Designing for Outer Space:

Design, UX &HMI Development for Next Generation Space Suits

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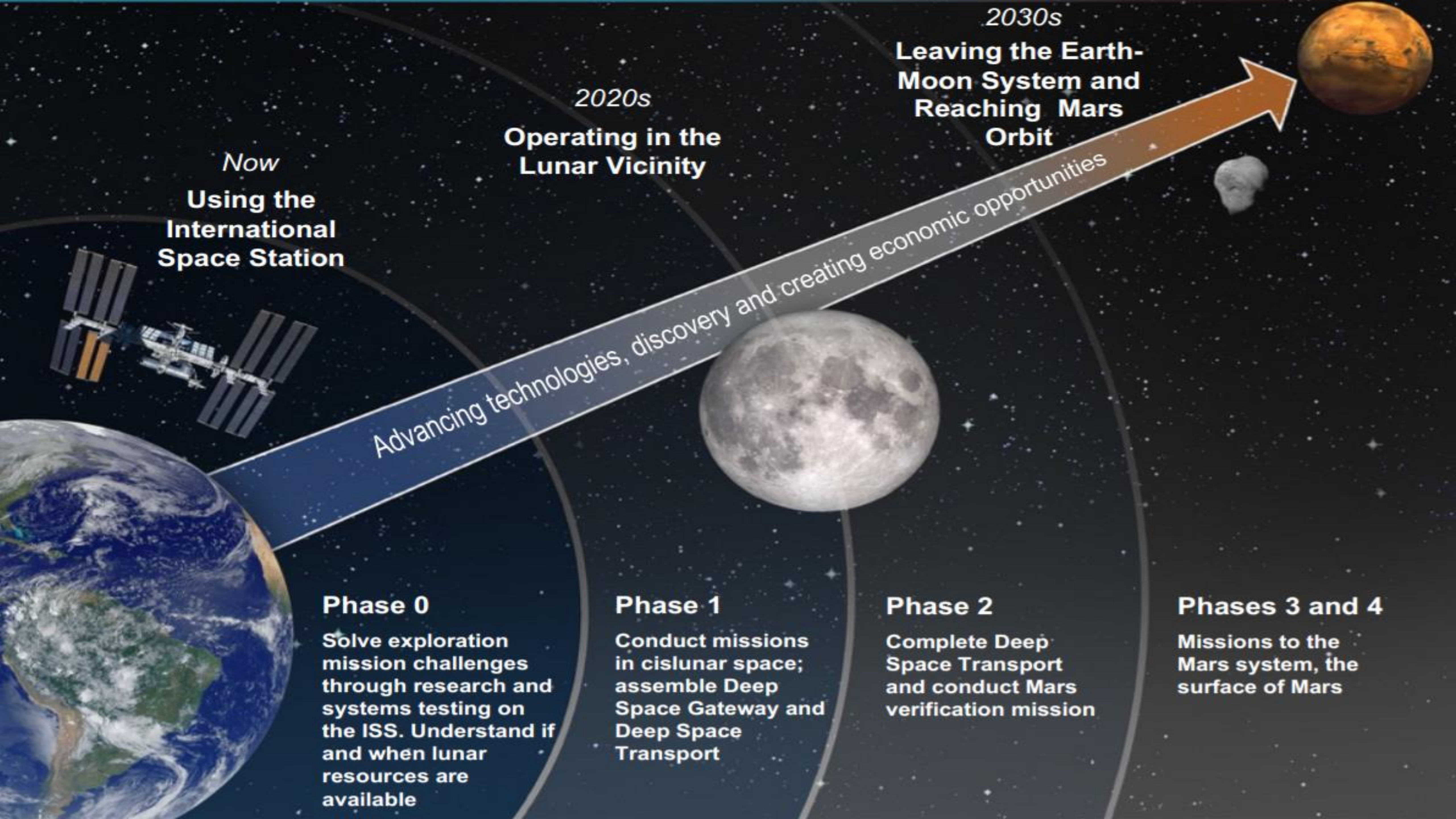


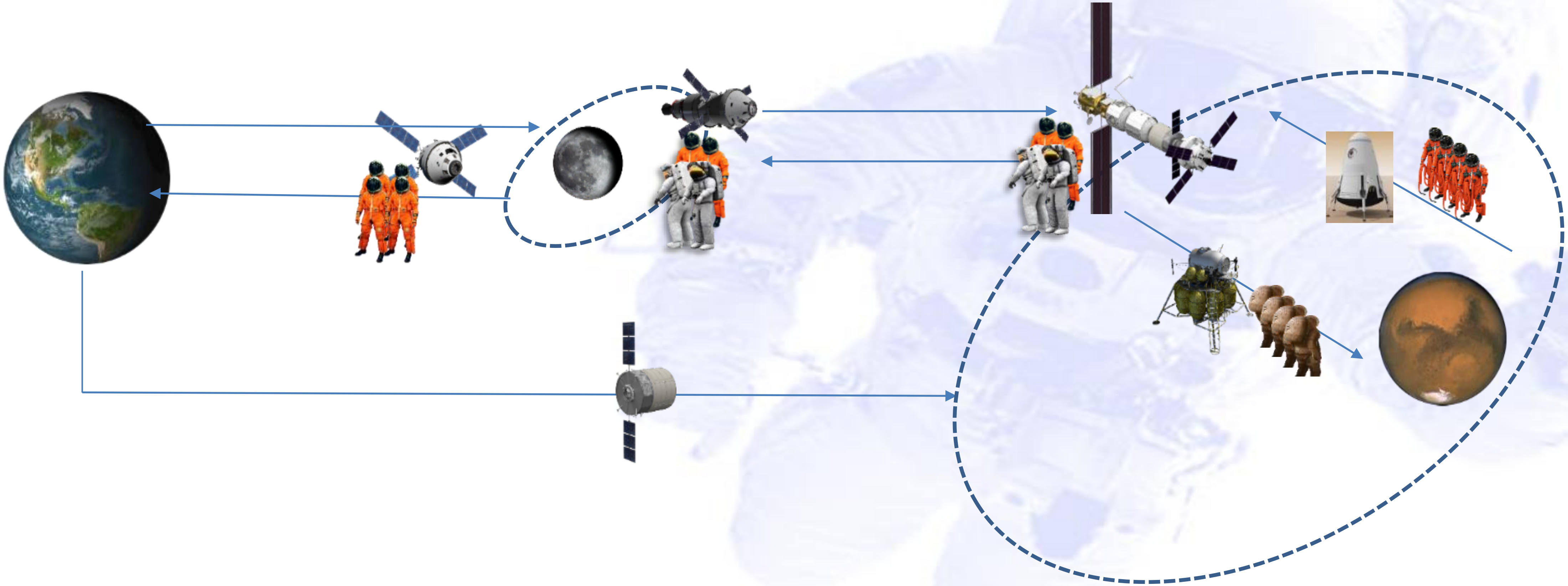
Now
Using the International Space Station
2020s
Operating in the Lunar Vicinity
2030s
Leaving the Earth-Moon System and Reaching Mars Orbit
Advancing technologies, discovery and creating economic opportunities
Phase 0
Solve exploration mission challenges through research and systems testing on the ISS. Understand if and when lunar resources are available
Phase 1
Conduct missions in cislunar space; assemble Deep Space Gateway and Deep Space Transport
Phase 2
Complete Deep Space Transport and conduct Mars verification mission
Phases 3 and 4
Missions to the Mars system, the surface of Mars

Role of the Space Suit

- Protect astronaut from environmental hazards in all mission phases
  - Minimal pressure environment
  - No breathable atmosphere
  - Micrometeoroids
  - Thermal extremes
  - Radiation
  - Toxic substances
- Enable astronaut to efficiently perform work in mission phases
  - Unpressurized mobility to operate vehicles and access safe havens
  - Pressurized mobility to construct/maintain habitats and perform science
  - Operate, configure, stow, and transport tools
  - Ingress, egress, and receive consumables from vehicles

Notional Mission Concept Definition

Mars Vicinity & Surface

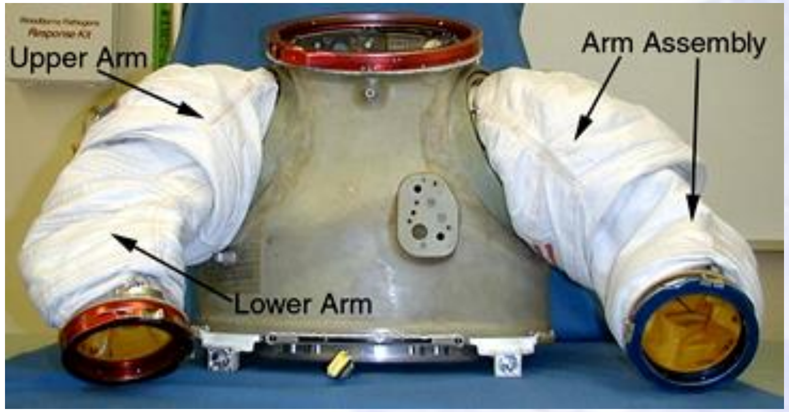


Design for Flexible Architecture

1. Identify architecture driving parameters from mission and system perspectives
2. Establish boundary cases for each parameter
3. Generate a reference design based on most likely scenario
4. Validate reference architecture using combination of prototype testing and analysis with increasing fidelity
5. Document impacts and first level detail of alternate approach when decisions must be made to mature integrated system at cost of precluding one or more future development paths

Parameter	Bounding Cases	Impact
Gravity Field	0g – 0.38g	Mobility
Dust/Dirt	None- Chemically Reactive	Softgoods wear
EVA Duration	4h – 8 h	Wear, mass
EVA Frequency	2/month – 4/week	Wear, Logistics
EVA Tasks	Assembly - Science	Mobility
Airlock Type	Airlock - Suitport	Upper torso
# Crew / Mission	2 - 6	Sparing, Logistics
Logistics Flow	No resupply-6 mo	Sparing, Logistics
Crew Anthropometry	1^{st}-99^{th} percentiles	Sparing, Logistics, Customization

Primary Pressure Garment Assemblies



EMU Upper Torso

EMU Lower Torso

EMU Helmet with EVVA and ERCA

Phase VI Gloves

EMU Boots

Upper Torso Architecture Driving Requirements

- Vehicle Interfaces
  - Don/doff fixture (rear entry vs. waist entry)
  - Consumables routing (connectors on and off suit)
- Mobility
  - Defines shoulder/arm mobility by placement of shoulder bearings
  - Impacts cross-reach by placement of life support controls
- Visibility
  - Helmet interface angle impacts
- Sizing
  - Inter-related with mobility, fit, and comfort such that a detriment in one will affect performance overall
  - Choices on sizing both affect and are affected by launch mass, logistics chain, and sparing philosophies

Sizing vs. Fit

- Fit is a subjective term implying a garment that is both aesthetically pleasing and a pleasure to wear
  - For functional clothing, also enables usability for intended tasks
- NASA Programs dictate fit requirements in terms of generic percentiles that must be further decomposed by the applicable systems
  - Space Shuttle Extravehicular Mobility Unit (EMU) was required to fit crew from the 5^{th} to 95^{th} percentiles
  - Constellation Program mandated all systems accommodate 1^{st} to 99^{th} percentiles
- NASA has historically interpreted fit as synonymous with sizing
  - Range of space suit sizing considered to meet requirements when the design can be shown analytically to be scaled to fit the desired population
  - Approach fails to consider dynamic fit of garments that can and do impact the wearer's ability perform tasks

Adjustability Required for “Full Range”

Dimensions (in inches)	1st		5th		95th		99th
Stature	58.5	-1.7	60.2	14.5	74.7	1.9	76.6
Eye height- sitting	26.2	-0.9	27.1	6.9	34	1.0	35
Hip breadth- sitting	12.4	-0.7	13.1	4.4	17.5	0.8	18.3
Bideltoid breadth	14.9	-0.7	15.6	5.7	21.3	0.8	22.1
Foot length	8.5	-0.3	8.8	2.8	11.6	0.4	12

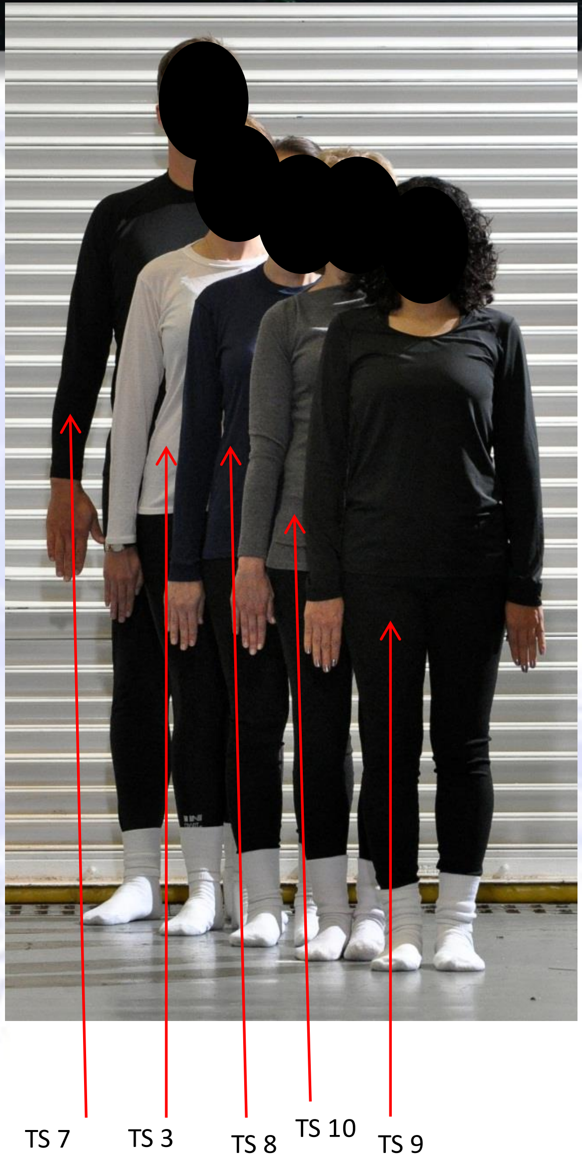
Accommodating the “full range” of adjustability requires a trade between cost, logistics, and performance.

Source: Rajulu, S. and J. Dory; “Anthropometric Requirements for Constellation” Report to NASA Advisory Council, July 15, 2009

Percentile Fallacy

Table 1. Percentile Variation for Small Females (%)

	TS2 (%)	TS3 (%)	CM4 (%)	CM5 (%)	CM6 (%)	TS8 (%)	TS9 (%)	TS10 (%)
Biacromial Breadth	6	28	67	60	28	1	1	1
Bicep Circ.	93	56			13	20	28	47
Bi-Deltoid	44	57	10	24	4	13	3	13
Chest Breadth	91	61			34	45	45	12
Crotch Height	49	82	60	38	7	30	14	38
Hip Breadth	95	76	25	65	1	35	21	67
Stature	60	92	61	70	4	67	18	43



No such thing as a completely 5th percentile person – we're all a combination of several percentiles

Notes: Blue = minimum %-ile, Gold = maximum %-ile, CM = Crewmember, TS = Test Subject

Space Suit Critical Dimensions

Design Concern	Critical Dimension	Numerical Code from Table B1-1	Minimal Clothing	
			Min (cm [in])	Max (cm [in])
Maximum vertical clearance	Stature, standing	805	148.6 (58.5)	194.6 (76.6)
Placement of headrest	Vertical trunk diameter	N/A	55.9 (22.0)	75.9 (29.9)
Leg length	Crotch height	249	66.5 (26.2)	95.8 (37.7)
Knee break	Knee height mid-patella	873	39.6 (15.6)	57.9 (22.8)
Torso sizing	Chest breadth	223	23.6 (9.3)	39.4 (15.5)
Torso sizing	Chest depth	236	19.1 (7.5)	30.2 (11.9)
Neck ring and helmet sizing	Head length	441	17.3 (6.8)	21.6 (8.5)
Maximum circumference of upper leg	Thigh circumference	852	47.8 (18.8)	71.9 (28.3)
Maximum circumference of upper arm	Biceps circumference flexed	111	22.9 (9.0)	40.4 (15.9)
Torso sizing	Chest circumference	230	75.7 (29.8)	118.6 (46.7)
Arm sizing	Inter-wrist distance	N/A	115.1 (45.3)	161.8 (63.7)
Functional arm break, arm length	Inter-elbow distance	N/A	72.6 (28.6)	101.3 (39.9)
Lower torso sizing	Waist depth	N/A	15.0 (5.9)	30.0 (11.8)
Lower torso sizing	Hip breadth	457*	29.7 (11.7)	40.6 (16.0)
Arm sizing	Wrist-to-wall distance	N/A	54.6 (21.5)	77.7 (30.6)

*For standing measurements, the largest female hip breadth is larger than the largest male hip breadth; therefore, female data are used for both the Min dimension and the Max dimension.

Z-2 Pressure Garment Development

- Goal of project was to validate pressure garment mobility architecture and sizing approach for smaller sized crew
- Design of upper torso was meant to address most common complaints about the current ISS space suit
  - Lack of overhead mobility
  - Reduced work envelope for those with short arms and/or narrow shoulders
  - Reduced visibility for those with shorter torsos
  - Contact with shoulder bearings during task completion
- Budget and schedule only permitted single build of upper torso
  - Anthropometric requirements reduced to target smaller range
  - Selected specific maximum and minimums based off anthropometries of identified crew and engineering test subjects

Z-2 Sizing Requirement Selection

ID	Gender	Stature (cm)	Vertical Trunk Diameter (cm)	Chest breadth (cm)	Expanded Chest Depth (cm)	Waist depth (cm)	Hip breadth (cm)	Chest circumference (cm)	Buttock Circumference (cm)	Thigh circumference (cm)	Knee height mid-patella (cm)	Crotch height (cm)	Biceps circumference flexed (cm)	Wrist-to-wall distance (cm)	Inter-elbow distance (cm)	Inter-wrist distance (cm)	Head breadth (cm)	Head length (cm)
1	F	174.5	67.0	31.1	N/A	24.0	38.3	94.5	N/A	65.2	N/A	78.5	31.1	63.0	87.5	134.9	17.0	21.9
5	M	185.0	71.2	31.6	25.9	21.3	35.1	99.1	99.6	58.8	49.7	85.5	33.6	64.4	92.5	145.8	16.1	21.3
6	M	174.4	71.2	32.5	25.6	24.2	35.7	101.0	97.6	56.7	47.9	79.2	32.4	61.3	89.8	137.7	17.1	22.2
8	M	176.0	73.8	33.3	26.4	23.2	35.0	104.2	97.7	58.0	47.6	76.2	35.4	59.5	87.3	136.8	16.6	22.0
9	M	182.7	72.3	32.2	26.7	20.5	34.0	102.1	91.6	56.9	50.1	86.2	35.6	66.1	92.2	143.1	17.0	21.0
11	M	175.2	69.6	30.6	23.7	21.2	33.2	93.5	91.6	55.7	49.2	78.7	34.1	62.4	89.9	137.1	16.6	21.0
13	M	N/A	69.4	34.1	28.0	N/A	36.6	105.5	N/A	N/A	N/A	76.8	N/A	N/A	N/A	137.5	N/A	N/A
14	M	N/A	70.5	32.2	27.0	N/A	35.2	99.2	N/A	N/A	N/A	79.4	N/A	N/A	N/A	143.0	N/A	N/A
16	M	173.9	69.3	33.4	28.4	23.7	33.4	101.8	N/A	58.1	47.2	76.5	36.1	63.8	89.9	138.0	16.6	21.6
24	M	183.6	73.0	34.0	25.7	23.6	34.9	96.3	N/A	60.0	50.4	82.9	33.4	65.6	92.7	146.6	15.2	20.2
27	M	179.5	69.5	34.3	26.2	24.3	36.6	94.3	N/A	56.9	49.0	80.3	34.9	66.2	91.5	145.8	15.5	19.5
28	M	177.5	71.1	35.7	25.7	25.0	34.9	96.5	N/A	61.4	47.9	76.3	36.4	65.9	86.1	138.6	15.2	19.6
29	M	171.2	68.5	31.8	24.6	23.6	35.2	97.9	N/A	64.2	N/A	75.3	34.5	62.1	85.1	134.0	17.1	20.1
32	M	175.2	66.6	30.2	23.5	20.8	33.2	95.8	N/A	56.7	49.6	80.3	33.7	67.9	89.9	142.5	15.9	20.6
33	M	176.4	67.4	34.9	25.3	22.9	33.4	101.9	N/A	60.7	50.0	79.2	34.7	65.9	93.9	145.2	16.3	20.5
highlight indicates critical hierarch cluster result									109.2									
Font color indicates ENGR subject																		
Group MEAN		177.3	70.0	32.8	25.9	22.9	35.0	98.9	95.6	59.2	49.0	79.4	34.3	64.2	89.9	140.4		
Group MIN		171.2	66.6	30.2	23.5	20.5	33.2	93.5	91.6	55.7	47.2	75.3	31.1	59.5	85.1	134.0		
Group MAX		185.0	73.8	35.7	28.4	25.0	38.3	105.5	99.6	65.2	50.4	86.2	36.4	67.9	93.9	146.6		
Group Range		13.8	7.2	5.6	4.9	4.5	5.1	11.9	8.0	9.5	3.2	10.9	5.3	8.4	8.8	12.6		
Goal Range		25.4	7.6	7.6	5.1	5.1	5.1	20.3	12.7		10.2	15.2		10.2	10.2	20.3		

Z-2 Size Range

- Required Z-2 to "fit" reduced range of 13 critical dimensions
  - Fit was defined as "the ability to work efficiently without unreasonable size-related deficiencies, loss of circulation, or pressure points."
- Included specific maximum ranges for adjustability within single component
  - Ranges selected from lessons learned on previous design iterations

Single Size Suit Adjustability Ranges Compared to Percentiles for Critical Dimensions

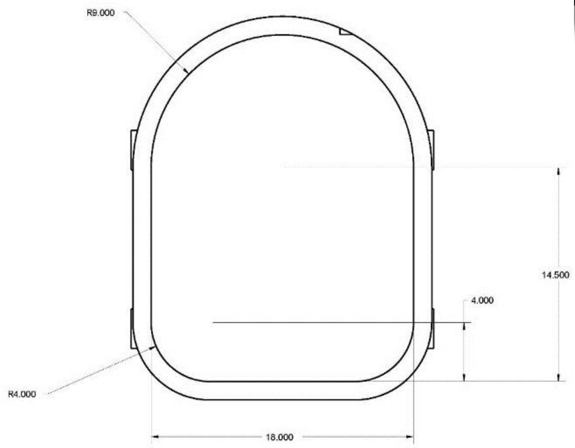
	Stature (in)	Vertical Trunk Dia. (in)	Chest breadth (in)	Expanded Chest Depth (in)	Hip breadth (in)	Chest circ. (in)	Thigh circ. (in)	Knee height (in)	Crotch height (in)	Biceps circ. flex (in)	Wrist-to-wall dist. (in)
Req Min	64.0	24.5	11.5	10	13.5	38	24	17.5	29.0	12	24
Req Max	71.0	27.0	13.5	11	15.0	41.0	26.0	19.5	32.0	14.0	26.5
Req Min	47F		61F/9M	63F/56M	34F/39M	71F/26M	64F/56M	31F	25F	75F/12M	36F
Req Max	60M		69M	92F/90M	90F/94M	94F/65M	92F/88M	93F/25M	86F/21M	73M	95F

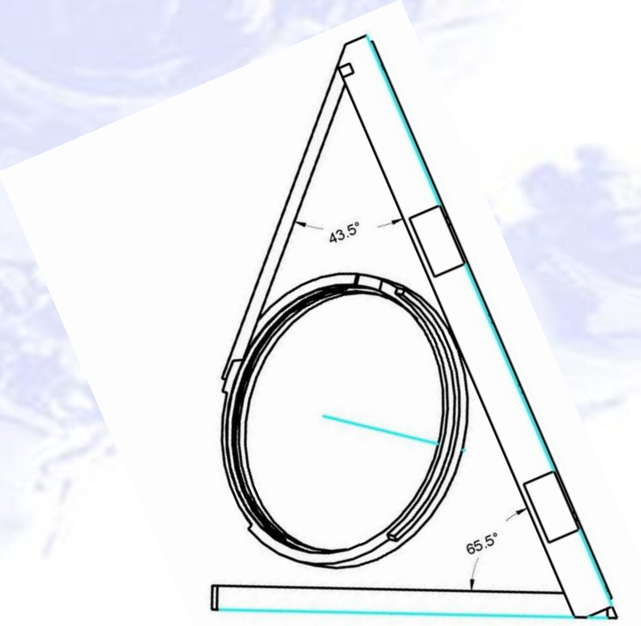
Anticipated Fit for Targeted Individuals Within Z-2 Single Size*

No Fit (Low)	Maybe (Low)	In-range	Maybe (High)	No fit (High)
1	3	25	5	3

Prioritization of Features

- Hatch
  - Highly desired to have same rear-entry hatch geometry across all sizes
  - Angle relative to vertical established as most advantageous for don/doff in previous prototype iteration
- Waist Disconnect Diameter
  - Highly desired to have single size interface between all upper and lower torsos
- Shoulder Bearings
  - Ideal orientation (pitch, yaw, roll) established over 20 years of testing
  - Adjustments in diameter and spacing between bearings critical to increasing mobility and avoiding injury





Shoulder Bearing Spacing

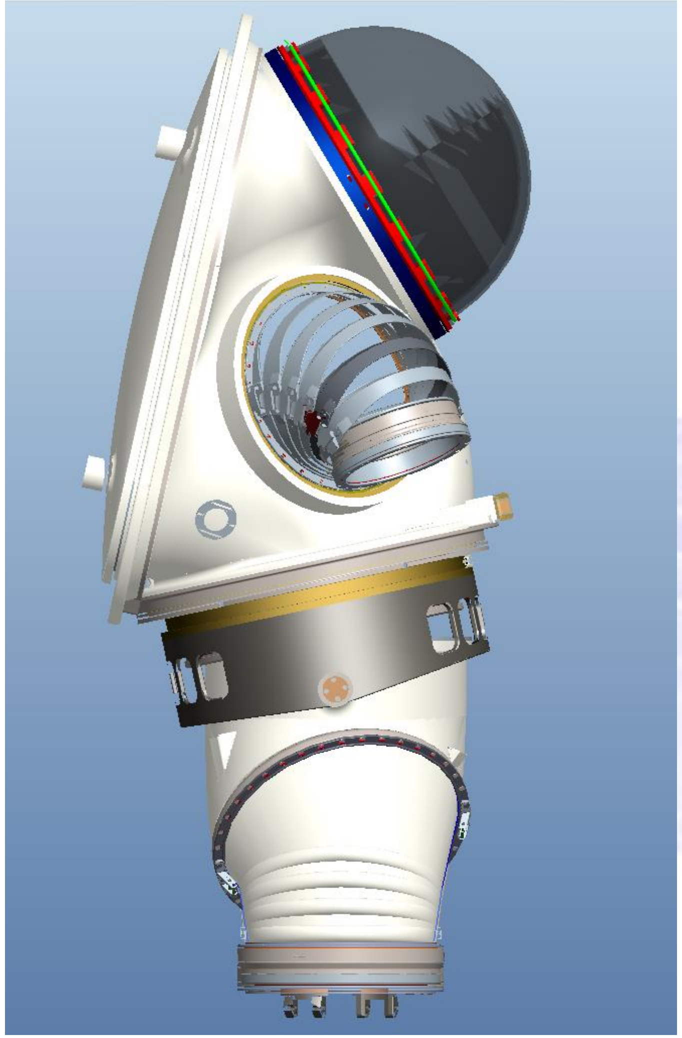
- Goals:
  - Avoid contact with acromion through full range of motion
  - Avoid neck impingement
  - Able to insert and remove arms in biomechanically favorable manner
  - Minimize total number of upper torsos required when range expanded to include full crew population

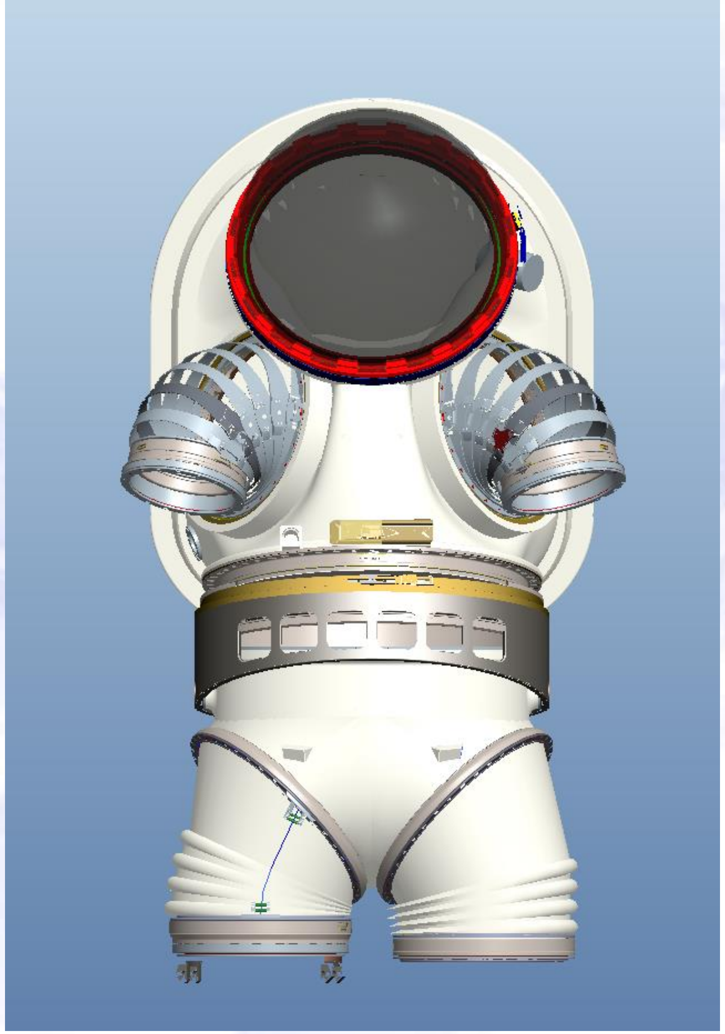
Ideal placement of shoulder joint relative to shoulder bearings

Shoulder Bearing Spacing

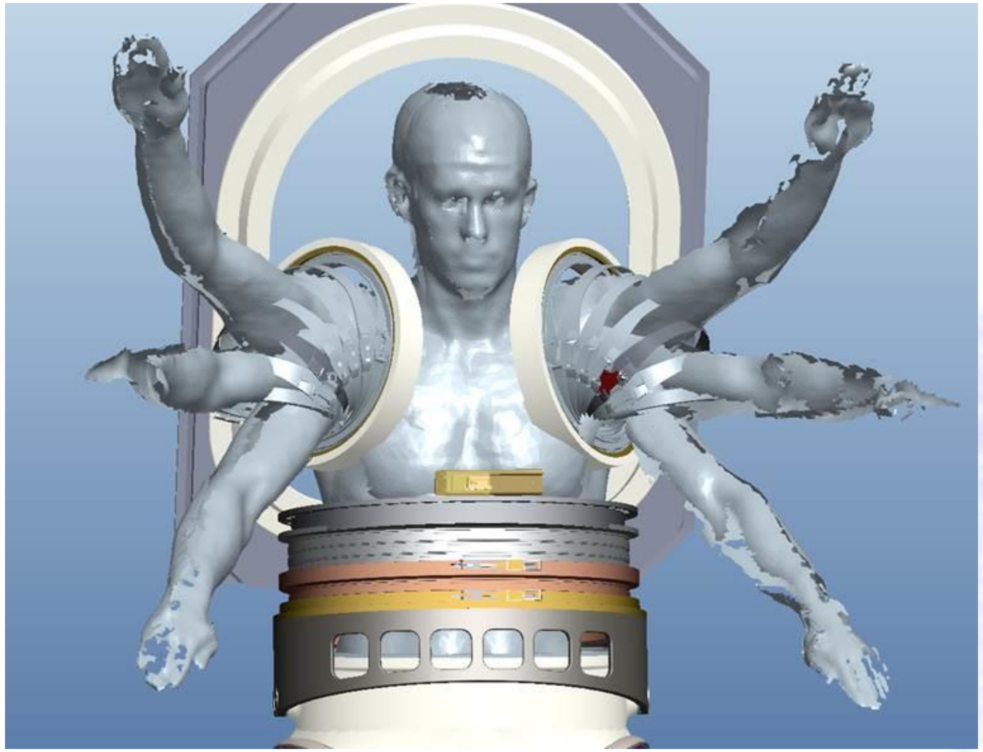
Comparison of 10in. diameter shoulder bearings spaced 7.5 in. (left) vs 10 in. (right) on 3D scan of subject with 5 %-ile bi-acromial breadth

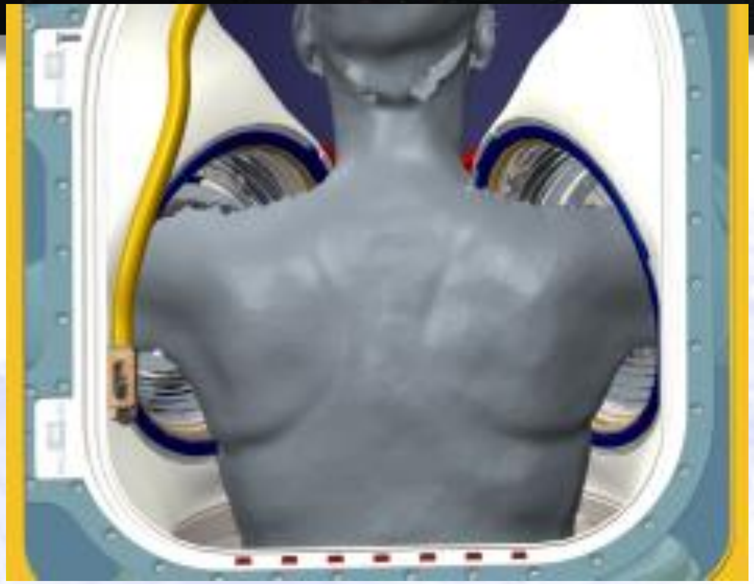
Complete Modelling of Upper Torso

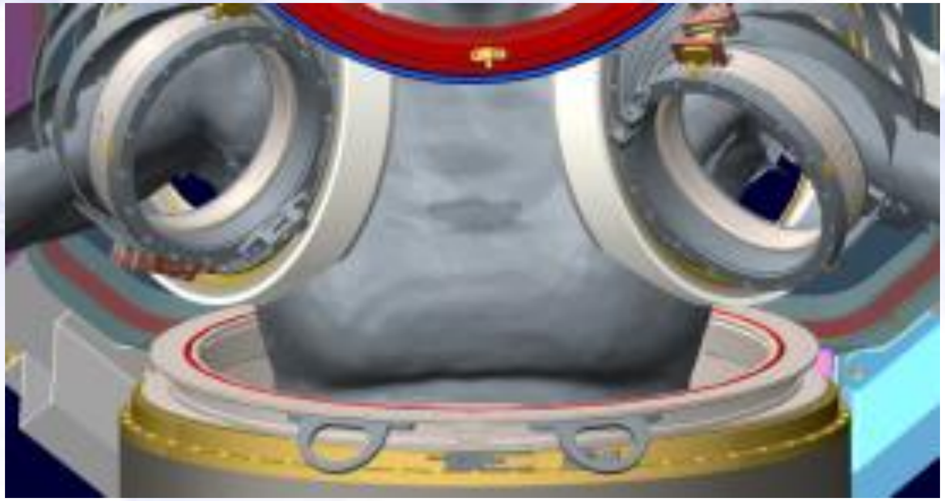




Digital Fit-checks







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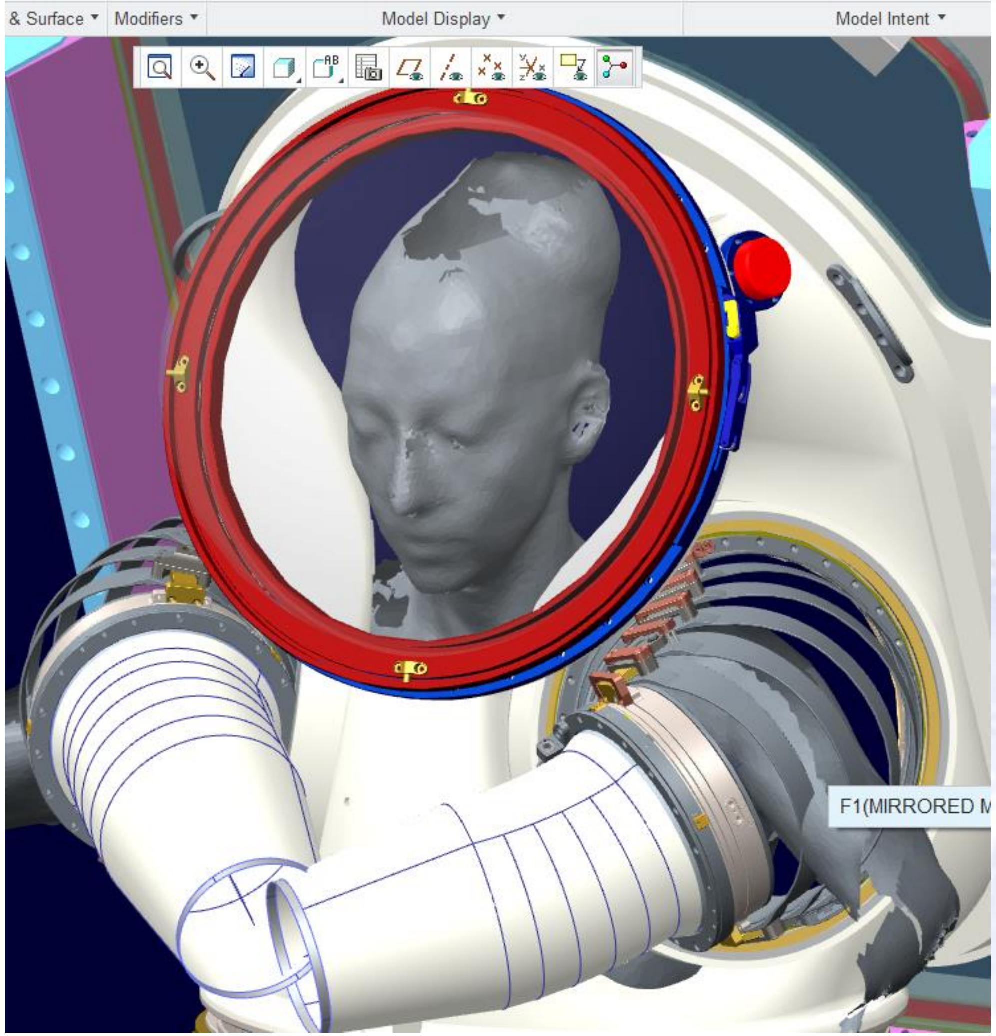
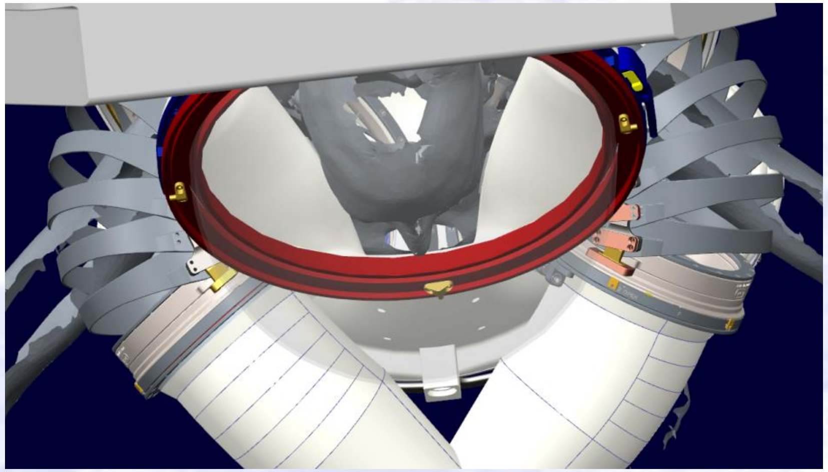
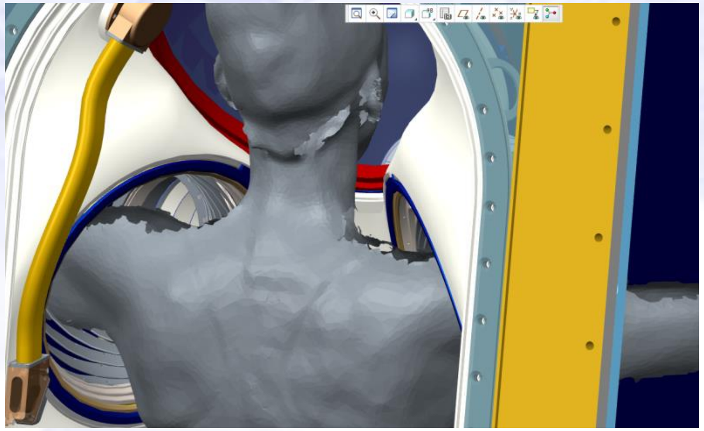






Fit Verification Prototype

- 7 Subjects; 3 engineering & 4 crew
- VTD (S7-24.3”; S18-28”; E3-28.5”)
  - Fitcheck subjects with model
  - Set waist to configuration modeled
  - Compare shoulder placement and hip placement to model estimates
- Chest breadth and the impact of S (S7-11.7; S13-13.2; E3-14), chest depth (S16-9; S18-10.7), & Bi-acromial Breadth (S12-16.9; E1-13.3)
  - Evaluate placement of shoulder in scye opening
  - Evaluate room in front and back of chest and any padding that may be required
  - Identify any hot-spots or pinch points
  - Evaluate room for hatch cage and other internal interfaces:
    - Line routing, microphones, helmet neck ring, DIDB, vent duct, Purge valve and vent routing

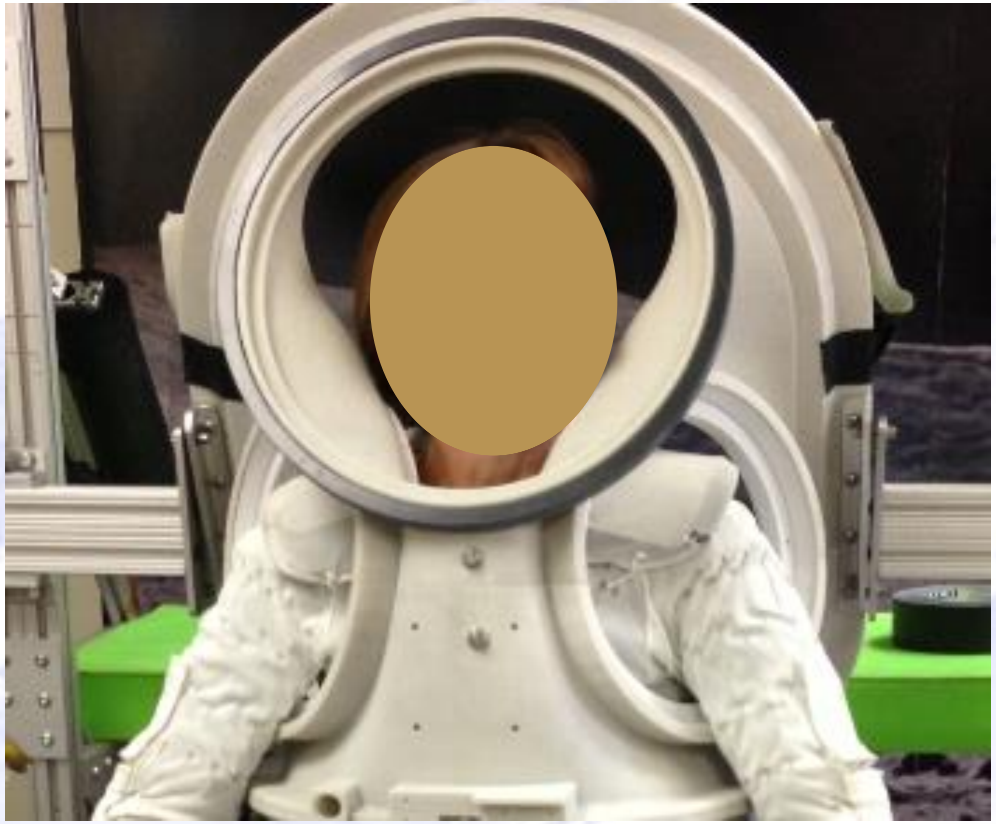
Rapid Prototype Fit-Checks





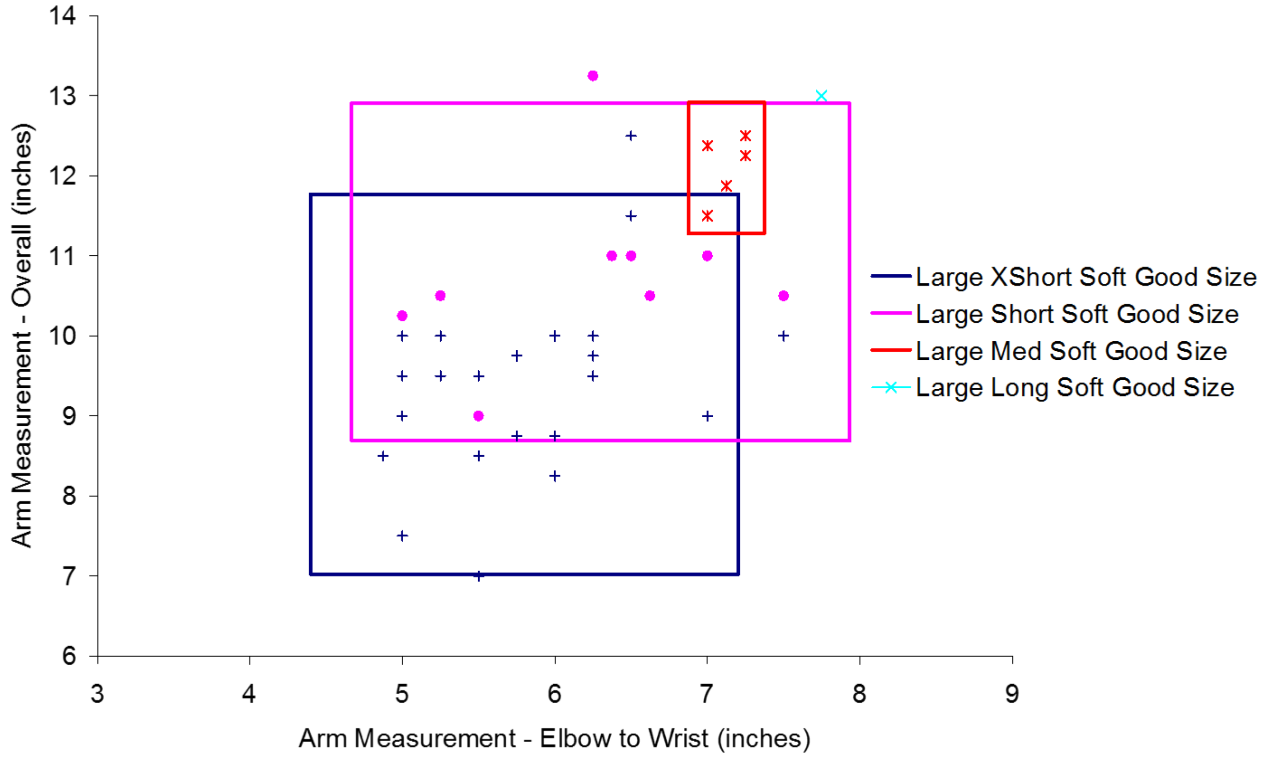



Rapid Prototype Fit-Checks



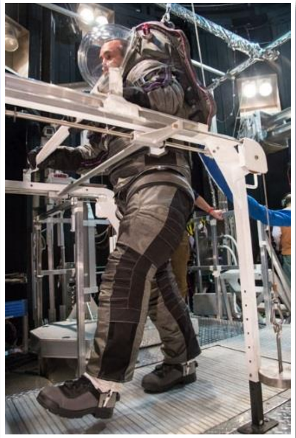
Complete Sizing Scheme

- Statistical analysis of historical sizing data compared with subject anthropometry and element adjustability to determine softgoods sizing
  - Waist
  - Lower arms
  - Lower legs



Fit Validation

- Fabricated high fidelity Z-2 pressure garment
- Completed pressurized fit-checks with same 7 boundary test subjects
  - Demonstrate isolated ROM
  - Demonstrate functional tasks
  - Verify no shoulder impingement
  - Verify head centered in helmet
  - Verify fingers stay in gloves
  - Verify easy don/doff
  - Assess comfort and subjective fit



Forward Work

- Create full set of digital boundary manikins for 1st-99th percentile anthropometries
  - Conduct principle component analysis to confirm targeting correct "critical dimensions"
  - Determine active postures to model lower torso dynamic fit
- Continue to refine digital fit algorithms based on fit data collected from human-in-the-loop testing with pressurized suits