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Mars Spacesuit Mass Requirements

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Historical Suit Numbers

- Mars Exploration Extravehicular Mobility Unity (MxEMU) is being developed
  – Mars gravity is 2.3 times Lunar gravity (3/8th vs 1/6th Earth gravity)
- Mass centric design will be critical to support a crewmember on Mars
- Table shows historical comparison of relative suit weights across gravity fields
  – Historically, 40% of mass has been PGS and 60% has been PLSS (+/- 5%)
  – Human weight assumes an average male at 180lbm (82kg)
- Regeneration, modularity, and fault tolerance have increased the weight of the xEMU in comparison to previous suits

Suit Relative Weight Comparison

	Apollo, lbf (N)	EMU, lbf (N)	Orlan, lbf (N)	xEMU, lbf (N)	Avg., lbf (N)
Earth PGS*	60 (266)	110 (489)	88 (391)	167 (742)	106 (472)
Earth PLSS	110 (489)	141 (627)	143 (636)	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)

PLSS and PGS Mass Breakdown

- PLSS components were bucketed below, and a packaging factor (structure, cover, manifolds, fasteners, tubing, and harnesses) is added
  - xEMU PLSS mass – 209lbm dry + 16.3lbm consumables + DCU 7.6lbm
- For PGS – increased mobility is a large weight driver
  - Apollo used the suits for crew survival as well, necessitating minimal mass, but sacrificed mobility
  - EMU was optimized for microgravity – minimal/no lower body mobility
  - xEMU PGS designed for both upper and lower body mobility

PLSS Suit Mass Breakdown

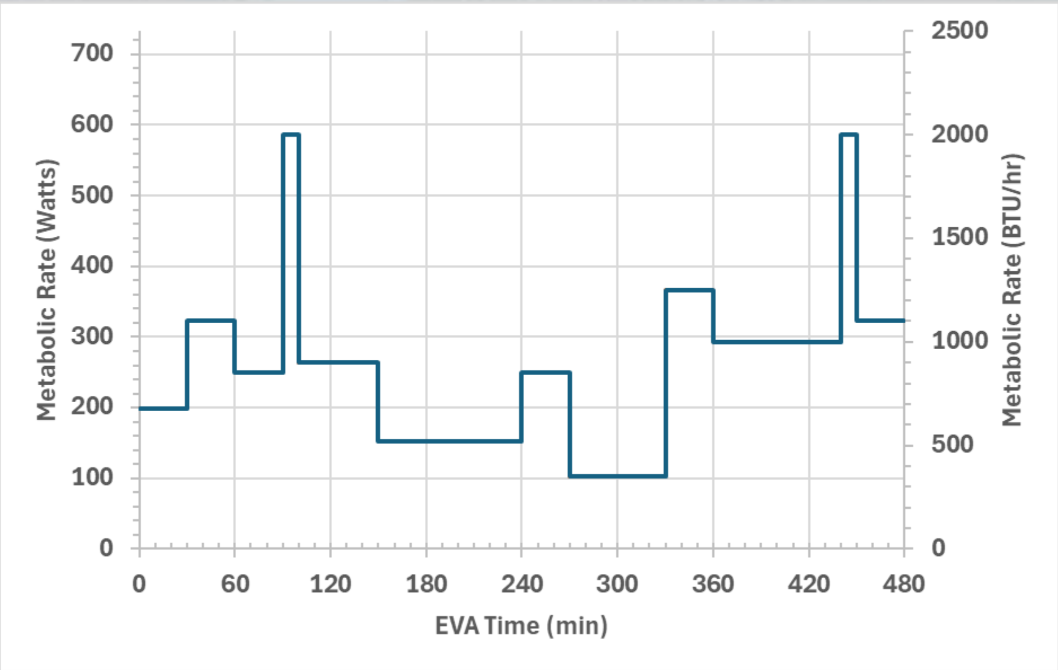
	Apollo (lbm) [5]	EMU (lbm) [5]	xEMU (lbm)	Average (lbm)
Oxygen Loop	37.1 (58%)	33.6 (51%)	47.7 (46%)	39.5 (51%)
Thermal Loop	9.6 (15%)	6.5 (9%)	14.3 (13%)	10.1 (13%)
Avionics	6.7 (10%)	15 (23%)	21.6 (21%)	14.5 (18%)
Power Supply	9.5 (15%)	10 (15%)	19.2 (18%)	12.9 (16%)
Components	63.1	65.2	103.0	77.1
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

xPGS Suit Mass Breakdown

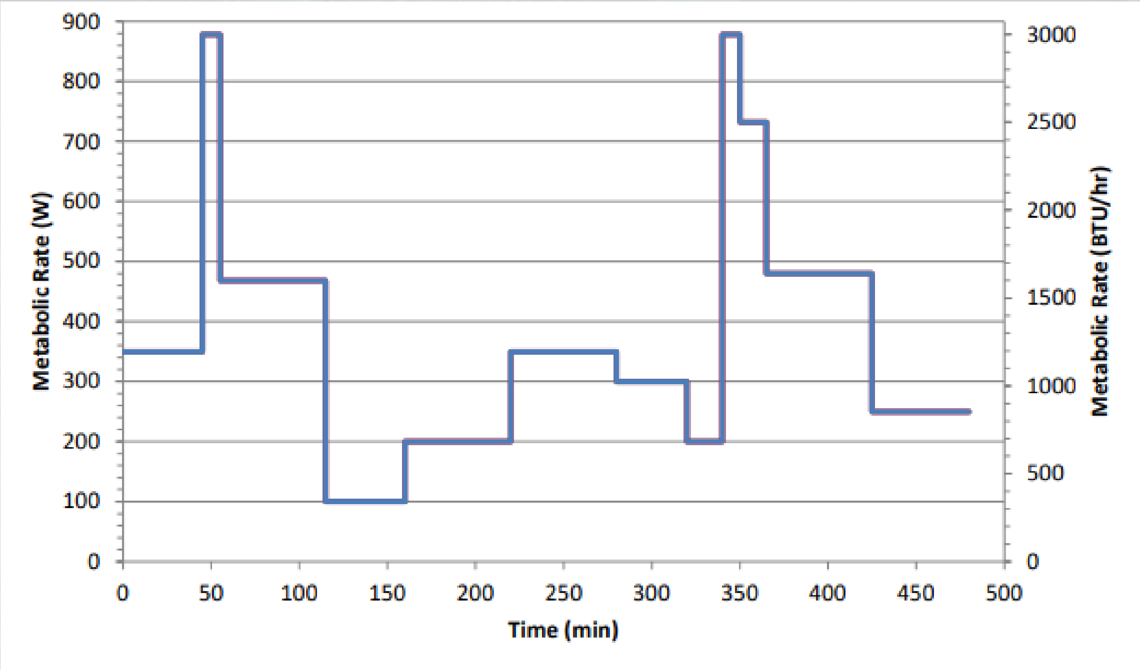
Component	Mass (lbm)
Waist brief hip (long)	36.0
Hard Upper Torso Assembly	29.0
Hatch Assembly (regular, dry)	29.0
Environmental Protection Garment (all components)	22.0
Shoulders (small)	11.5
Boots	9.4
Legs	7.3
Liquid Cooling and Ventilation Garment (LCVG) (wet)	6.5
Helmet	6.3
Arms	4.4
Extra Vehicular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

Metabolic Profiles

- Maximum mass drivers may include traverse, peak task exertion, and fall recovery
- Metabolic rate of the crewmember is estimated based on the below profiles
  - ISS/EMU requirements at 1000 BTU/hr average
  - EVAs have been increasing beyond 1000 BTU/hr avg. on ISS and future missions will be in a planetary gravity field (either Lunar or Mars) leading to an expected 1200 BTU/hr for future mission sizing



ISS EVA Metabolic Load Profile



xEMU Max Transient Metabolic Profile

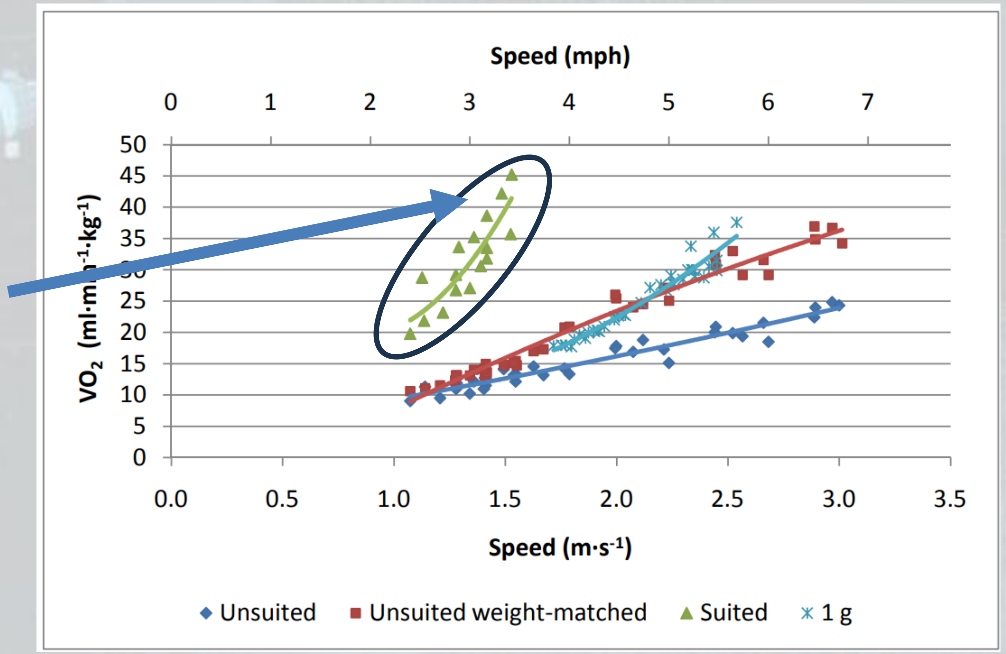
Existing Studies

- There are limited suit studies for Mars gravity testing, though they help give an idea of the challenges expected on Mars
- **10-km Walkback Study**
  - This NASA study tested suited performance for a 10km walkback at both lunar and Mars gravity offloads for a fixed suit mass
  - Did not vary weights
  - Did not test at lower walking speeds (2.2mph was considered maximum nominal speed for Apollo)
  - Demonstrated a significant effort in operating in Mars gravity
- **Fall Recovery Testing**
  - University of Maryland tested fall recovery with a weighted PLSS in their buoyancy lab
  - Demonstrated significant mobility challenges with PLSS weights tested (both 70 and 100 kg)
  - Was not suited/pressurized (wetsuit only)

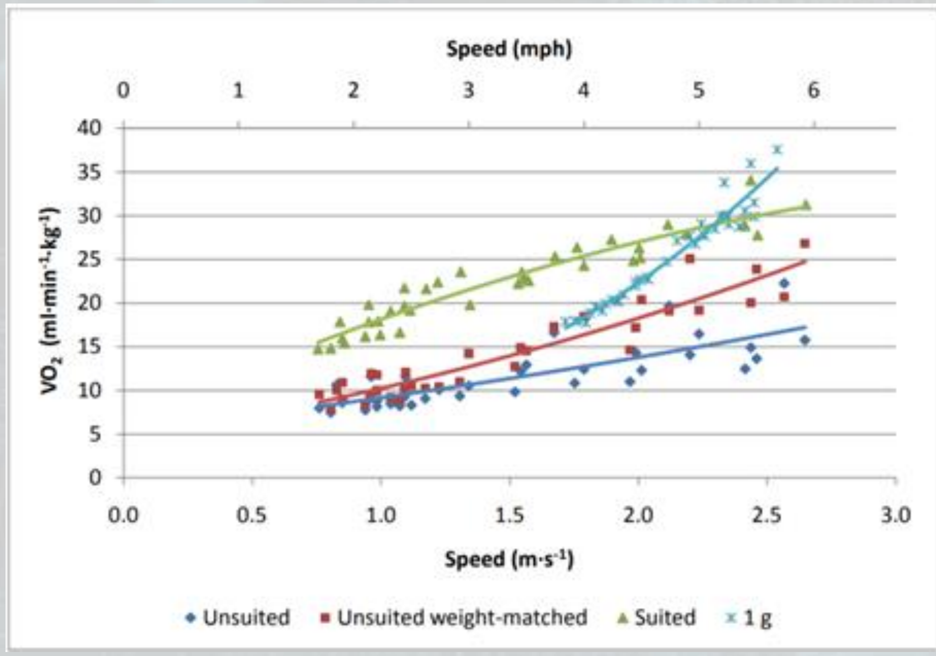
10-km Walkback Study

Fall Recovery Testing

Hits $VO2_{max}$ at 3.5mph on Mars



Martian Offloading



Lunar Offloading

10-km Walkback Study Data

Aerobic Modeling for Maximum Suit Mass

- To model a maximum suit mass with existing data, aerobic maximums are used as a limiting factor for walk backs
- Metabolic rate can be correlated to mass and VO2 rates assuming an average respiratory rate
  - Note VO2 is sometimes reported in L/min and other times ml/min/kg and must be converted depending on the application
- $VO2_{max}$ (ml/min/kg) has a minimum flight rule set at 36 ml/min/kg for EVA
  - Nominal VO2 should not exceed 35% $VO2_{max}$ for an 8-hour workday, or 50% if trained for aerobic, and ~35% for anerobic (lifting)
  - Crewmembers may be expected to handle ~43% $VO2_{max}$ for an EVA due to training and mix of aerobic and anerobic work
  - For a 5th percentile female, this would be 760 – 1100 BTU/hr (35-50% $VO2_{max}$)
  - Future missions may consider heightened requirements (weight and $VO2_{max}$ minimum) to meet higher exploration requirements (1200 BTU/hr average)

$VO2_{max}$ 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

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)

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

$$MetRate\left(\frac{kcal}{min}\right) = 4.039\left(\frac{kcal}{L}\right) * VO2\left(\frac{L}{min}\right) + 1.157\left(\frac{kcal}{L}\right) * VCO2\left(\frac{L}{min}\right)$$

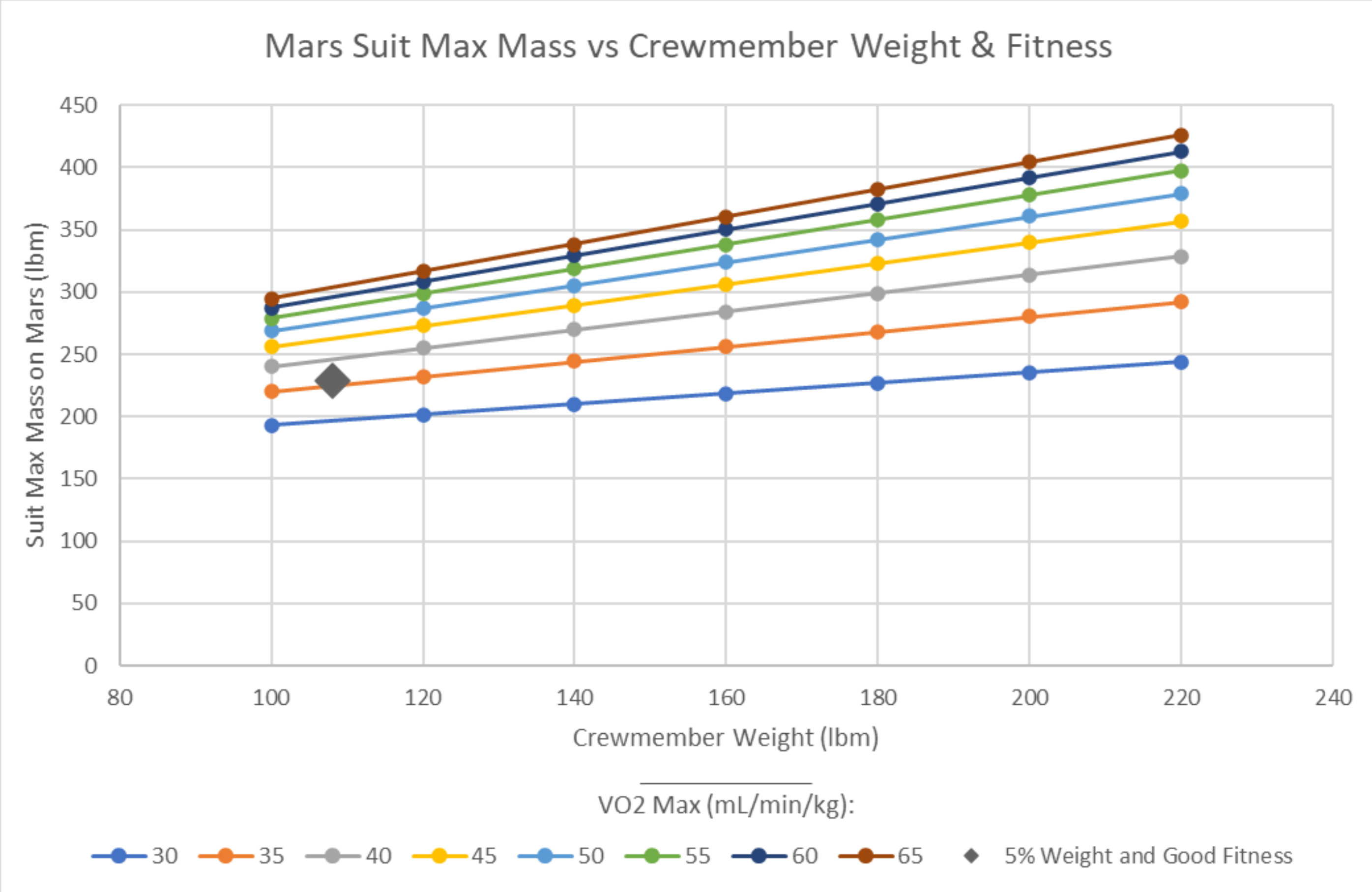
$$MetRate\left(\frac{BTU}{hr}\right) = (0.961 + (0.275 * RER)) * VO_2\left(\frac{ml}{min * kg}\right) * mass(kg)$$

Considerations

- **Crew Physical Characteristics**
  - For current mission profiles, missions must consider 1^{st} to 99^{th} percentiles in potential crew masses
  - Mars may consider more limitations such as 5^{th} – 95^{th} percentile to be in line with previous requirements/Apollo including custom sizing suits
- **NIOSH Carry Limit**
  - NIOSH max carry weight limit is 51 lbf for lifting loads
- **Suit Restricted Mobility**
  - Based on the 10km walkback study, it is estimated approximately 14 VO2 (ml/min/kg) is added against baseline unsuited walking due to the pressurized suit restrictions
- **Deconditioning**
  - Deconditioning is expected to decrease $VO2_{max}$ by approx. 15-25% based on historical evidence
  - At the time of EVA, a crewmember is expected to have 36ml/min/kg $VO2_{max}$. Therefore, at time of launch, a crewmember should have 15-25% higher $VO2_{max}$ (43-49 ml/min/kg)
- **Pressure Offload**
  - The pressurized column of the suit provides a net force to offload some of the mass off the shoulder of the astronaut
  - During walking this is approximately 48lbf based on testing
- **Tool/Sample Carry Mass**
  - A 50 lbm of tool/sample weight is assumed in estimations

Initial Estimates

- System Mass is a combination of suit, crew, and carry mass
  - $System_{mass} = (Suit_{mass} + Crew_{mass} + Carry_{mass})$
- The perceived force the crewmember feels is a combination of system force on Mars minus the pressure offload
  - $Crew\ Percieved\ Mars_{force\ (f)} = System_{mass} * Accel._{Mars} - Pressure\ Offload_f$
- The crew capability is a combination of the crew mass on Earth, and the NIOSH carry load reduced by the restricted mobility factor
  - $Crew\ Capability_f = \left(Crew_{f,earth} + NIOSH_{f,earth}\right) * \ Restricted\ Mobility_{\%}$
- The max suit mass is determined by setting the crew perceived force equal to the crew capability and solving for suit mass
  - $Max\ Suit_{mass} = \left(\frac{(Crew_f + NIOSH_f) * Restricted\ Mobility_{\%} + Pressure\ Offload_{lbf}}{Accel._{Mars}}\right) - Crew_{mass} - Carry_{mass}$
- For a 5th percentile female (108lbm) with the 36 ml/min/kg VO2max requirement – results in a total suit mass of **229lbm (104kg)**
  - This will be 40% less than the xEMU (376lbm – 170kg)



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

Significant suit mass reduction for Mars will be required

Walking Speed and Walkback

- Average walking speed on earth is 3.1 mph
- Apollo EVA average walking speed
  - Failed rover walkback assumption: 2.2 mph <1hour (1.7mph for >1hour)
  - Apollo 15: 0.7-1 mph (first EVA), 1-1.4mph (second EVA)
- Walkback after failure
  - Walkback from a failure is assumed as limiting case for most EVA backup sizing and maximum distance away from the craft
  - Assuming either 30 minute or 1-hour walkback and 2.2mph walkback this is a maximum radius away from the craft of 1.1 miles (30 minute) or 2.2 miles (1 hour)
  - With mass constraints, the 30-minute walkback may be preferred so the design will close
- Metabolic rates during walkback – assuming RER at 0.85
  - Average crewmember would have 1700 BTU/hr
  - Large (95th percentile mass) crewmember would be 2300 BTU/hr
  - While higher than average of 1200 BTU/hr, traverse tasks are considered above average effort tasks, though the backup systems must be sized with this in mind
- Comparison to walkback study
  - Assuming a 50% maximum exertion of $VO2_{max}$ for walkback (18ml/min/kg (36ml/min/kg *50%)), at 2.2mph this would be 19ml/min/kg based on the walkback study
  - A slightly lighter weight suit compared to the walkback suit (265lbm) could be tenable – though more testing is required.

Validation of Model – Argos Testing

- To validate and/or refine the prior model, a suited test using Active Response Gravity Offload System (ARGOS) will be required
  - The PLSS mass will be varied for a parameterized test
  - The above model will help bound the upper and lower limits of the PLSS mass
  - Test will include a pressurized PGS
  - Subjects will be varied to cover a wide range of crewmembers
- Test will gather gait, task kinematics, metabolic rate, heart rate, workload, and subjective workload ratings
- Data from this effort will continue to aid in MxEMU suited requirements by generating crew physiology modeling states based on EVA workload

Prior 10-km Walkback Study

Packaging Factors

- Packaging factor is the ratio of total system mass/volume to combined component mass/volume
- There is a tradeoff between volume and mass packaging factors
  - Apollo had a high low packaging factor, and high volume, while EMU was opposite
  - Smaller volume suits - mass will increase
  - Larger volume provide more flexibility on structural design allowing for mass savings
- EMU was limited in depth/volume to fit in between inter deck hatchways
- Apollo used components as structure to save weight rather than a monolithic structure system like the backplate on the xEMU
  - This creates a more integrated, less modular suit
- A larger volume Mars PLSS with integrated components may be considered to reduce mass

PLSS Suit Mass Breakdown

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Suit Mass Budget Strategy Proposed

- Based on historical data, the PLSS is typically 60% of the suit mass, and the PGS is 40% of the suit mass
  - This is applied here for the 229 lbm (104kg) limit
- PLSS Mass Budget Strategy
  - Larger volume factor to provide flexibility for lower system mass
  - Return to single fault tolerant such as EMU/Apollo
  - Reduce modularity, while favoring integration and using components for structure
  - Reduce regeneration options
  - Reduced EVA time
- PGS Mass Budget Strategy
  - Emphasis on improved mobility, while balancing mass
  - Lighter, waist entry design
  - Reduced cycle life
  - Custom suit sizing
- Both
  - Implement lightweight advanced materials
  - Increased crew fitness, tightened crew sizing requirements, and exercise countermeasures

Mars Suit Mass Allocation

Subsystem	Mass	%
PLSS Mass	137 lbm (62kg)	60%
PGS Mass	92lbm (42kg)	40%
Overall Suit Mass	229lbm (104kg)	

Mars PLSS Subsystem Mass Allocation

	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

Conclusion

- The current government reference design (xEMU) is 376lbm (170kg)
  - Mars suits are estimated to have a maximum of **229lbm (104kg)**
  - Mars suits will require a 40% mass savings compared to xEMU
- ARGOS testing will be required to verify and validate this estimate
- Walkback and maximum radius from craft will need to be limited in distance to allow return to cabin in case of failure
- Split between PGS (40%) and PLSS (60%) historically
  - 137 lbm (62kg) for the PLSS and 92lbm (42kg) for the PGS
- Mars suit will need to be designed with a mass centered focus to operate
  - Lean on Apollo principles to save mass: integrated, custom design, single fault tolerant
  - Reduced EVA time
  - Implement advanced materials
  - Increased crew fitness, tightened crew sizing, and exercise countermeasures

Thank you!

Questions?

For references, please see associated paper

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