outside of the Space Shuttle and the International Space Station. Upper torso mobility was required for translation and maintenance tasks while lower torso mobility was not needed. This resulted in an architecture with a heavier upper torso mass, but lighter Lower Torso Assembly (LTA) mass.

Conversely, in a surface EVA context, both upper torso mobility (for tool manipulation, sample collection, assembly and science tasks), as well as lower torso mobility (for walking, site placement, and kneeling) are required. These mobility needs are the primary driver behind the typically higher mass of surface exploration suits, and the reason why the exploration PGS (xPGS), the government reference design advanced planetary suit, is 57 lbm (26kg) higher than the EMU Space Suit Assembly (SSA), which is 51 lbm (23kg) higher than the Apollo Pressure Garment Assembly (PGA) before that.

The detailed breakdown of the xPGS suit masses is summarized in Table 3. Note also the mass of the hatch assembly—the rear entry architecture of the xPGS Hard Upper Torso (HUT)—makes donning easier and helps to mitigate dust intrusion into the suit through multiple EVAs. But there is a significant mass penalty seen on both the hatch, and the HUT hatch opening surrounding structure.

Table 3. xPGS Suit Mass Breakdown

Component	Mass (lbm)
Waist brief hip (long)	36.0
Hard Upper Torso Assembly	29.0
Hatch Assembly (regular, dry)	29.0
Environmental Protection Garment (all components)	22.0
Shoulders (small)	11.5
Boots	9.4
Legs	7.3
Liquid Cooling and Ventilation Garment (LCVG) (wet)	6.5
Helmet	6.3
Arms	4.4
Extra Vehicular Visor Assembly (EVVA)	4.0
Gloves	4.3
Total	169.7

II. Existing Models and Studies

A. Drivers for Maximum Mass on Mars

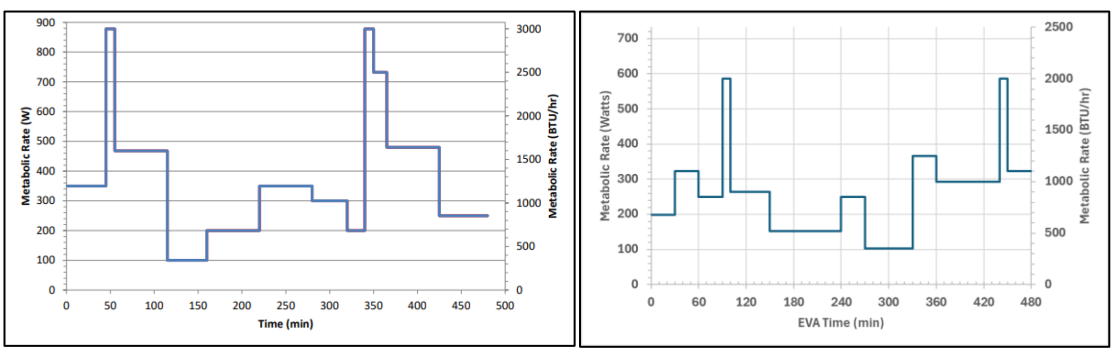
There are multiple factors that could limit the maximum suit mass on Mars. Expected primary factors include maximum extended metabolic rate for traverse, peak task exertion, and fall recovery. Each factor may depend on multiple variables, such as crew weight and fitness, tool mass, deconditioning, pressure offload, and injury risk. There has been limited previous work on Mars suit mass and while this study attempts to characterize mass limit impacts from these different perspectives, there is not enough data at this point to drive a fully conclusive limit. The intent is to provide an estimate for a maximum suit mass on Mars to help drive early designs and studies. MxEMU design work is expected to require a paradigm shift towards a mass-centric design driver whereas previous suit designs for microgravity and the Lunar surface have not emphasized mass to the same degree due to the lower gravity.

B. Metabolic Profiles

A large driver for suit mass is the metabolic rate that the astronaut sustains during EVA. A higher gravity field will increase the metabolic rate cost to operate a suit with the same mass. Metabolic rates are limited by physiological factors, including individual size and fitness. To avoid exceeding these limitations on metabolic rates, the suit mass and other design factors influencing metabolic rates must be optimized for Mars.

For background, crew metabolic rates during the Apollo and Shuttle/ISS EMU Programs were just below 1,000 BTU/hr (293 Watts) [7]. However, an increasing number of EVAs on ISS have been exceeding 1000 BTU/hr [7] and are shortened to less than 8 hours due to suit available consumables. Additionally, a diverse set of exploration activities for the Lunar surface are predicted to have higher metabolic rates, therefore the metabolic average rate for exploration suit sizing is currently at 1200 BTU/hr (352 Watts) [7]. It is expected that the average BTU/hr will be higher for Mars exploration due to the increased gravity, though characterizing this is future work and the Lunar value of 1200 BTU/hr is used as a starting point here.

Another factor is the peak metabolic rate that the person and/or suit system can withstand. The xEMU specifications require a short duration capability to manage a 3000 BTU/hr peak rate for 10 minutes for the max transient profile [7]. The ISS EVA profile has an average metabolic rate of 850 BTU/hr with a peak of 2000 BTU/hr built from Apollo, Skylab, and Shuttle missions [8]. Figure 1 shows two metabolic profiles for xEMU (1a) and the ISS EVA (1b) profile that are used to size and test the suit.



(a) xEMU Max Transient Metabolic Profile [7] (b) ISS EVA Metabolic Load Profile [8]

Figure 1. Suited metabolic rates

C. Task Exertion Testing

NASA has done extensive characterization of microgravity EVA workloads. Microgravity EVAs occur in two to three events lasting six to eight hours in the suit. These EVAs are generally separated by six to eight months. Workloads are expected to increase as NASA moves to more exploration surface EVA paradigms for Artemis lunar operations and longer duration Martian operations. There is limited experience in completing exploration EVA with Apollo missions being the last opportunity for lunar surface tasks. NASA has developed extensive analog test facilities including the Neutral Buoyancy Laboratory (NBL) and Active Response Gravity Offload System (ARGOS) that enable early characterization and development of advanced suits. Workload characterizations and task capabilities for Lunar operations have been completed to understand how surface operations will impact crew ability to perform while staying within consumable limits. Lunar surface EVAs are expected to increase in cadence (e.g., 24 hours of EVA in a week) and include more full body workloads—a drastic difference from microgravity EVA operations for ISS. Moving beyond lunar surface EVA, there is limited information on how the Martian gravity environment and Earth-independent operations will impact crew performance during EVA.

NASA has an ongoing study that has investigated the ability to perform tasks upon landing on the Martian surface [16]. As part of this study, crew returning from ISS missions don the xEMU PGS in the ARGOS test facility. ARGOS offloading is set to Martian gravity, and early work has been completed to drive understanding of offload settings and simulation quality. Crew are asked to perform EVA tasks including lander egress, traverse, and geology. Preliminary results have shown an increase in general workloads due to increased gravity equivalents, suit mass, and crew deconditioning. Crew workloads will be impacted by both deconditioning that occurs on transit to Mars and the mass of the suit. Along with mass, fitness and planned EVA tasks should be taken into consideration in the hardware development and capabilities.

Another NASA study has shown that metabolic costs for functional tasks, such as walking and object relocation, can vary significantly based on mobility of suit designs [25]. The Mark III (MKIII, 64 kg mass) and Rear Entry I-suit (REI, 43 kg mass) and Demonstrator (27 kg mass) suits were compared across 6 subjects with the Demonstrator having up to 60% higher metabolic costs even though it was the lightest suit. This finding underscores the importance of considering mobility, as well as mass, in optimizing suit design for Martian operations.

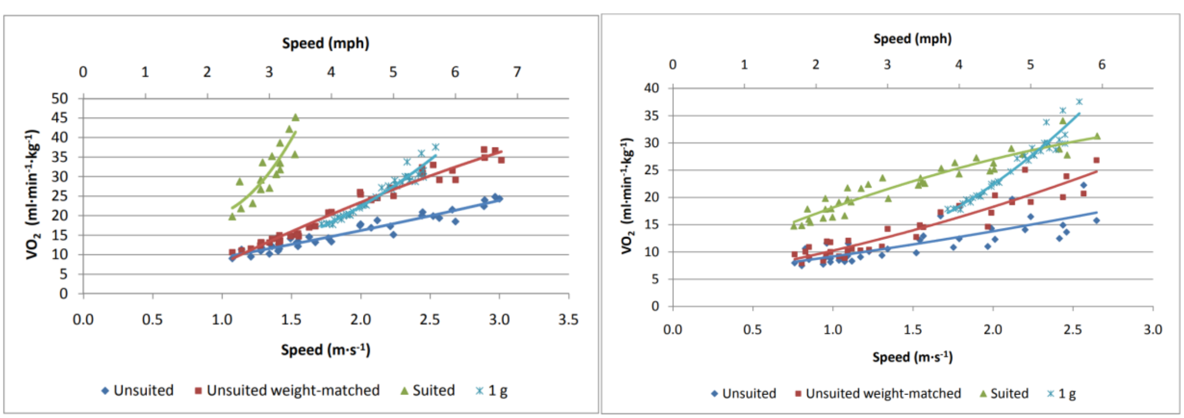
D. 10-km Walkback Study

A previous study tested a 10-km walkback with Lunar offloading [9]; however, it did explore some test points with Mars offloading. Figure 3 was taken from the study and illustrates the metabolic rates from a suited test simulating (a) Mars and (b) the Moon compared to suited, unsuited, and unsuited weight-matched [9]. Unsuited weight-matched would have test subjects wear a simulated weight for the suit and gravity enviroment when walking on the treadmill. The results indicated feasibility concerns with the MKIII suit in Mars gravity as the combination of higher gravity load and suited constraints imposed a significant physiological burden. For a Mars offload, subjects approached near Volumetric Oxygen Maximum ($VO2_{max}$) during brisk walking (<3.5mph) and small increases in walking speed resulted in significant increases in metabolic rate [9]. With the same suit in lunar offloading, it was shown that the suited crewmember can easily reach higher speeds. This study showed that the suit design will have to be changed or reduced in mass to better perform the walkbacks for Mars. The MKIII tested in this study had a mass of 265 lbm (120 kg) which is already significantly lower than the xEMU mass: 391 lbm (177 kg) [9]. Results demonstrated that the Mars suit mass will need to be lowered significantly below the MKIII suit based on this test.

Figure 2. 10-km study [9]

The study team suggested additional assessments to determine the individual effects of factors such as inertial mass, center of gravity shifts, pressure-volume work, and kinematic constraints. This study's authors also acknowledged their limited subject pool (six male astronauts) and suggested that future testing would benefit from an expanded subject pool that would include female subjects and subjects with a wider variety of anthropometry.

This test also illustrated some insightful differences between suited and unsuited weight-matched conditions, which could be used to help determine the metabolic cost required to operate the suit not including the weight of the suit.



(a) Martian Offloading (b) Lunar Offloading

Figure 3. EVA walkback study metabolic rates ($VO2_{max}$) vs. walking speed [9]

E. Fall Recovery Testing

The University of Maryland has investigated the effect of PLSS mass on Mars EVA task performance through a series of functional recovery tasks including kneel, prone, and supine recovery, as well as step/up down [18]. Shirtsleeve testing was conducted in 1G and in an NBL with varying backpack weights representing Mars-equivalent PLSS masses (0 lbm/kg, 154 lbm (70 kg), and 220lbm (100 kg)). This preliminary evaluation suggested that current PLSS mass projections, at both 154 lbm (70 kg) and 220lbm (100 kg), may present substantial mobility challenges for Martian surface operations. Larger male subjects, representing the upper 20% of the crew size range, experienced significant difficulty with the 220lbm (100 kg) configuration, and even the 154 lbm (70 kg) configuration posed considerable challenges. These feasibility concerns may be amplified in more comprehensive testing that includes realistic suit weight, a pressurized PGS, center of gravity (CG) simulation, and a subject pool more representative of the potential crew population, as well as deconditioning and fatigue effects expected after long-duration microgravity transit and Mars EVAs.

Figure 4. University of Maryland weight studies [18]

An earlier parabolic flight study compared the Apollo A7LB, Shuttle EMU, and MKIII suits simulated lunar and Martian gravity to assess full-body mobility characteristics [19]. Fall recovery from both prone and supine positions were significantly influenced by suit mass and mobility design, with Mars gravity presenting the greatest challenge. While the MKIII was the heaviest suit and required overcoming more inertia to regain an upright posture, its increased mobility compared to the two lighter suits enabled better fall recovery capability, including multiple recoveries within the first parabola. In contrast, the Apollo suit, with limited hip, waist, and shoulder mobility, required several parabolas to recover from prone position (reported as very difficult by the subject) and the Shuttle EMU suit, designed for microgravity, could not recover. Mobility features, such as joint bearings, waist rotation, and hard vs. soft components, had major implications on task feasibility, CG control, and stability. Increased mobility also reduced fatigue and shortened learning curves. Understanding the interaction between suit mass and mobility is critical for optimizing design and ensuring sufficient EVA task capability, particularly for those tasks that are safety critical. For instance, increasing suit mass to enable greater mobility can sometimes be a good trade, depending on the mission requirements and suit architecture.

III. Aerobic Modeling of a Maximum Suit Mass for Mars

A. VO2 as a modeling driver

Crewmembers go through extensive evaluations for spaceflight or testing, one of these being a $VO2_{max}$ test that measures the maximum oxygen uptake of the individual in ml/min/kg. It is a good measure of human fitness and can be used for comparing fitness levels across a variety of human body sizes and weights. $VO2_{max}$ can also help set thresholds for test termination criteria.

$VO2_{max}$ can also be reported in liters per minute (L/min). This can sometimes be more useful when designing hardware and comparing capability of the hardware to meet requirements. It is very important to understand the distinction and specify units, since they use the same term, but have different applications. In the following hardware discussions, $VO2_{max}$ (L/min) will be favored to compare hardware capability, and $VO2_{max}$ (ml/min/kg) will be used for discussing human fitness levels.

$VO2_{max}$ (ml/min/kg) across human weights can also be correlated to metabolic rate (in kcal/min) using the Perronet formula [21] in equation 1. To get metabolic rate in BTU/hr, equation 1 can be reformulated using a respiratory exchange ratio (RER) = 0.85. RER is 0.7 for low intensity activity, 0.85 for average activity, and close to 1.0 for high intensity activity [22]. It is assumed for $VO2_{max,}$ RER would be close to 1.

$$MetRate\left(\frac{kcal}{\min}\right) = 4.039\left(\frac{kcal}{L}\right) * VO2\left(\frac{L}{min}\right) + 1.157\left(\frac{kcal}{L}\right) * VCO2\left(\frac{L}{\min}\right) \text{ [21] } \mid \quad 238\frac{BTU}{hr} = \frac{Kcal}{min} \tag{1}$$

$$MetRate\left(\frac{BTU}{hr}\right) = (0.961 + (0.275 * RER)) * VO_2\left(\frac{ml}{\min * kg}\right) * mass(kg) \mid \text{Assuming: } RER = \frac{VCO2\left(\frac{L}{\min}\right)}{VO2\left(\frac{L}{\min}\right)} = 0.85 \tag{2}$$

Using the above formula, Table 4 shows the metabolic rate compared across different human masses and fitness levels.

Table 4. Metabolic Rate vs. VO2 (ml/min/kg) and Mass

BTU/HR (RER=.85)	VO2 (ml/kg/min)						
Mass lbm (kg)	10	15	20	25	30	35	40
120 (55)	652	978	1304	1630	1955	2281	2607
140 (64)	760	1141	1521	1901	2281	2662	3042
160 (73)	869	1304	1738	2173	2607	3042	3476
180 (82)	978	1467	1955	2444	2933	3422	3911
200 (91)	1086	1630	2173	2716	3259	3802	4345
220 (100)	1195	1793	2390	2988	3585	4183	4780

In many cases $VO2_{max}$ (ml/min/kg) is also set as minimum fitness level criteria for flight. Currently that is set at 36 ml/min/kg for surface EVAs [10]. This may be increased to handle more demanding missions and environments like Mars.

As a tolerance limit for an 8-hour workday, $VO2_{max}$ is not expected to exceed 35% on average for untrained personnel, and 50% average for trained personnel on a bicycle/treadmill [12]. As a crewmember is expected to be trained, it is assumed that for missions they should be able to support a 50% average $VO2_{max}$ for 8 hours (if just considering walking). Capability is reduced by 20–40% for lifting /anaerobic exercises [12] leading to a limit of ~35% $VO2_{max}$ for lifting activities. As EVA is a mixed activity (split between aerobic and anaerobic activities), then the tolerance limit would be between 35% and 50% of $VO2_{max}$ or ~43% $VO2_{max}$ average. The VO2 must then be sized for the smallest crewmembers, which for exploration is a female with a 5th percentile weight and a 36ml/min/kg $VO2_{max}$. Using equation 2 above with the RER of 1.0 for peak/anaerobic output, a mass of 108 lbm (49 kg) for a 5th percentile female, and a $VO2_{max}$ of 36ml/min/kg, this crewmember has an estimated metabolic rate of ~2200 BTU/hr. Using 35%–50% of $VO2_{max}$ as noted above would result in a met rate range of 760–1100 (avg: 940) BTU/hr maximum over an 8-hour EVA. For other crewmembers, this range may be much greater, and the suit should be sized to handle the larger range. But the EVA profile should consider capabilities of the individual in the suit. This is reflected in the current suit sizing of 1000 BTU/hr for Shuttle/ISS and 1200 BTU/hr for exploration [7]. Designers of exploration and Mars suits may have to consider heightened requirements (weight and $VO2_{max}$ minimums) for crewmembers to handle higher metabolic rates.

B. Considerations for Maximum Mass Based on Aerobic Limits

For overall mass of the suit, there are many considerations expected to drive the mass of the suit. For a model based on aerobic limits of the human, the main factors are:

1. Crew physical characteristics
2. Human weight carry limit as defined by NIOSH
3. Suit restricted mobility
4. Deconditioning over mission journey
5. Pressure offload of the suit
6. Additional tool/sample carry weight

The following sections attempt to estimate mass factors for each of these considerations to combine them into an overall equation to predict an optimal suit mass.

1. Crew Physical Characteristics

Current NASA standards related to crew physical characteristics [17] include a mass range of 94 to 243 lbm (1st percentile female to 99th percentile male). There is also a range of fitness levels reported as $VO2_{max}$ (ml/min/kg).

Table 5 and Table 6 show a mass percentile and fitness level breakdown [17], [23]. The 30–39 age range is shown for average astronaut ages, though other age ranges should be considered

Table 5. Human Mass Percentile Chart

Mass Percentile	1%	5%	25%	50%	75%	95%	99%
Male, lbm (kg)	120 (55)	138 (63)	164 (74)	181 (82)	199 (90)	225 (102)	243 (110)
Female, lbm (kg)	94 (43)	108 (49)	128 (58)	142 (65)	156 (71)	176 (80)	191 (87)

Table 6. $VO2_{max}$ Ranges (ml/min/kg)

$VO2_{max}$	1%	5%	25%	50%	75%	95%	99%
Male age 30–39	27	31	37	42	48	54	58
Female age 30–39	23	26	31	35	40	47	52

While recent exploration suit designs have been working toward meeting 1st–99th percentile accommodation requirements, historically, both custom suit sizing (Apollo) and fleet sizing (EMU) based on a 5th–95th percentile range have been used [6]. It is expected that custom suit sizing will be considered for Mars and there may be limitations at the ends of the sizing spectrum for initial missions. Therefore, for this report, a 5th percentile female mass was considered as the limiting case, to represent the low-end range for crew mass without overly constraining the suit design at this early stage (see section C below).

2. NIOSH carry limit

According to the National Institute for Occupational Safety and Health (NIOSH), the maximum weight a human can safely carry is 51 lbf under ideal conditions (e.g., infrequent, close to body, no twisting) [4]. This is for hand carried lifting which may not be directly analogous in all suit usage cases (e.g. combined PLSS mass vs carry mass), but is used as a starting factor that may be refined later.

NIOSH Max Carry Weight = 51 lbf (227 N)

3. Suit Restricted Mobility

A design goal of the optimal pressurized space suit is to minimize impact on human (shirtsleeve) mobility and energy expenditure to the extent possible. While effective suit design, including bearings and other mobility elements, will attempt to minimize this as much as possible, the suit will inherently take extra work to operate. This provides a significant driver for a maximum mass model based on aerobic fitness that will affect the maximum suit mass a human can operate. In the 10-km walkback study [9], a comparison was made between a suited and unsuited subject carrying the equivalently weighted suit mass on Mars. VO2 (ml/min/kg) was measured for both cases and depending on walking speed, there was a difference of 10–18 ml/min/kg in VO2 between suited and unsuited conditions [9]. Therefore, an average value increase of 14 VO2 (ml/min/kg) could be assumed to operate the suit on Mars. The mean subject $VO2_{max}$ (ml/min/kg) was 48ml/min/kg with little variation [9].

This metabolic rate increase with mobility restriction could be used as a type of knock down factor on the maximum weight a human can support assuming no extra loads. A formula to estimate the percent weight reduction is shown below.

$$\boldsymbol{Suit\ Restricted\ Mobility}_{\%} = \mathbf{1} - \frac{\mathbf{14}\left(\frac{ml}{\min kg}\right)}{\boldsymbol{VO2_{max}}\left(\frac{ml}{\min kg}\right)} \tag{3}$$

For instance, an average human weight of 162 lbf combined with the NIOSH limit for carrying of 51 lbf (227 N) results in this human being able to support a total weight of 213 lbf. Assuming a 14 VO2 (ml/min/kg) additional cost of work for operating the suit and a fitness level of 48 $VO2_{max}$ (ml/min/kg), the suit restricted mobility factor would be 71%. This would reduce the maximum weight that the example human can support while continuously walking and working against the mobility restrictions of the suit to 151 lbf, including their own weight.

4. Deconditioning

It is expected that crewmembers shall maintain an in-mission $VO2_{max}$ at or above 36.5ml/min/kg for surface EVAs [10]. $VO2_{max}$ deconditioning historically has been observed from 15%–25% [10], thus pre-mission $VO2_{max}$ would need to be from 43–49ml/min/kg to maintain 36.5ml/min/kg at the time of EVA. For a Mars mission, conservatively, the crewmember must have a pre-mission $VO2_{max}$ at the upper end of the range (≥49ml/min/kg). To account for deconditioning in the suit design model, a $VO2_{max}$ = 36.5ml/min/kg would be used as input. It would also be important to test the suit weight with either test subjects at a similar 36ml/min/kg level, or approximately 25% higher relative mass to ensure the same crewmembers can handle the weight after deconditioning.

Along with aerobic deconditioning, long duration spaceflight significantly reduces musculoskeletal capacity. Over 3–6-month missions in microgravity, crew can experience up to a 30% loss in both muscle mass and lower limb strength [20]. This effect poses challenges for successful EVAs, including reduced suited task performance, increased fatigue, and elevated injury risk. Exercise countermeasures, including resistive devices, are required during long-duration missions to minimize muscle atrophy.

5. Pressure Offload

The PGS can provide a variable amount of pressure offload from the pressurized legs supporting the weight of the suit and depending on the current task. A preliminary proof of concept test was conducted to evaluate this effect in the xPGS. Load cells installed in the shoulder straps measured the total amount of force applied to the shoulder from the weight of the suit. The PGS weight can be variable based on suit configuration and sizing, though in the pressure offload study the xPGS weighed an average of 180 lbf [11]. With an unpressurized suit, the strap force measured 161 lbf on average [11]. Therefore, about 19 lbf of the suit weight is supported in other locations such as the arms.

There were multiple activities considered in the study: walking, standing, squatting, kneeling, and shrugging [11]. However, to inform the maximum weight for the Mars suit, we concentrated on standing and walking, since those activities result in longer-term loading. For best fit in the suit, a nominal strap tension was determined during suit sizing. For a standing configuration with nominal strap tension, the strap force measured 79 lbf (351 N) [11]. For a walking task with nominal strap tension, the strap force measured 113 lbf (503 N) [11] average. The pressure offload would be the difference between the weight of the suit and the measured strap load. For standing, that would be 101 lbf of offload and for walking that would be 67 lbf. Subtracting the 19 lbf supported elsewhere, that would be 82 lbf offload for standing and 48 lbf offload for walking. When walking the legs are no longer straight upright so they provide less pressure offload. As walking is a standard task that is expected to be a limiting factor for extended high metabolic loads and it is the more conservative case, the 48 lbf offload will be used as a standard offload factor. It is notable to consider that while this factor is not gravity dependent (same amount of offload force will be applicable to Mars or Earth), it is suit architecture dependent and will need to be refined for a Mars suit design.

Pressure Offload = 48 lbf (213 N)

6. Tool/Sample Carry Mass

It is expected that the crew may need to carry tools and/or samples during EVA, which contribute to the maximum load a crewmember can support. NASA system compatibility standards EHP-10028 has a 149 lbm (67 kg) carry limit for Lunar operations. However, this would likely be too much mass to pick up on Mars so 50 lbm was used as an initial estimate for carry mass. This number may be updated once more information is known on Mars mission requirements and based on the final suit mass.

$Carry_{mass}$ = 50 lbm (23kg)

C. Modeling a Max Suit Carry Mass on Mars

The above weight factors can now be used as inputs into equations for estimating maximum suit mass.

1. Equations and Assumptions

The system mass is a combination of suit mass, crew mass, and carry mass.

$$\boldsymbol{System_{mass}} = (\boldsymbol{Suit_{mass}} + \boldsymbol{Crew_{mass}} + \boldsymbol{Carry_{mass}}) \quad (4)$$

The crew perceived force on Mars is a combination of the total system mass multiplied by the gravity field minus the pressure offload force provided by the pressurized suit. The pressure offload force is the reduction in force they will feel on their shoulders when pressurized and walking. The pressure offload force is not affected by the gravity field.

$$\textbf{Crew Percieved Mars}_{force\,(f)} = \textbf{System}_{mass} * \textbf{Accel}_{Mars} - \textbf{Pressure Offload}_{f} \mid \textbf{Accel}_{Mars} = 3.73\frac{m}{s^2}, 12.2\frac{ft}{s^2} \quad (5)$$

The crew capability represents the amount of downward force the crew can handle in any gravity field. The capability is calculated based on earth down force values. Crew capability is a combination of the crewmember's own weight/force on Earth, and the NIOSH carry limit (51 lbf (227 N)) on Earth, factoring in the mobility restriction due to the pressurized nature and bearing friction of the suit.

$$\textbf{Crew Capability}_f = \left(\textbf{Crew}_{f,earth} + \textbf{NIOSH}_{f,earth}\right) * \textbf{Restricted Mobility}_{\%} \quad (6)$$

The crew perceived force on Mars must not exceed the crew capability force. Therefore, the maximum mass of the suit for Mars is determined by setting the crew capability force equal to the crew perceived Mars force.

$$\textbf{Max Suit}_{mass} = \left(\frac{(\textbf{Crew}_f + \textbf{NIOSH}_f) * \textbf{Restricted Mobility}_{\%} + \textbf{Pressure Offload}_{lbf}}{\textbf{Accel}_{Mars}}\right) - \textbf{Crew}_{mass} - \textbf{Carry}_{mass} \quad (7)$$

2. Initial Estimates

Figure 5 takes the above equation and varies the factors for crewmember weight and fitness to demonstrate how the maximum suit mass varies based on the individual's weight and fitness level. It is important to note that this graphic adopts many assumptions from the previous equations and is intended to be a preliminary model that will be refined with focused testing.

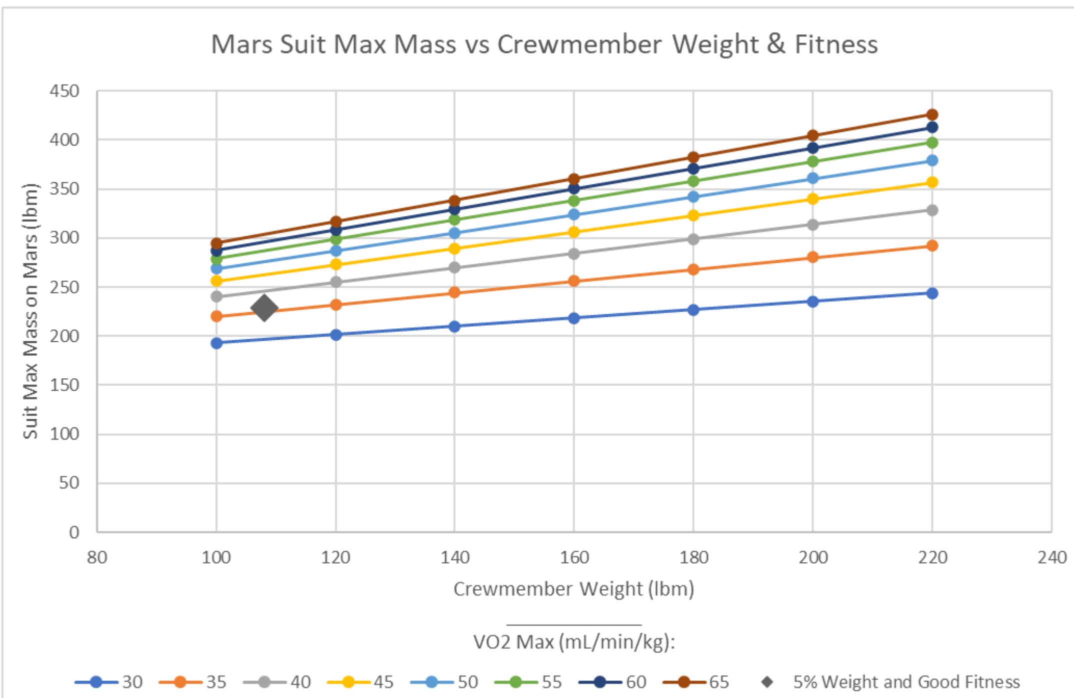


Figure 5. Max Suit Mass vs Crewmember Earth Weight (lbm) and Fitness (VO2 Max, mL/min/kg)

To size the suit, it is important to bound the equation to the potential end ranges for crewmember mass and fitness. For this initial suit mass estimate, a 5th percentile female mass of 108 lbm (49 kg) was considered as discussed previously. Using this crew mass and the 36 ml/min/kg VO2 Max requirement results in a total suit mass of **229 lbm (104kg)**.

3. Walking Speed

On Earth, a person's average walking speed is 5.0 kph (3.1 mph) [13]. In general, crew walked at much lower speeds during Apollo EVAs. It was assumed that for a walkback from a failed rover, the crew could walk at 3.6 kph (2.2 mph) for 1 hour or 2.7 kph (1.7 mph) for greater than 1 hour [14]. For Apollo 15, the crew walked between 1.1

and 1.6 kph (0.7–1 mph) during the first EVA, then improved to 1.6–2.2 kph (1–1.4 mph) during the second EVA most likely due to not walking any significant distances, operating mostly around the lunar module or at geology stops [14].

Walking back after a failure/terminate case is typically considered a limiting factor for safe distances a crewmember can travel from the craft. For a walkback on Mars, either 30 minute or 1-hour walkback are being considered. Assuming the same 2.2 mph walking speed from Apollo, this would be 1.1 miles (1.8 km) or 2.2 miles (3.5 km) respectively. The overall walkback duration will be dependent on hardware capabilities and mission priorities. Although, without additional backup/ambulatory systems, it is expected that the maximum distance away from the craft will not exceed a 1-hour walkback or 2.2 mile (3.5 km), assuming sizing in the suit allows for a walkback that long.

Data from the walkback study [9] can be extrapolated to predict the expected BTU/hr. For a 2.2 mph walking speed, the VO2 consumption rate was approximately 19 ml/min/kg [9]. Therefore, an average crewmember (162 lbm) with a RER of 0.85 would have a metabolic rate of approximately 1700 BTU/hr while a larger male crewmember (95th percentile mass of 225 lbm) would have a higher metabolic rate of approximately 2300 BTU/hr. While this does exceed the assumed average 1200 BTU/hr, traverse is considered to require a higher metabolic rate than many other EVA tasks and when combined with periods of rest and lower effort tasks, the average metabolic rate may even out the near the 1200 BTU/hr. However, the larger crewmember metabolic rates may help to illustrate an upper limit for the metabolic rate that the suit may need to handle for short periods of time.

Assuming the $VO2_{max}$ at the time of EVA is maintained at 36ml/min/kg, and maximum exertion is limited to 50% $VO2_{max}$ (18 ml/min/kg) for a walkback at 2.2 mph, then the $VO2_{max}$ = 19 ml/min/kg estimated as part of the walkback study at 2.2mph would be close to the limit for sustained capability. Therefore, a suit of slightly less mass (~250 lbm (114 kg)) than the 265 lbm (120 kg) suit tested as part of the walkback study could be tenable. Although, the walkback speed of 2.2mph is an assumption that will need to be verified. This matches closely to the model estimated in the previous section. However, the suit mass will need to be significantly lowered if there is a desire to operate at higher speeds or run for extended periods.

IV. Suit Mass Budget Strategy

A. Physiology Requirements Development and Testing

To establish a suit mass budget, it is essential to define the main physiological requirements that directly relate to suit mass. These requirements include factors influencing both metabolic rate and overall suit mass:

- Metabolic rate profiles and peak sustained rate
- Suit architecture and mobility
- Crewmember size, strength, and fitness
- Functional task capability (e.g., fall recovery, traverse)
- Nominal and off-nominal suit pressures
- Traverse speed and distance
- Exercise countermeasures

Destination and mission parameters (expected mission number of EVAs and expected EVA duration) will also drive physiological requirements and overall suit design.

A combination of suited testing and computational simulations will be conducted to characterize the primary drivers of suit mass and their relationship to mission parameters. Initial efforts will focus on evaluating the simulation quality of varying PLSS mass conditions in NASA's ARGOS environment under Mars gravity offloading. This test will provide baseline data on mass-dependent settings to inform subsequent studies.

As part of the workload characterization effort, task capability and metabolic energy during extended simulated EVA tasks at Martian offloading will feed suit and physiology requirements. Data collection will include gait and task kinematics, metabolic rate, heart rate, workload, and subjective workload ratings. This dataset will be used to update an effort of Martian physiology capabilities through the development of a Crew State and Risk Model (CSRM) to aid in correlations for Mars and predict metabolic rates across EVAs on the Martian surface. Data from this effort will continue to aid in MxEMU suited requirements by generating crew physiology modeling states based on EVA workload. Continually, as part of this development the Mars based traverse workload and fatigue states will help to inform suit mass limit.

A parametric study will also be planned to evaluate the impact of varying suit mass on metabolic rate, task exertion, and task performance. Functional performance testing will assess capabilities such as fall recovery, reach, balance, object relocation, and ground access across multiple suit mass configurations. These tests will directly inform the

MxEMU mass limit and provide input data for modeling efforts. An effort will be made to select subjects covering a wider range of potential crew anthropometry than previous studies, including ensuring that females are represented.

Modeling and simulation tools will be leveraged to provide estimates for mass factors that are difficult to test or where we are currently lacking sufficient data, such as suited fall injury risk. Potential increased likelihood of adverse fall outcomes on Mars due to higher impact forces and accelerated fall dynamics related to suit mass and CG location will be addressed.

As Mars concept of operations evolve and new data are gathered from lunar and low-Earth orbit missions, physiological requirements will need iterative refinement. For example, some expected refinement will be based on additional data on anthropometric and physiological changes during/after exposure to microgravity and partial gravity environments.

Initial testing to inform Mars requirement and suit design development will likely be performed using existing xEMU suits with architecture that may or may not reflect future MxEMU architecture. Once an MxEMU prototype is available, testing will need to be repeated to validate prior findings and suitability of the design, including evaluation of suit mass and architecture changes on mobility and workload.

B. Packaging Factors

An important factor in predicting future suit mass and volume is the packaging factor of the suit. The packaging factor is the ratio of total system mass/volume to combined component mass/volume. While the component mass and volume are considered in architecture studies for the overall system, the PLSS itself must also provide structure, electrical, and plumbing to keep the system together and functional. The packaging factors for the Apollo, EMU, and xEMU suits are shown above in Table 2.

Between the Apollo and EMU PLSS, it can be surmised that there is a tradeoff between volume and mass. In Table 2 for suits with higher mass packaging factors there is a lower volume factor and vice versa. For a small volume suit, mass will increase, or for a lower mass suit, volume will increase. It is postulated that a larger volume provides more flexibility on structural design allowing for more efficient mass savings, if the volume is not restricted. There are also external architecture requirements that drive favoring volume or mass for packaging. For instance, the airlock hatch size on the ISS defines the maximum depth of the EMU PLSS which would decrease volume and increase complexity and mass.

Apollo used Aluminum subcomponents (sheet metal and wetted Aluminum loops), since long term corrosion was not a concern [5]. On the other hand, suit mass was less of a concern when designing the EMU. It was intended for long term, multiple uses in zero-G but was constrained by a requirement to fit between inter deck hatchways, limiting its volume. Therefore, many of its systems are designed with stainless steel parts and dense packaging, which require more support structure that drives up mass [5]. It is evident that the different design philosophies and requirements for each system have guided their packaging factors.

For Mars, it is expected that lower mass will be a priority. Therefore, requirements and the design philosophy will need to be carefully selected to prioritize mass reduction and keep the mass packaging factor low. Following some of the design philosophy from Apollo suits where it can apply may help with mass. To start with, allowing for a larger volume on the Mars PLSS may be key to lowering the mass packaging factor. A Mars PLSS may also consider using components as structure like Apollo did. Additionally, investments in lighter mass systems and advanced materials such as thermoplastics may be required as aluminum cannot be considered for wetted locations due to the long-term journey to Mars.

A Mars Architecture study was recently completed [15]. While the xEMU has a packaging factor of 2.0 and was used to estimate suit mass for the Mars EMU, lower packaging factors like Apollo at 1.7 may be considered to re-model the mass estimates from the study to be able to meet overall weight budgets. Although, those packaging factors must ensure that mass is a driving factor in the design to assume certain models of schematics meet allocations.

C. PLSS/PGS Mass Allocation

To start with mass budget, the mass of the overall suit can be broken down into PLSS mass and PGS mass. Based on historical data from Table 1, the 60% PLSS and 40% PGS mass breakdown is used as a starting estimate. The PGS mass has been increasing in recent years to improve mobility, so the PGS may consider a higher mass allocation that may be adjusted during design evolution. For the 60% PLSS, 40% PGS split, a 229lbs (104kg) suit as estimated above, would have the PLSS mass to be 137 lbm (62 kg) and PGS to be 92 lbm (42 kg).

D. PLSS Mass Budget and Trades

For a 137 lbm (62 kg) initial mass allocation for the PLSS, an initial/simple approach that prioritizes mass would take the historical percentage breakdown and apply the Apollo packaging factor of 1.7. Table 7 shows a potential mass allocation breakdown to provide a starting estimate with the design based on percentages from Table

2. It should be noted that this is just an initial breakdown to help bound the design, and the exact breakdown is expected to change as the project evolves.

Table 7. Mars PLSS Initial Mass Breakdown

	Average Percent	Mars PLSS lbm (kg)
Oxygen Supply	51%	41.1 (18.6)
Thermal Loop	13%	10.4 (4.7)
Avionics	18%	14.5 (6.5)
Power Supply	16%	12.8 (5.8)
Packaging	-	56.4 (25.6)
Components	-	80.5 (36.6)
Total	-	137 (62.2)
Packaging Factor	-	1.7

In conjunction, a study is being conducted to compare all different configurations of components and stack the options by mass [15]. This study is intended to determine both the max EVA duration the suit can meet and the overall mass. From this study, a preliminary plan for designing a Mars PLSS has been started [24]. For instance, Lithium Hydroxide (LiOH) may be traded in to favor a lightweight CO_2 removal solution, but LiOH is not regenerable like the Rapid Cycle Amine (RCA) swing bed or Metal Oxide (MetOx) Canisters [24]. Also, reducing modularity to favor mass, such as integrating structure into the components or combining the backplate and hatch for the HUT, could help improve the packaging factor [24],[5]. Lastly, advanced materials are considered to lower the mass of individual components and thus overall PLSS mass by ~15% [3]. The next step will be to conduct performance assessments to further refine the estimates, which will inform the design. Furthermore, a review and adaptation of xEMU requirements to MxEMU requirements that accommodate a mass-centric design could help with both packaging and individual component/system mass. Adaptions may include items such as reduced EVA duration, single fault tolerance, and reduced terminate time [24],[15]. Additionally, communication delay with Mars may change or reduce requirements for PLSS informatics systems.

If physical design constraints do not support other mission requirements (e.g., required EVA duration), more novel approaches may be considered, such as a consumables cache or an umbilical with a follower robot for the life support system [18].

Lastly, of note, the PLSS recommended mass of 137 lbm (62 kg) is lower than the 154 lbm (70 kg) tested in the University of Maryland fall recovery study. Even though that study did not include PGS mass and other considerations, the subjects had difficulties performing the fall recovery task while wearing the 154 lbm (70 kg) PLSS, and they had significant difficulties while wearing the 220lbm (100 kg) PLSS [18]. Future verification will be required to ensure this PLSS mass combined with the PGS is acceptable.

E. PGS Mass Budget and Trades

From a pressure garment perspective, one of the largest architectural challenges for Mars is the fact that sufficient mobility is required to conduct Mars surface EVAs. But unlike lunar surface EVAs, the mass penalty associated with superior mobility (as seen in the xPGS architecture, a high mobility but heavy PGS) is incurred, resulting in diminished subject strength and increased fatigue. On the Moon, the xPGS weighs 28 lbf, but on Mars, the same suit would weigh 63 lbf. While the crew may not feel this full 63 lbf due to pressure offloading and other factors, it is still likely untenable. Advanced development of low-mass structural and bearing components are in work at NASA, but the xPGS already demonstrated significant mass savings by changing from the EMU's stainless-steel bearings to Titanium, and to fabricating a composite HUT structure. Continued development of low-mass alternatives may reduce some individual component masses by up to 30%, but others are unlikely to change or may increase due to more challenging surface impact resistance requirements for Mars.

Therefore, regardless of what a Mars PGS mass target becomes for NASA, it is very likely that a significant architectural change from the xPGS is required–one that eschews a rear entry design for a lighter waist entry design, and simplification of the mobility system (for example, soft shoulders instead of rolling convolute; elimination of ankle bearings, etc.).

As such, a reduced mass PGS for Mars may see notable mass savings in components like the HUT, shoulder, hatch, and waist brief hip, as they may benefit from both advanced material developments and mobility compromises. Conversely, components like arms, legs and EPG will likely see minimal mass savings, because they are made from soft materials, which are already low density and cannot be reduced in surface area. Other components like the helmet, EVVA, gloves and boots may see modest mass reductions through design optimization.

Additionally, one aspect that must be considered for potential mass reduction in a Mars suit is cycle life. Designing the PGS for maximum life, either in a Sustaining Lunar or long-duration Mars Design Reference Mission (DRM) context, typically requires additional mass for environmental durability and ease of maintenance. However, if a suit were to be designed to support only a limited number of EVAs (for example, a 30-day Mars surface DRM), this will allow for mass reductions due to simplification of interfaces, design for maintenance, and environmental durability.

Lastly, while the EMU and xEMU were designed for maximum sizing using adjustable axial restraint brackets and sizing rings, these sizing features significantly add to the overall mass. A custom-sized suit for each crewmember would likely result in significant mass savings, and overall improved mobility and comfort. While this has not been done since Apollo, it appears that a custom-sized EVA architecture may be considered for a Mars mission, allowing for significant improvements in PGS system mass and performance.

Going forward, it will be important to coordinate these assumptions and decisions to ensure that any Mars PGS undergoing development aligns with expected mission architectures, reference missions, and requirements.

V. Conclusion

Previous suit designs of xEMU, while sufficient for lunar EVAs, have far exceeded the mass budget for a Mars suit. The current xEMU mass is 391 lbm (177kg). An initial estimate for a Mars suit mass would suggest limit of 229 lbm (104 kg), 56% of the current xEMU mass. This assumes a 5th female crewmember, 36mL/min/kg VO_2 max fitness level, restricted mobility due to pressurized suit, pressure offload, a 51 lbm NIOSH carry limit, and 50 lbm reserved for carrying tools/samples/equipment. This estimate will require substantial testing efforts using the ARGOS test facility to verify that the estimates and breakdowns are correct and the most efficient. Regardless, the difference is large enough that even after refining the mass, significant redesign and mass savings efforts will need to be implemented to build a suit for Mars.

A Mars suit will need to be designed with a mass-centered mindset to operate efficiently. Consistent long-term direction and resources will be key to meeting this goal. Based on historical data, the preliminary estimate for a maximum Mars suit mass will be broken into 60% PLSS mass (137 lbm (62 kg)) and 40% PGS mass (92 lbm (42 kg)). Suit designers may use multiple methods to lower mass. It is expected that they will lean on the principles that kept the Apollo suit mass low, while using advanced technologies and materials available today to lower mass but maintain full capability. Furthermore, the selected crew will need to be in excellent physical condition. Appropriate exercise countermeasures for the crew will need to be implemented during/after transit to mitigate deconditioning effects and help them maintain a minimum $VO2_{max}$ (36 ml/min/kg) for EVAs.

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