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Human Systems Integration –
Human Space Exploration EVA Spacesuits

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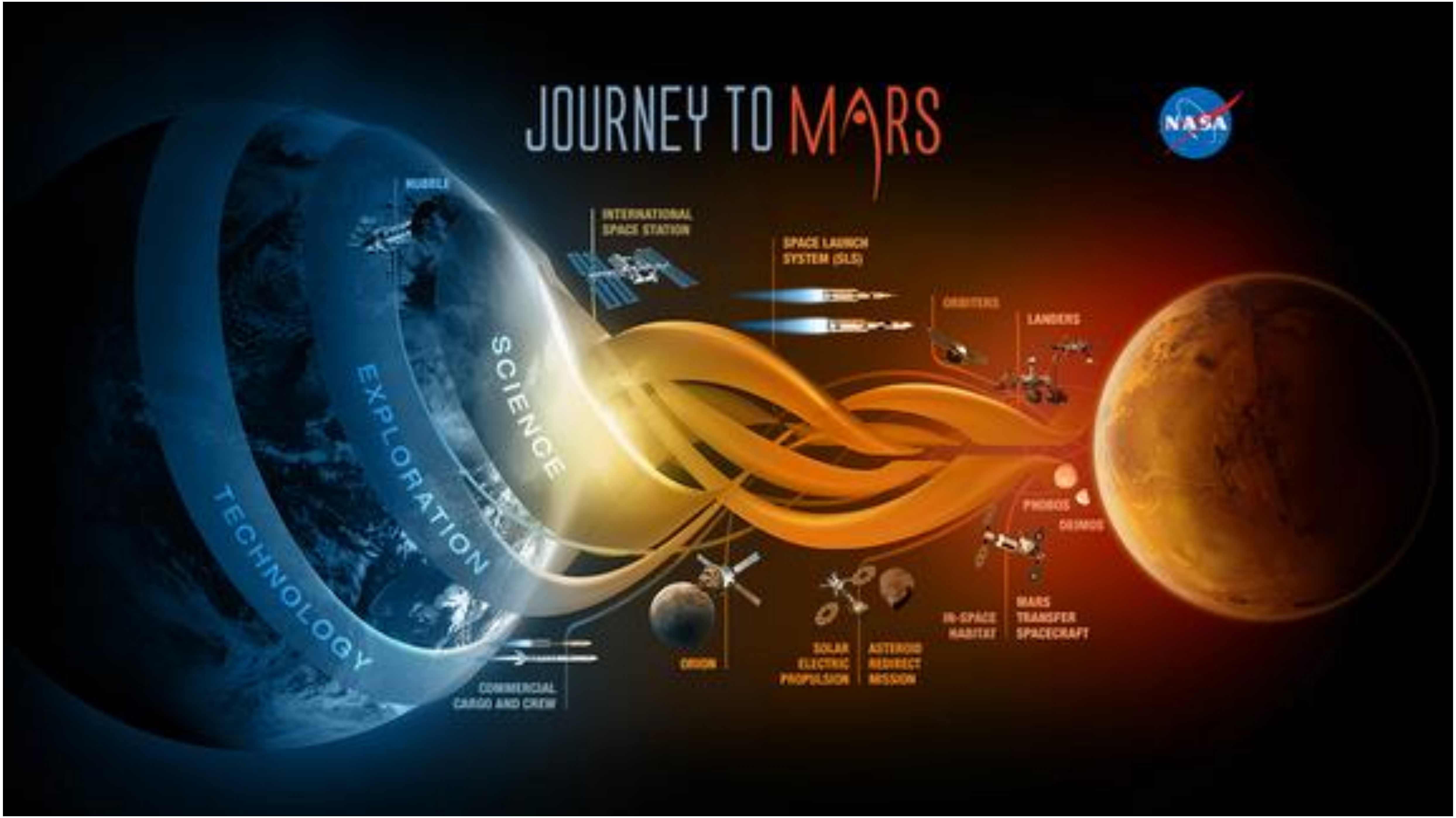
Director, Aerospace Human Systems Laboratory

Topics

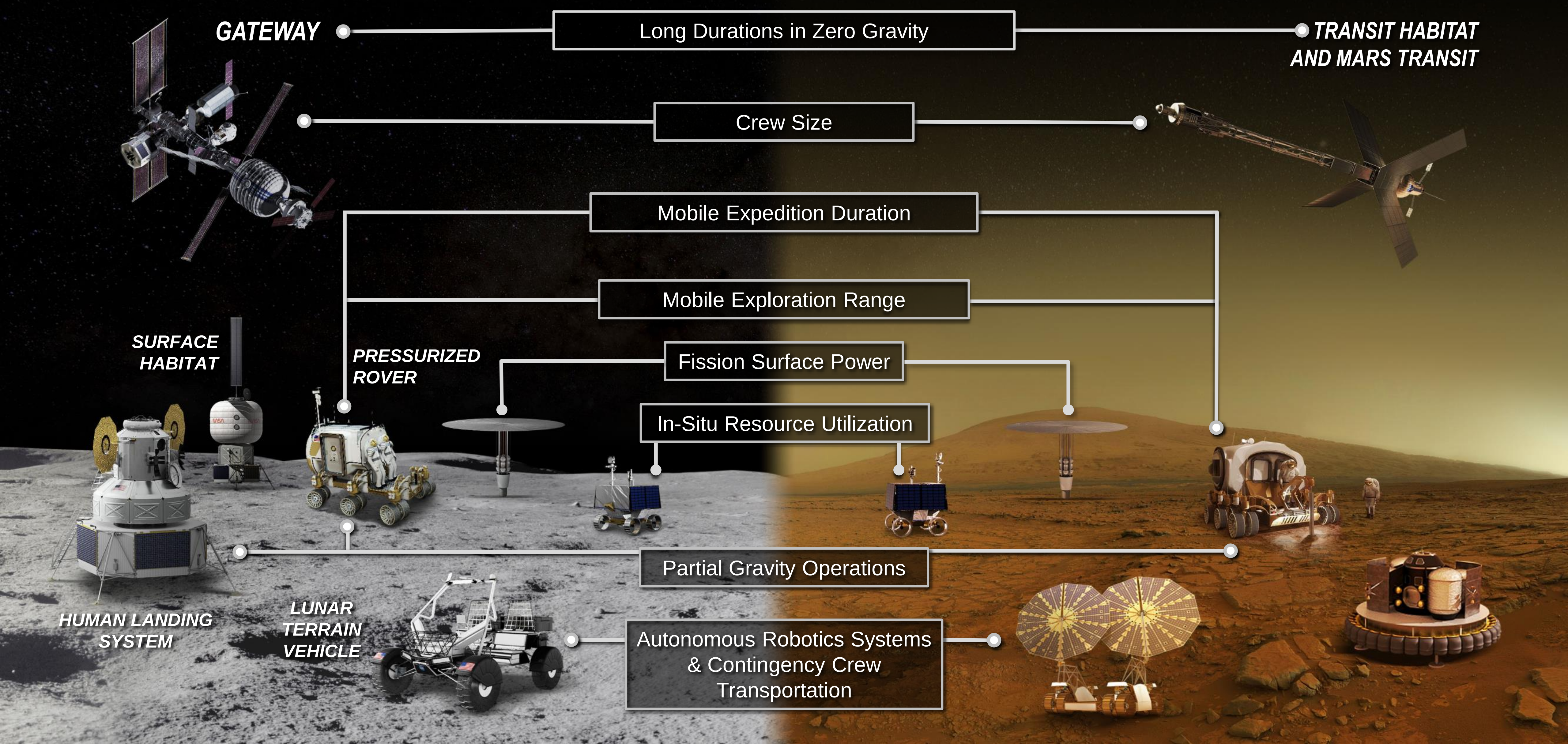
- Defining Human Systems Integration
- Designing for Space Extreme Environments
  - Space Environment Design Drivers
- Integrating Humans into an EVA Spacesuit
  - Historical Overview of Apollo and Space Shuttle/ISS EVA Spacesuit Design
  - Intersection of HSI, Bioastronautics, Engineering Design
  - EVA Suit Design and Integration “Escapes”: Risks and Gaps
- Future EVA Suit Design Directions
  - Digital Human Modeling
  - The “Virtual Twin”
- Conclusions and Recommendations


National Aeronautics and Space Administration
NASA


JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
COMMERCIAL CARGO AND CREW

MOON AND MARS EXPLORATION

Operations on and around the Moon will help prepare for the first human mission to Mars



MOON AND MARS EXPLORATION

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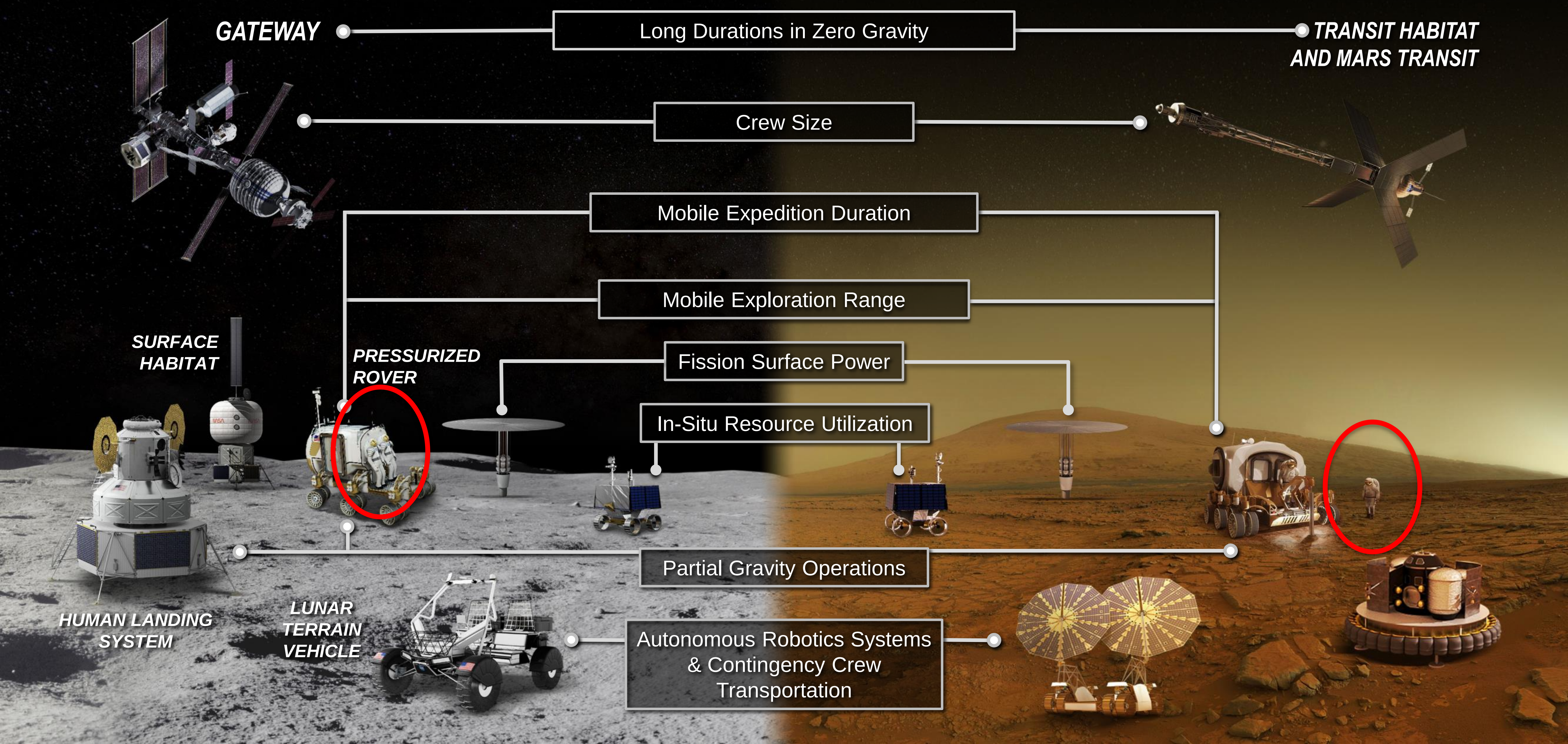


The Moon to Mars Architecture is Inherently Common

IN ORBIT

DEEP SPACE AGGREGATION
Assembling a complex ship in deep space

MARS TRANSIT HABITAT
Round the clock, years-long operations of a Mars-class habitat and life support system

ORBIT TO SURFACE OPERATIONS
Operating an orbiting outpost that deploys a lander and its crew to a planetary surface

COMMERCIAL RESUPPLY AND REFUELING
Leveraging the space logistics supply chain for industry provided cargo deliveries

CREW HEALTH & PERFORMANCE
Studying how the human body and mind adapt to deep space hazards

A roundtrip mission to Mars will take about two to three years—and once the ship's course is set, there's no turning back.

As much as is possible, lunar systems will be designed for dual Moon-Mars operations.

Integrated missions in the lunar vicinity prepare us for successful Mars missions.

ON THE SURFACE

SPACESUIT ADVANCEMENTS
Improving spacesuit design across Artemis missions with astronaut input and private sector innovation

MOBILE OPERATIONS
Living and working 'on the go' inside a mobile habitat for weeks at a time

PLANETARY PROTECTION
Mitigating dust transfer and establishing pristine sample curation protocols

HUMAN ROBOTIC EXPLORATION
Robots pre-positioning surface assets and conducting reconnaissance for astronauts

HUMAN RESILIENCE
Learning how humans can survive and thrive in a partial gravity environment

ARTEMIS: LANDING HUMANS ON THE MOON

ENABLING DIVERSE TECHNOLOGIES AND APPLICATIONS


Space Launch System


Orion spacecraft


Human Landing System


Surface Operations


Gateway

Exploration Ground Systems

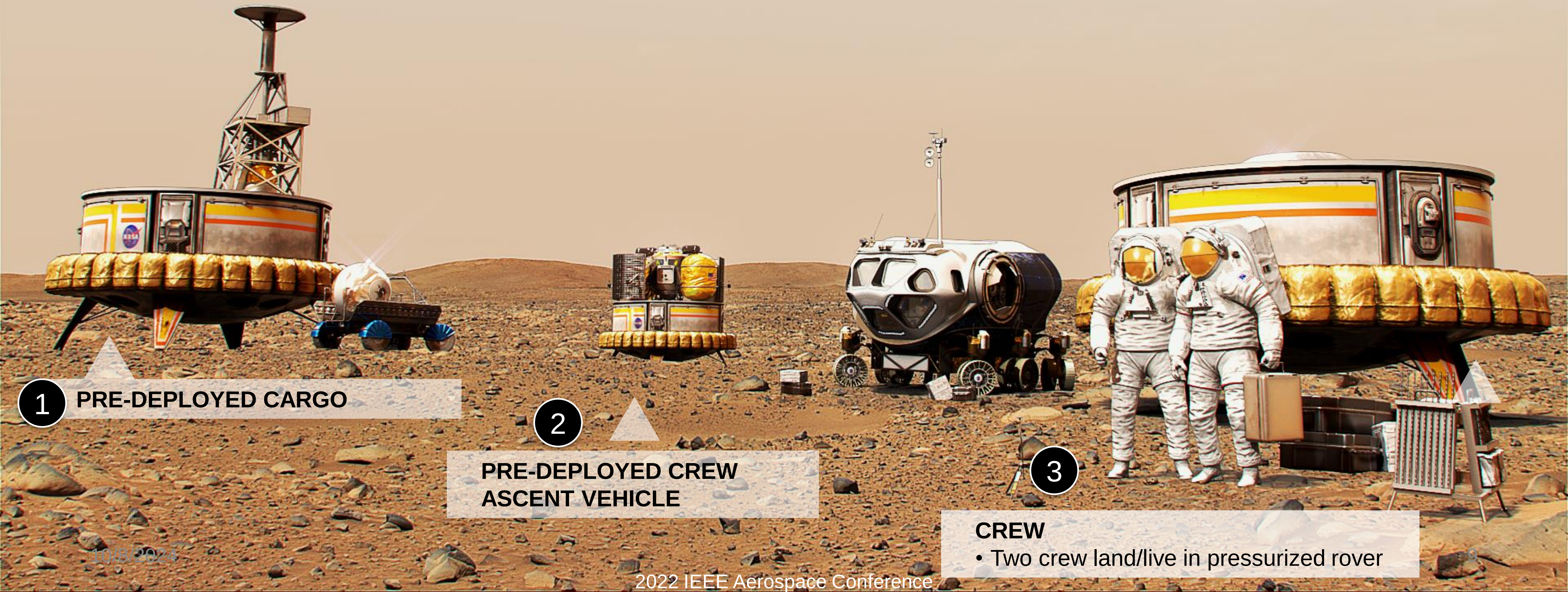

Space Communications & Navigation


Surface Mobility


Spacesuits


Artemis Base Camp

SAC21 First Mars Reference Mission *(NASA STMD 3-2022)*



HOW HSI Is Defined by the DOD

Human Systems Integration (HSI) is the systems engineering process and program management effort that provides integrated and comprehensive analysis, design, and assessment of requirements, concepts, and resources for human factors engineering, manpower, personnel, training, safety and occupational health, force protection and survivability, and habitability (DoDI 5000.95, Glossary).

These HSI domains are interrelated and interdependent and must be among the primary drivers of effective, efficient, affordable, and safe system designs. HSI integrates and facilitates trade-offs among these domains and other systems engineering and design domains but does not replace individual domain activities, responsibilities, or reporting channels (source: DAU).

The goal of HSI is to ensure human performance is optimized to increase total system performance (TSP) and minimize total system ownership costs (TOC). Incorporating HSI early in system design promotes more successful and effective transition of capability to the warfighter.

https://www.cto.mil/sea/hsi

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HOW HSI Is Defined by NASA

Human Systems Integration

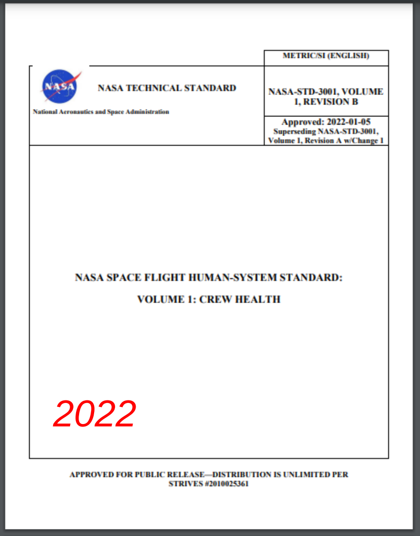
There is no such thing as an "unmanned" system. A system is comprised of the human, the hardware, and the software. Human Systems Integration is a system engineering discipline that applies knowledge of human capabilities and limitations throughout the design, implementation, and operation of hardware and software. It is an interdisciplinary and comprehensive management and technical process that focuses on the integration of human capabilities and limitations into the system acquisition and development processes to enhance human system design, reduce life cycle ownership cost, and optimize total system performance.

https://www.nasa.gov/wp-content/uploads/2015/07/jsc-hhp-human-systems-integration-2021.pdf

https://ntrs.nasa.gov/api/citations/20205007852/downloads/AIAA%20Next%20Gen%20-%20HSI%20Plan.pdf

NASA DOCUMENTS AND REQUIREMENTS

- **The NASA-STD-3001 is an Agency-level, two-volume suite of documents that address the human needs for space flight.**
  - Volume 1, “Crew Health” covers the requirements needed to support astronaut health. Examples include medical care, nutrition, sleep, and exercise.
  - Volume 2, “Human Factors, Habitability and Environmental Health” covers the requirements for system design that will maintain astronaut safety and promote performance.
    - Examples for this volume include a design of the food facilities, bathroom design, a layout of workstations, seating and crew restraint design, lighting requirements, and environmental requirements.



METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

NASA-STD-3001, VOLUME 1, REVISION B

Approved: 2022-01-05
Superseding NASA-STD-3001, Volume 1, Revision A w/Change 1

NASA SPACE FLIGHT HUMAN-SYSTEM STANDARD:

VOLUME 1: CREW HEALTH

2022

APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED PER STRIVES #2010025361

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

Office of the Chief Health and Medical Officer
Controlled by: David Francisco

NASA-STD-3001, Volume 2, Revision D

Approved: 2023-09-15
Superseding NASA-STD-3001, Volume 2, Revision C

NASA SPACEFLIGHT HUMAN-SYSTEM STANDARD

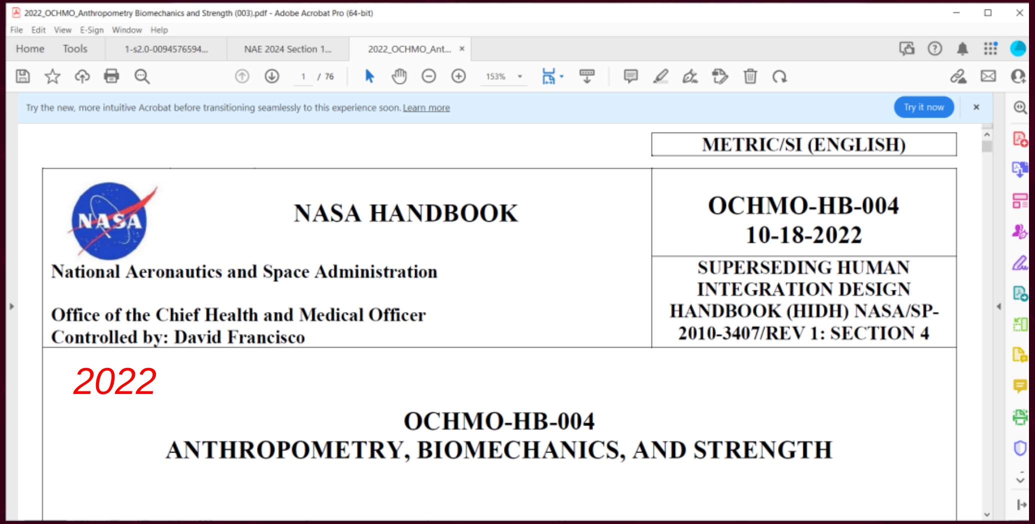
VOLUME 2: HUMAN FACTORS, HABITABILITY, AND ENVIRONMENTAL HEALTH

2023

NASA DOCMENTS

- **A companion document to NASA-STD-3001 Volume 2 is the Anthropometry, Biomechanics and Strength Handbook**

The is a compendium of human space flight history, lessons learned, and design information for a wide variety of disciplines and provides background information on the rationale for human-system design standards.



Human Systems Integration

- https://www.nasa.gov/humans-in-space/commercial-space/leo-economy/nasa-shares-lessons-human-systems-integration/

3 MIN READ

NASA Shares Lessons of Human Systems Integration with Industry

Commercial Low Earth Orbit Development Program

APR 23, 2024

ARTICLE

Human Systems Integration (HSI) for Extravehicular Activity (EVA) Spacesuits

Interdisciplinary Space Systems Engineering: Protection from the Extreme Environments of Space

Bioastronautics: Understanding Changes in Human Physiology Due to Space, Development of Countermeasures and New Technologies, Space Medicine and Health Care, and Environmental Control and Life Support Systems/Monitoring

Digital Human Modeling (DHM) and Human Factors: Mobility and Operations

Designing For Extreme Environments

Human Protection in Extreme Environments

- **Mountain Climbing**
  - Increasing Altitude/decreasing pressure
  - Decreasing Temperatures
  - Decreasing PPO2

- **Deep Sea Diving**
  - Increasing Pressure
  - Need for supplemental Oxygen
  - Need for CO2 removal
  - Decompression Sickness

- **Higher Altitude Flight**
  - Free Fall – Weightlessness
  - Vacuum
  - Extreme Temperatures
  - Micrometeoroids
  - Radiation

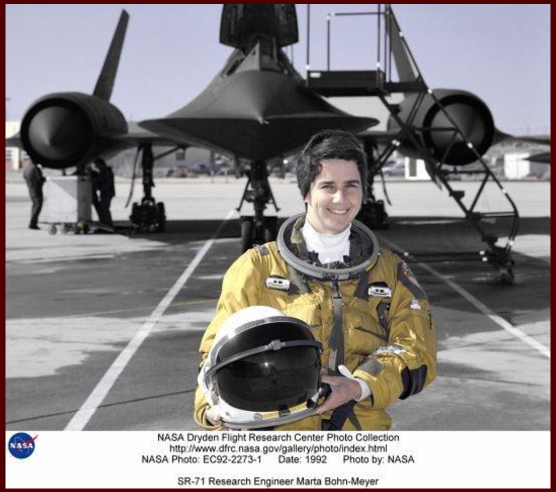
Wiley Post Aviation Pressure Suit, 1934 Aviation Record 50,000 ft

- *The body of the suit had three layers:*
  - *long underwear,*
  - *Inner black rubber air pressure bladder*
  - *Outer layer of rubberized parachute fabric.*
- *The outer layer was glued to a frame with **arm and leg joints** that allowed him to operate the flight controls and to walk to and from the aircraft.*
- *Attached to the frame were pigskin gloves, rubber boots, and an aluminum-and-plastic diver's helmet.*
- *The helmet had a removable faceplate that could be sealed at a height of 17,000 ft (5,200 m), and could accommodate earphones and a throat microphone.*
- *The first flight using the suit occurred on September 5, 1934, at an altitude of 40,000 ft (12,000 m) above Chicago.*
- ***At 50,000 ft** (15,000 m), Post discovered the **jet stream** and made the first major practical advances in pressurized flight.*

Mallan, Lloyd. Suiting Up For Space: The Evolution of the Space Suit. New York: The John Day Company, 1971.

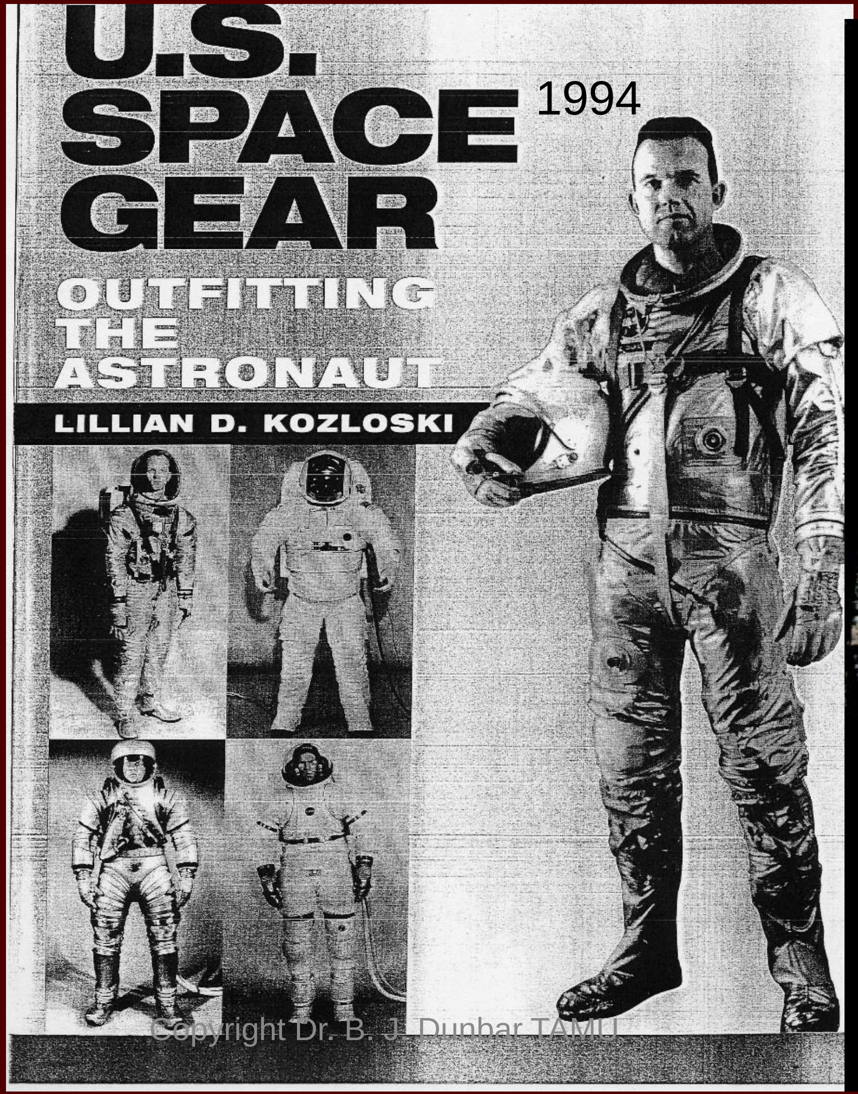
Pressure Suits (Launch & Entry are IVA – Not EVA)

- X-15
- SR-71
- Mercury
- Space Shuttle
- Soyuz Sokol
- SpaceX
- Boeing Dreamliner



Space: Spacecraft Environmental Control and Life Support Systems (ECLSS) and Personal Protection became new design drivers

- Pressure Control
- Thermal Control
- Atmospheric Composition Control
- Mobility and Human Factors
- Micrometeoroid Protection
- Radiation Protection
  - UV
  - Solar Particles
  - Galactic Cosmic Rays
- Minimal Mass
- Launch and Entry Pressure suits vs EVA suits



1994

Smithsonian
Amanda Young
2009

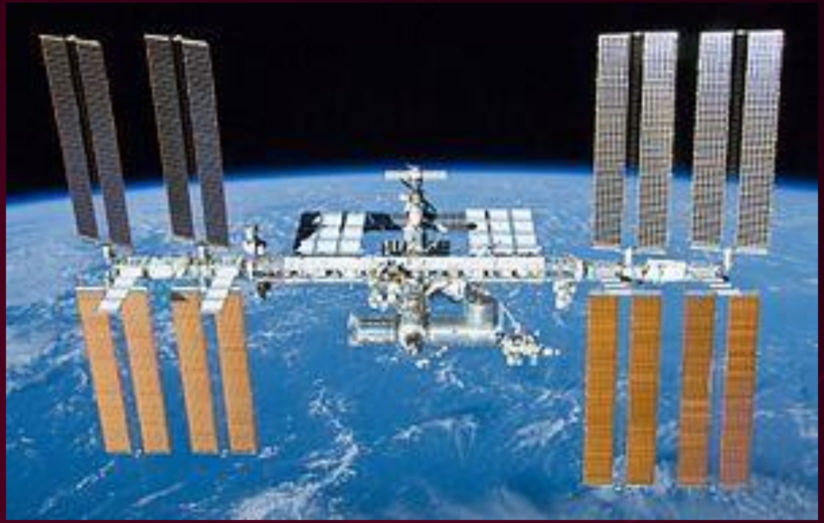
The Russian Custom IVA SOKOL Pressure Suit

HSI, Engineering and Bioastronautics Challenges

Space Suits: Form Fitting Space Habitats

Bruce McCandless using the Manned Maneuvering Unit (MMU) during Space Shuttle STS-41B in 1984

- Pressure Vessel
- Communications
- Life Support Systems
- Thermal management
- Displays and Controls
- Battery Power
- Computers
- Attitude Control
- Advanced Materials
- Radiation Mitigation
- Micrometeoroid Protection
- Sensors

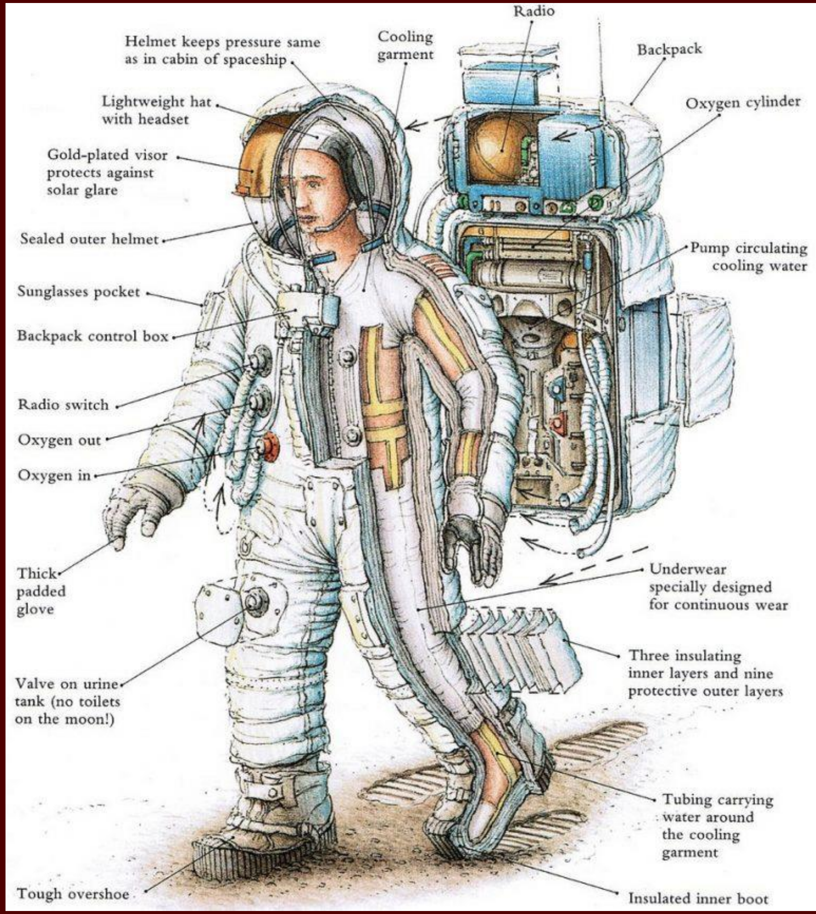


International Space Station

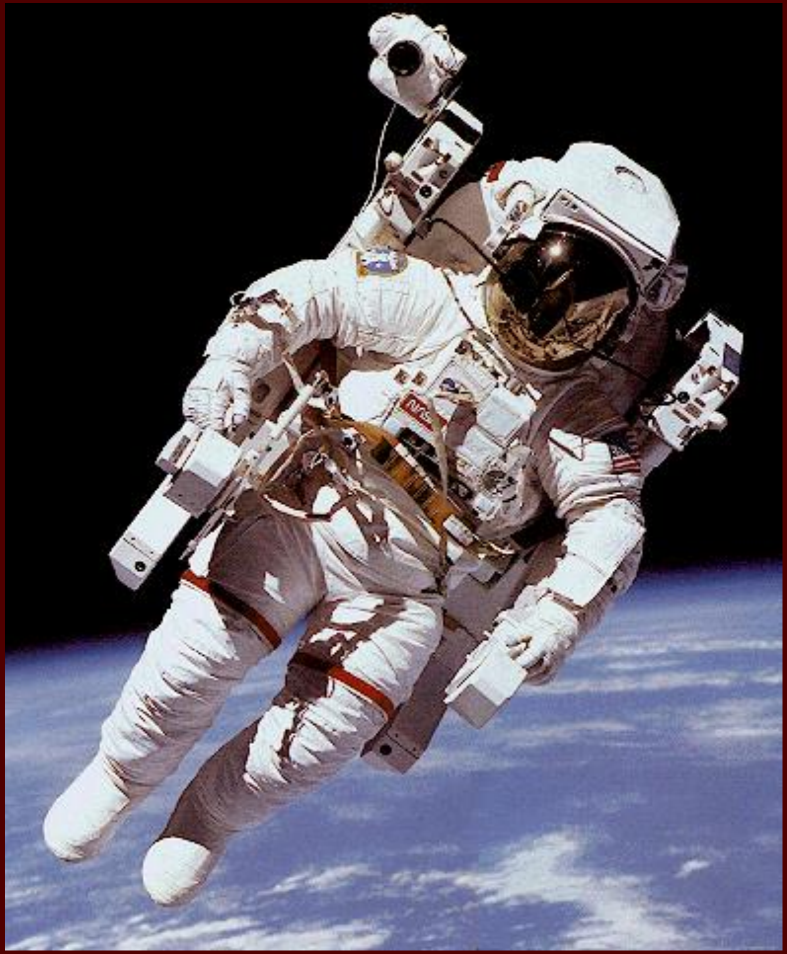
EVA Suits: Human Shaped Spacecraft

- Pressure Vessel
- Communication
- Life Support Systems
- Thermal management
- Displays and Controls
- Battery Power
- Computers
- Attitude Control
- Advanced Materials
- Radiation Mitigation
- Micrometeoroid Protection
- Sensors

  - **PLUS**
- **Mobility and Minimum Human Energy Expenditure**



Apollo /Skylab A7LB EVA Spacesuit



Space Shuttle/ISS EVA Spacesuit

Pressurization, Fit and Mobility

- EVA pressurized spacesuits provide critical life support and protection from the extreme environment of space, but they challenge mobility due to the required pressurization
  - Increased pressure results in decreased mobility
  - Poor fit also adversely impacts mobility

- International Space Station (ISS) operations and future Artemis and Mars missions require that EVA spacesuits be optimized for mobility

Apollo 11 astronaut during EVA (Credit NASA)

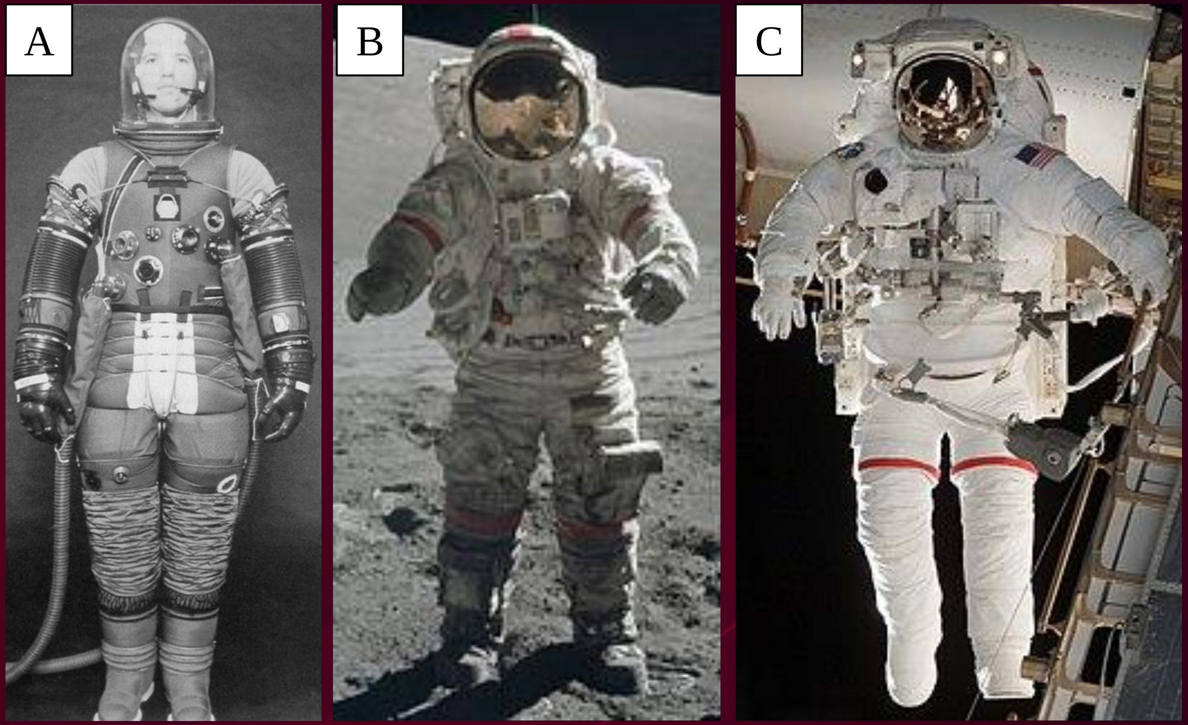
US History of EVA Spacesuits

Apollo-Skylab A7L/A7LB (1960s-1970s)

- 3.7 psid
- Lunar surface EVA during Apollo (1/6th g) and microgravity, EVA during Skylab
  - Primarily softgoods
  - Custom fit to each crewmember

Shuttle-ISS EMU (1981-present)

- Microgravity EVA only (no leg mobility)
- 4.2-4.4 psid
- Standard modular sizing
  - 5 Chest sizes (later reduced to 3)
- Mix of hard and soft components (e.g., HUT)



A) Apollo A7LB EVA suit pressure garment assembly (PGA) (Credit NASA), B) A7LB on the Moon (Credit NASA), C) NASA Astronaut in Low Earth Orbit (Credit NASA).

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Summary of Known Space Flight Medical Risks To the Human System and Subsystems

BIOASTRONAUTICS

Astronauts experience a spectrum of adaptations during space flight and even post flight

Behavioral Changes
Balance disorders
Cardiovascular deconditioning
Decreased immune function
Muscle atrophy
Bone loss

Additional influences include the unique Radiation environment and Nutritional/Food Limitations

Behavioral

SANS - Optical

Neurovestibular System
(Neurosensory, Neuromotor)

Cardiovascular System

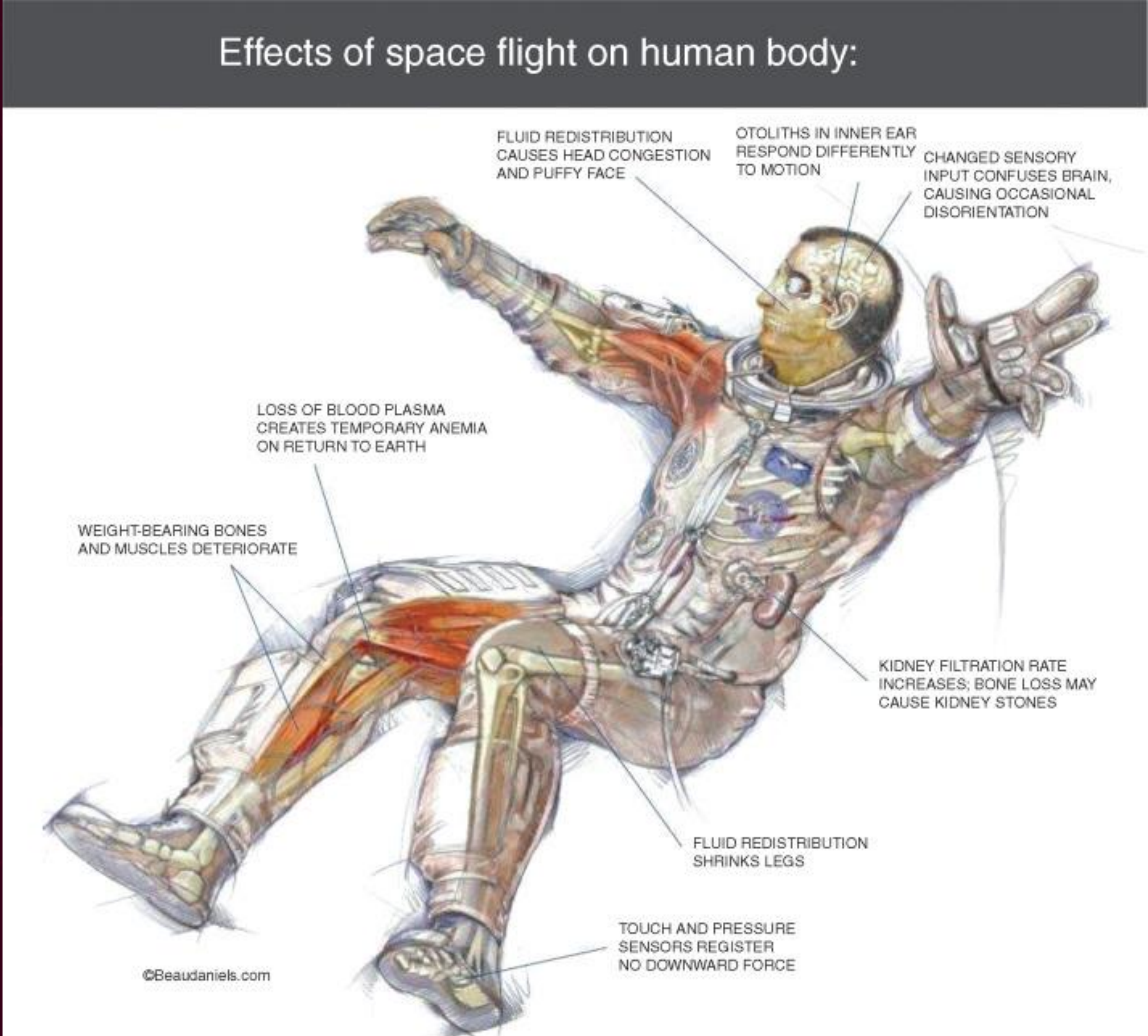
Immune System
(Endocrine)

Bone and Muscle Systems
(Musculoskeletal)

Credit: NASA

An EVA Spacesuit Perspective for the Effects of Space Physiological Changes

(Courtesy NASA HRP)



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NASA EVA Suit Risks and Design Goals

- NASA TX06.2.1 identifies spacesuit arm mobility via soft constant volume joints and enhanced patterning as a desired technology advancement.
- NASA Human Research Program (HRP) Integrated EVA Human Research Roadmap identifies the **Risk of Injury and Compromised Performance Due to EVA Operations** for moon-to-Mars mission architecture
- EVA-201 technology gap identifies the need to understand the tradeoffs between:
  - Suit operating pressures
  - Energy expenditure

Risk Ratings and Dispositions per Design Reference Mission (DRM) Category

DRM Categories	Mission Type and Duration	Operations		Long-Term Health	
		LxC	Risk Disposition *	LxC	Risk Disposition *
Low Earth Orbit	Short (<30 days)	4x2	Accepted	5x2	Accepted with Optimization
	Long (30 days-1 year)	4x2	Accepted	5x2	Accepted with Optimization
Lunar Orbital	Short (<30 days)	4x3	Accepted with Optimization	5x2	Accepted with Optimization
	Long (30 days-1 year)	4x3	Accepted with Optimization	5x2	Accepted with Optimization
Lunar Orbital + Surface	Short (<30 days)	5x4	Requires Mitigation	5x2	Accepted with Optimization
	Long (30 days-1 year)	5x4	Requires Mitigation	5x2	Accepted with Optimization
Mars	Preparatory (<1 year)	4x3	Accepted with Optimization	5x2	Accepted with Optimization
	Mars Planetary (730-1224 days)	5x4	Requires Mitigation	5x2	Accepted with Optimization

Note: LxC is the likelihood and consequence rating. The information above was last approved by the Human System Risk Board in 2/2023.

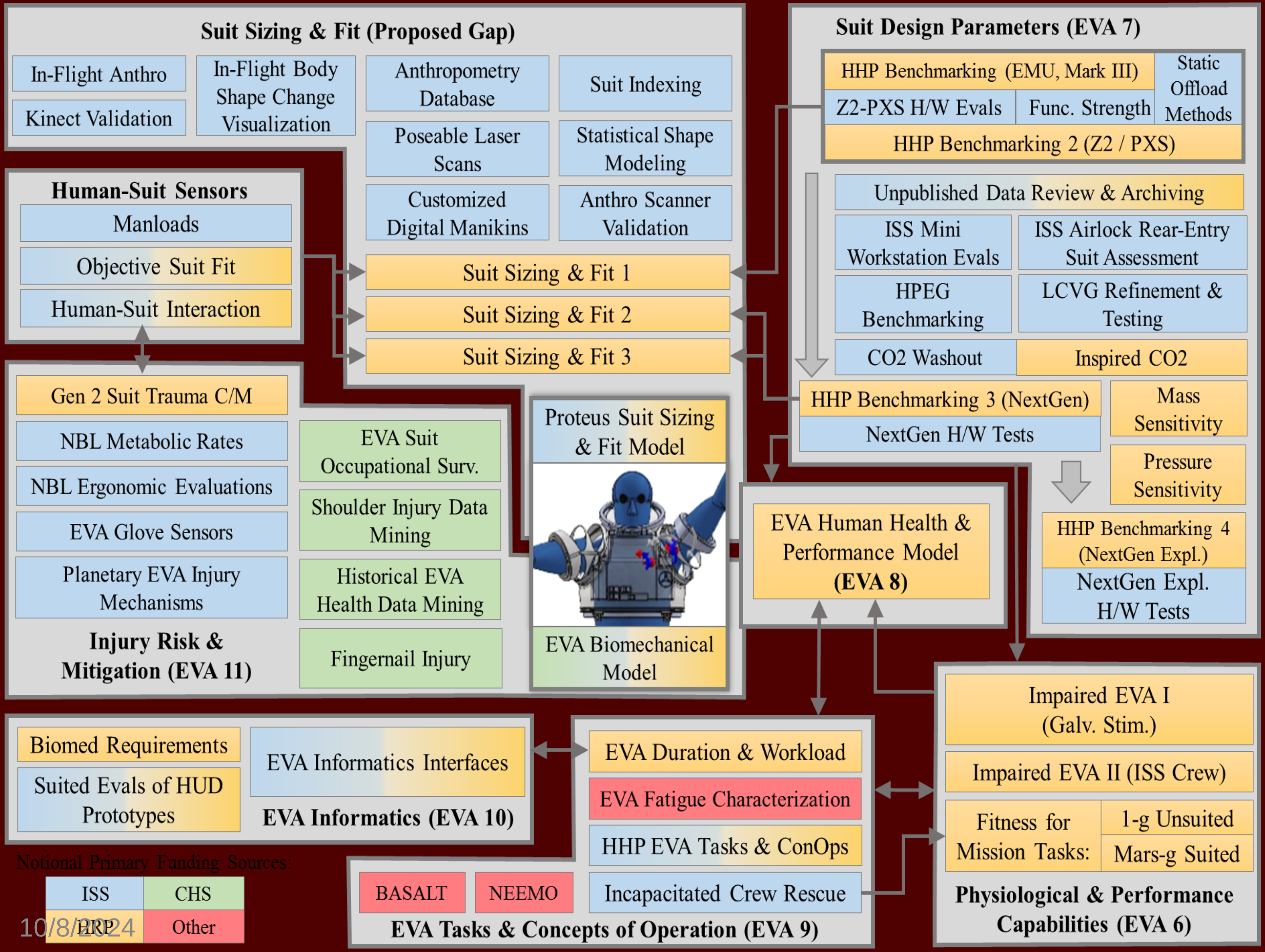
NASA Human Research Roadmap Risk of Injury and Compromised Performance Due to EVA Operations

EVA Technology Gaps

- The best publically available summary of EVA technology challenges is located in the 2015 NASA Technology Roadmaps and the 2020 Technology Taxonomy
  - TA 6.2 EVA Systems (27 candidates)
  - TA 7.3.1 EVA Mobility (7 candidates)
  - Portions of other sections

- Additionally, EVA related Human Health and Performance risks are captured in HRP Human Research Roadmap
  - 1 EVA general risk with ~7 gaps

Human Health Program (HHP) Risks and Gaps



Shoulder Injuries

Delaminated Fingernails

Increased Energy Expenditures

Bruising

No One Person Is a Fixed Percentile on all Body Measurements

Subject #	Chest breadth	Bi-deltoid breadth	Chest Circ.	Shoulder Circ.	Lower arm	Arm span	Stature
1	77	26	12	37	20	16	5
2	39	7	4	3	40	34	40
3	45	4	31	7	10	16	56
4	15	30	6	10	40	35	66
5	49	50	14	47	21	24	23
6	84	45	23	7	87	74	91
7	67	65	64	17	60	43	74
8	76	27	64	64	12	13	53
9	57	24	80	77	9	7	43
10	81	20	36	23	38	29	89
11	84	55	39	47	8	11	76
12	61	89	47	67	58	43	37
13	80	82	47	25	35	63	47
14	25	27	11	1	40	44	54
15	12	NA	4	NA	NA	<1	<1
16	20	2	30	2	<1	<1	<1
17	74	55	93	96	5	8	9
18	54	17	2	3	24	25	45
19	98	93	74	79	3	4	20
20	40	30	7	23	47	70	91
21	86	60	80	77	17	14	35
22	44	69	34	14	7	2	28
inimum Di	10.24	14.63	31.5	35.76	15.25	58	57.87
aximum D	12.88	17.88	39	43.25	18.5	74	67.13

NOTE: 1) Percentiles are from AMRL-TR-70-5
2) Span and Lower arm length percentiles are from NATICK/TR-89/044

Deep Dive of Space Environment

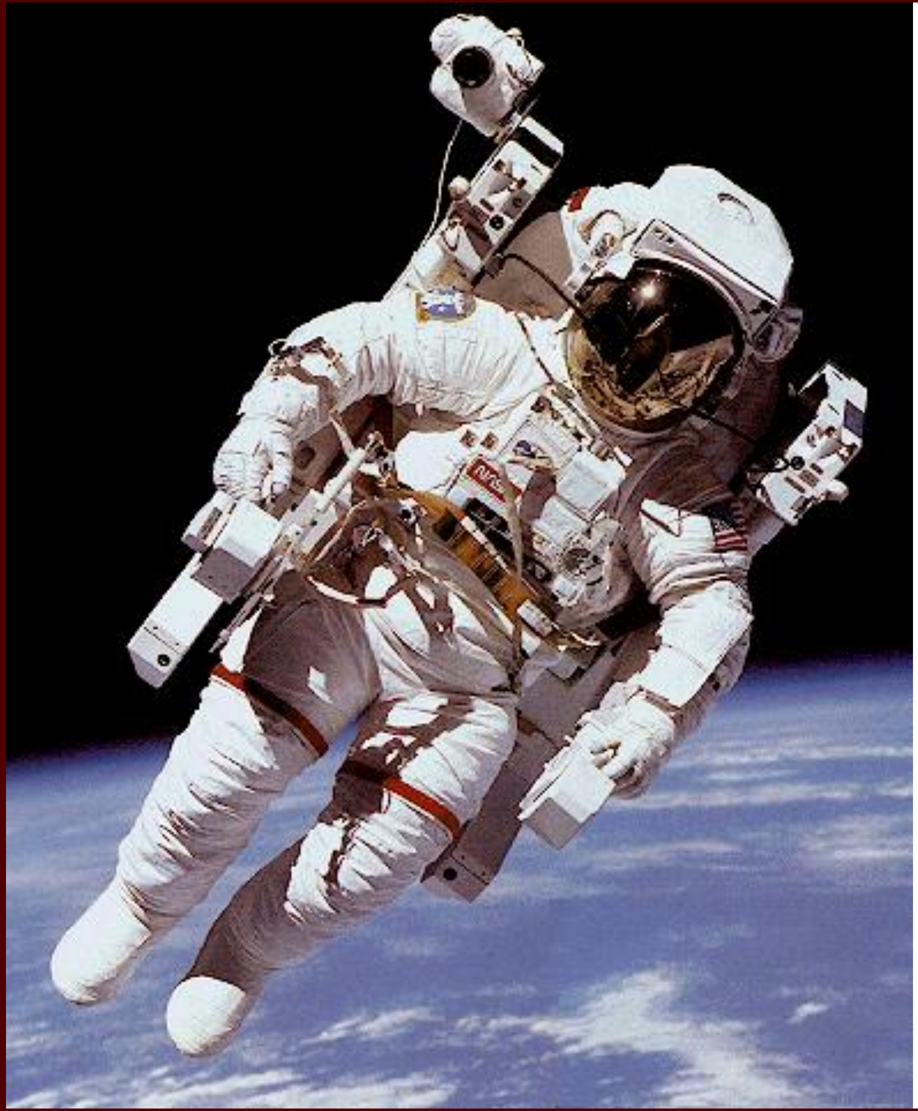
Humans Need External Pressure:

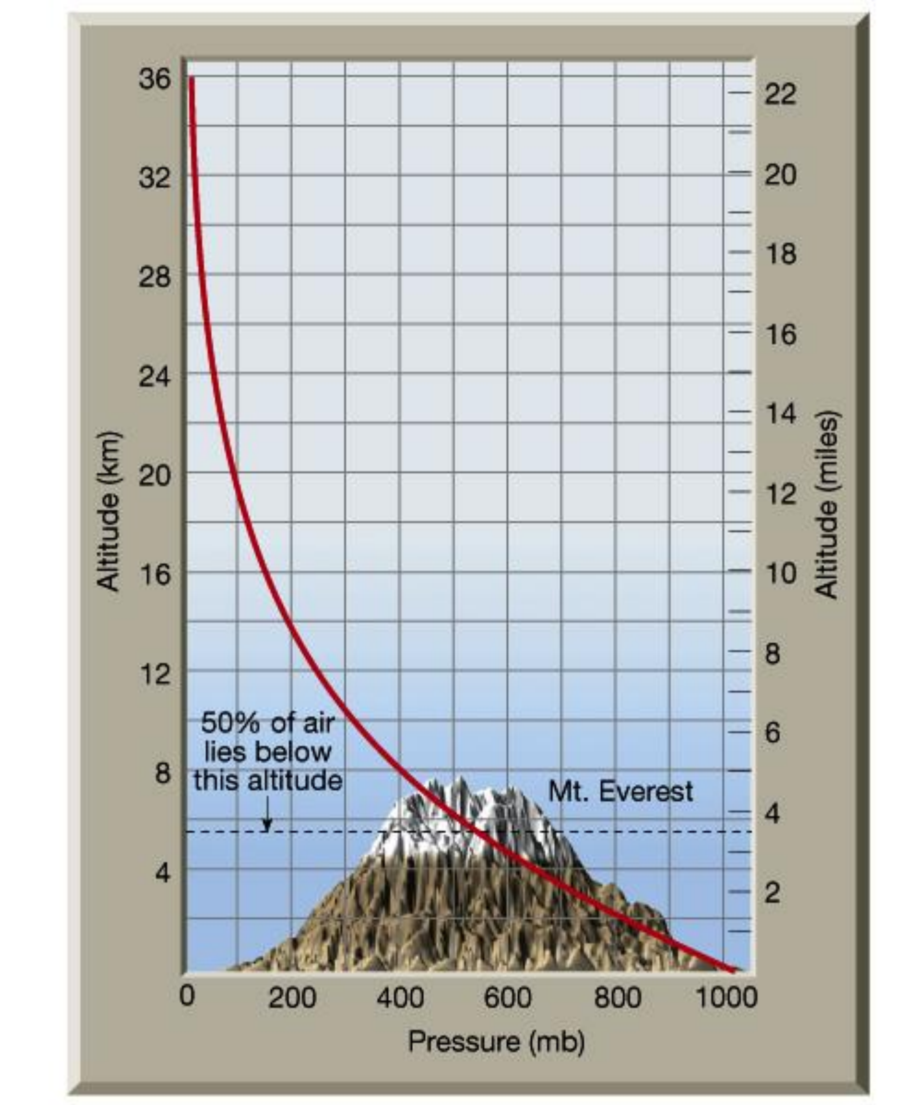
Lutgens and Tarbuck's *The Atmosphere*, 2001

Pressure on Earth = 1 atm (14.7 psi or 760 mm Hg of Oxygen and Nitrogen)

LEO at ~250 nm (Low Earth Orbit) and Lunar are Vacuum

EVA Suits have varied from Delta P of 3.7 PSI to 4.2-4.4





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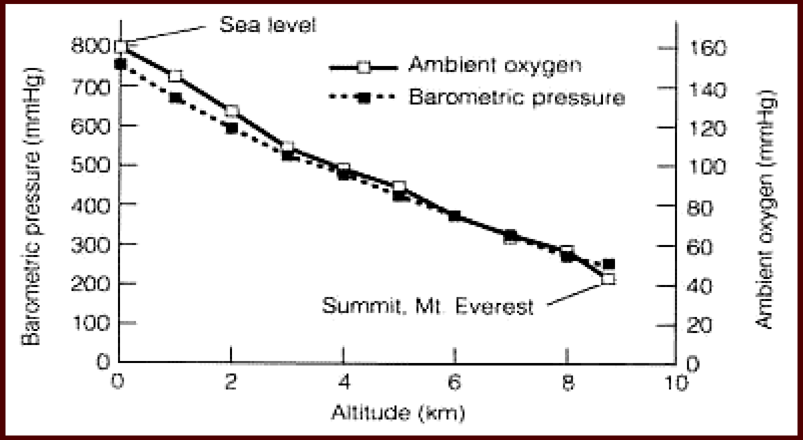
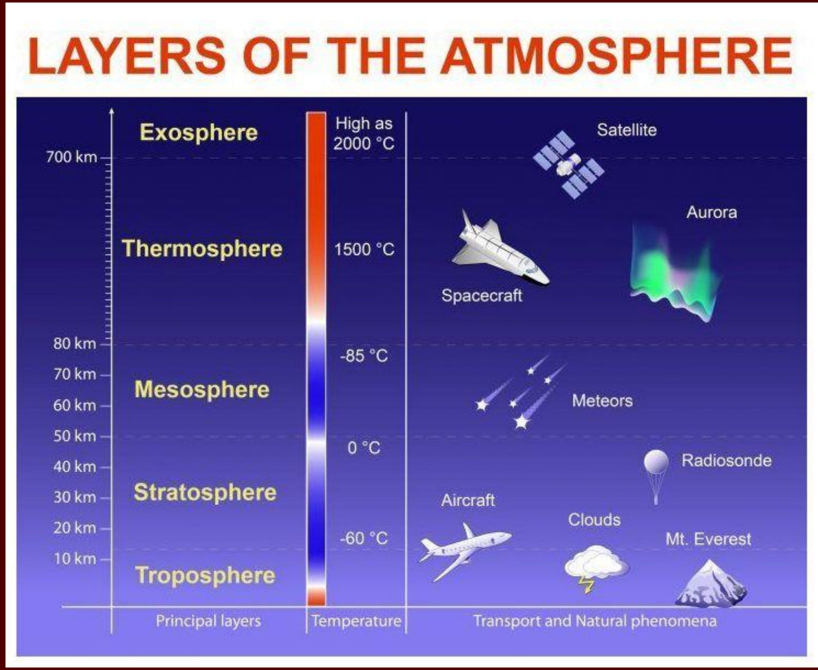
Human Pressure, PPO2 and CO2 Limits

- *Reduction* in total cabin pressure requires that the volume fraction of oxygen be *increased* (PPO2)
- Minimum Value of Pressure for human existence in a pure oxygen atmosphere is = 186.2 hPa (2.7 psi)
- Toxic Symptoms occur when humans are exposed to PP02 > 700 hPa (10.15 psi) over several days. (e.g. cough and hyperoxia)
- An increase of CO2 to 1-4% by volume leads to increased metabolic rate; greater PPCO2 leads to intoxication, lethargy, fatigue, sleepiness, headache → Respiratory Failure (Hypercapnia)

NOTE: Decreased Pressure correlates to increased mobility and decreased energy expenditures



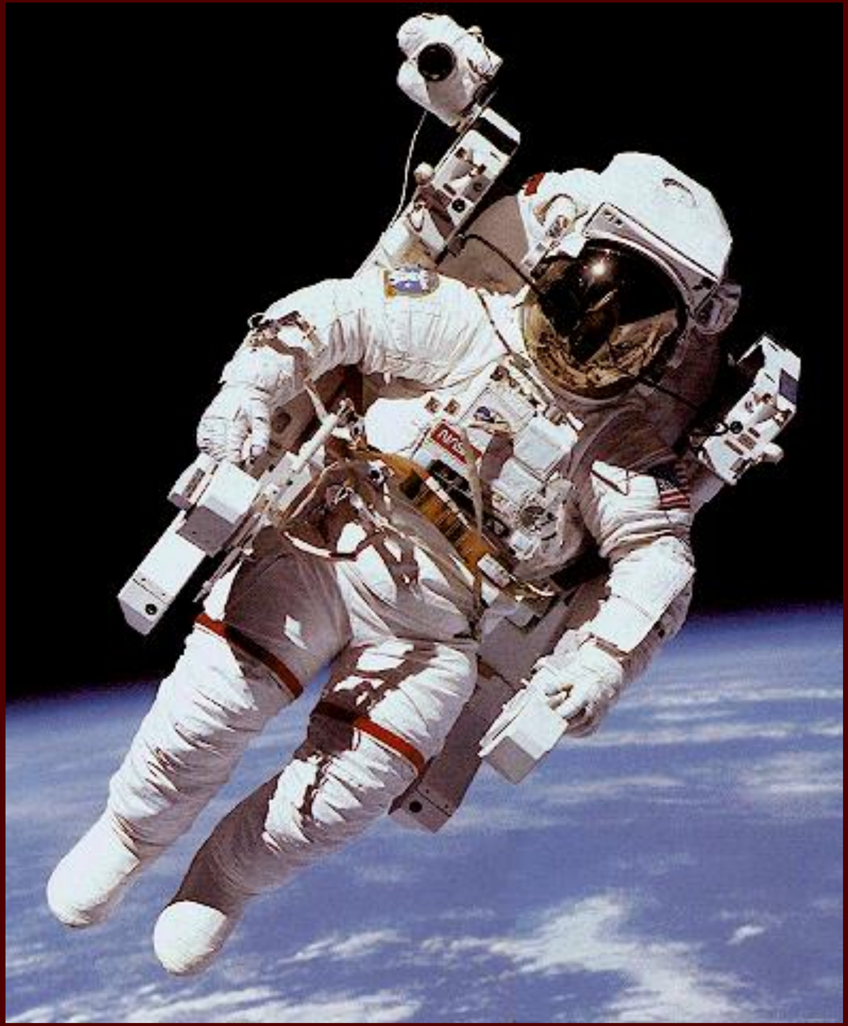


Humans Need Thermal Control

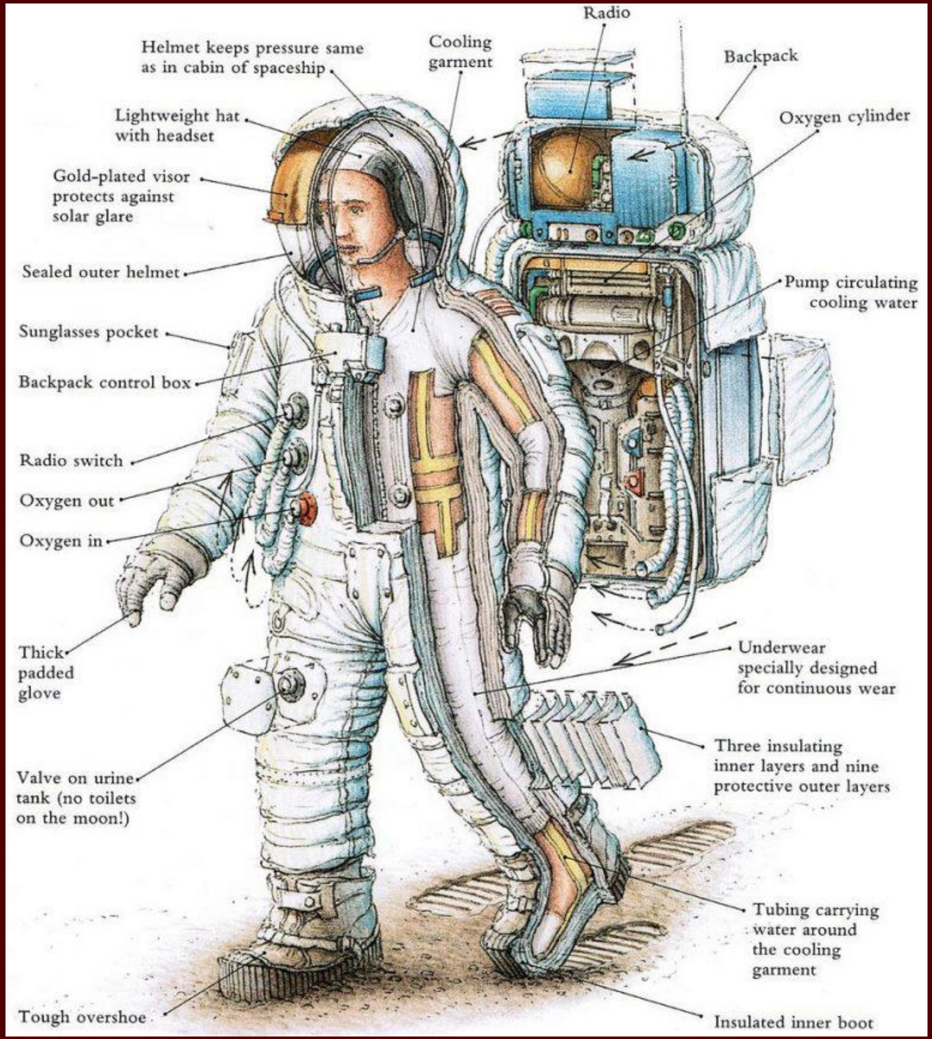
LEO is from ~-250 degree F to ~+250 degree F

Lunar South Pole: 100 K – 350K

Mars:



STS/ISS Pressure Garment

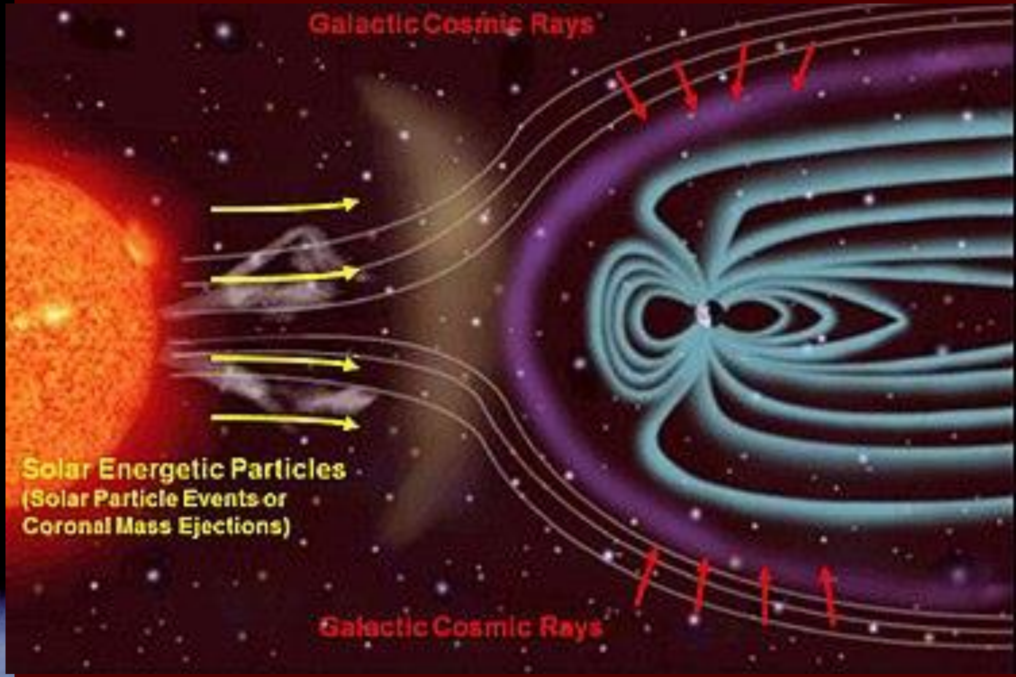


EVA Suit with Portable Life Support System

Radiation: what type and how to protect?

UV, Solar Particle Events, SPE, and Galactic Cosmic Rays (GCR)

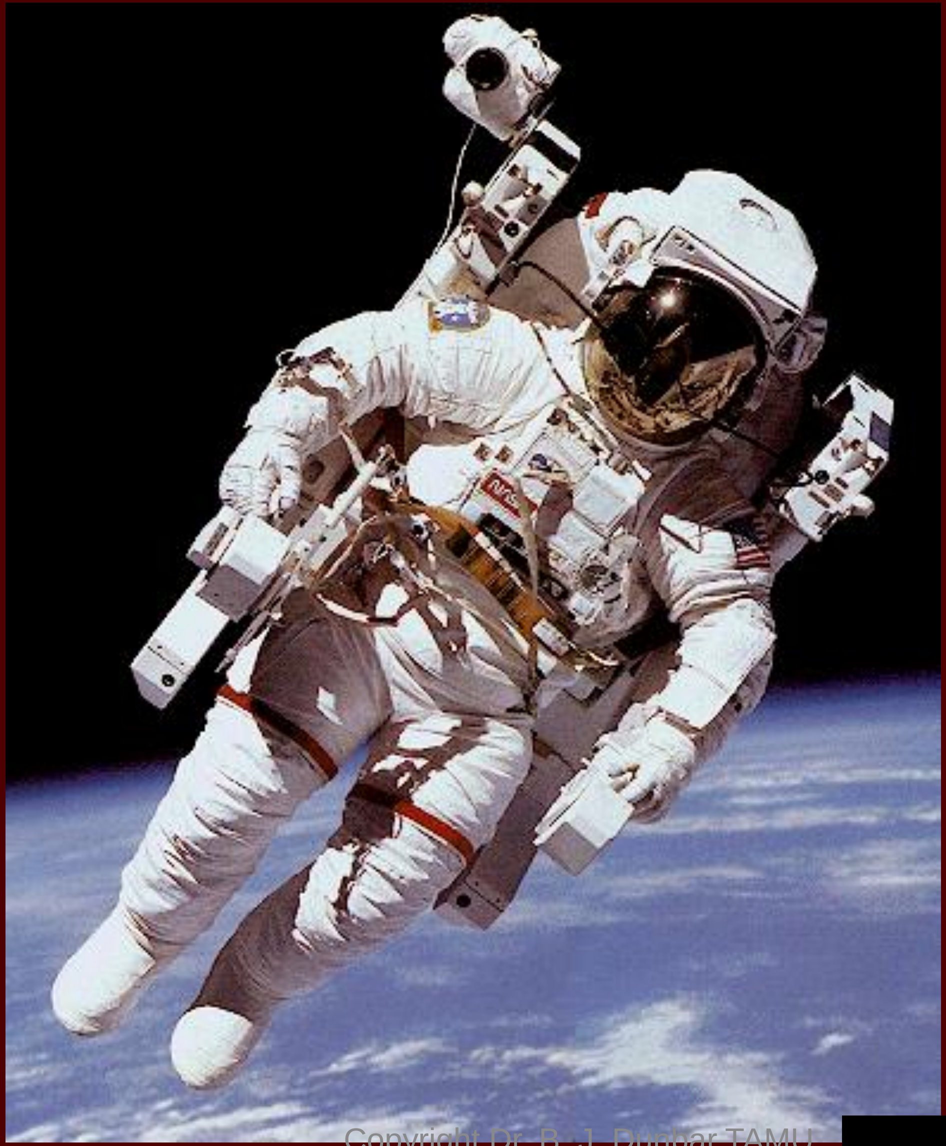
The EVA suit protects against UV, but provides little protection against Galactic Cosmic Rays (GCRs) or Solar Particle Events (SPEs)



UV, SPE and GCR

Humans Need Protection from Micrometeoroids

Micrometeoroids generally never reaching the surface of the Earth…but they do reach LEO, Moon and Mars



6.7 km / second *(14,987.5 mph)*

Apollo to Shuttle EVA Suits

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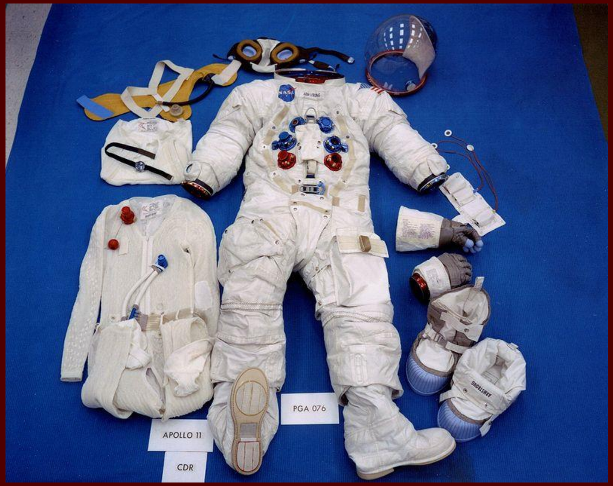
Apollo Suit A7L/B
(A7LB for Lunar Landings and Skylab)

First Landing: July 20, 1969
First Footstep, Neil Armstrong

Apollo EVA Suit Design Requirements

- Protect against vacuum
- Protect from jagged rocks/sharp edges
- Protect against +/- 350 deg F
- Flexible enough to stoop and bend for surface planetary operations (mobility)
- Protect against micrometeoroids
- Oxygen for 7 hour EVA
- Communication System

Apollo A7LB EVA Planetary space suit



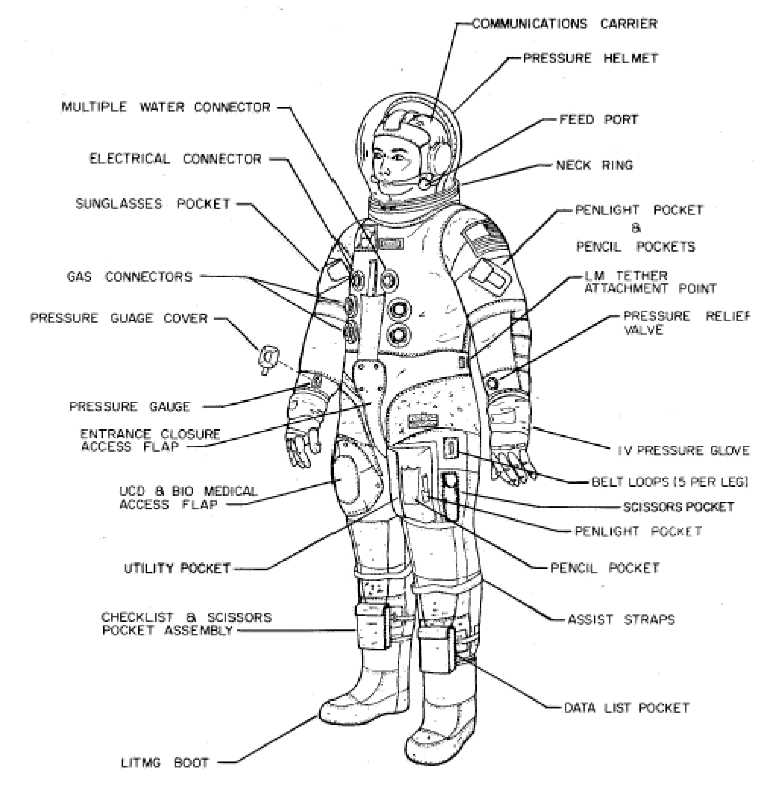


Figure I-5. - Extravehicular pressure garment assembly with arm bearing.

- **Manufacturer:** ILC Dover and Hamilton Standard (primary life support systems)
- **Missions:** Apollo 7-14
- **Function:** Intra-vehicular activity (IVA), orbital Extra-vehicular activity and terrestrial Extra-vehicular activity (EVA)
- **Operating Pressure:** 3.7 psi (25.5 kPa)
- **IVA Suit Mass:** 64.6 lb (29.3 kg)
- **EVA Suit Mass:** 78 lb (35.4 kg)
- **Total EVA Suit Mass:** 212 lb (96.2 kg)
- **Primary Life Support:** 7 hours
- **Backup Life Support:** 30 minutes

➢ During Mercury, Gemini, Apollo and Skylab programs all pressurized suits were **custom fabricated** to the individual. Each Apollo astronaut had three custom suits: one for flight, one for training and a backup.

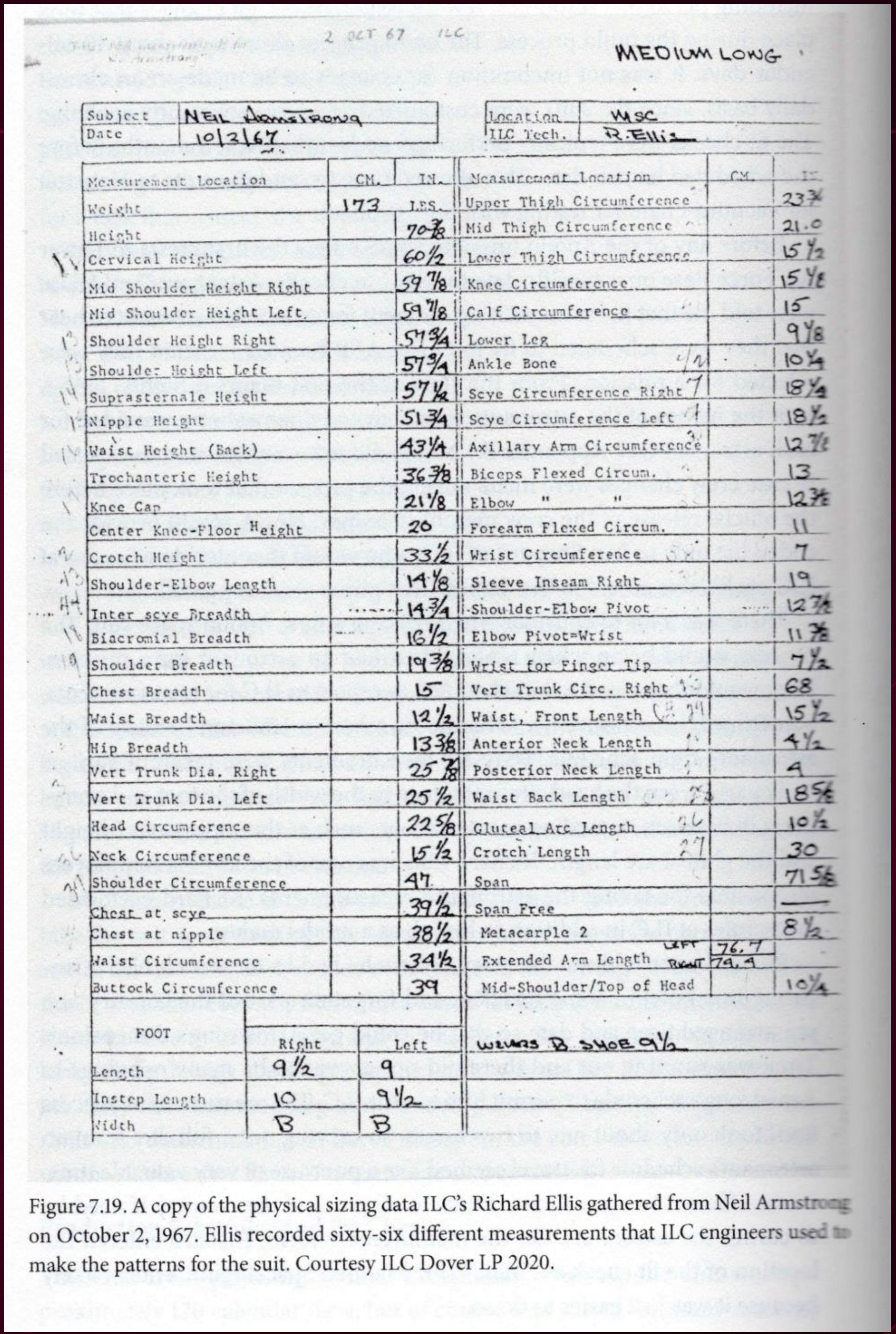
➢ 201 Suits Were Manufactured with NO failures during the Apollo and Skylab Programs

➢ Designed for Planetary Operations (bending, kneeling)

Each Apollo and Skylab Astronaut had 3 custom made suits fabricated by ILC:

- 1 for Flight
- 1 for Backup
- 1 for Training

Copy of the physical sizing data ILC's Richard Ellis gathered from Neil Armstrong on October 2, 1967. Ellis recorded sixty-six different measurements that ILC engineers used to make the patterns for the suit. Courtesy



2 OCT 67 ILC

MEDIUM LONG

Subject	NEIL ARMSTRONG	Location	MSC
Date	10/3/67	ILC Tech.	R. Ellis

Measurement Location	CM.	IN.	Measurement Location	CM.	IN.
Weight	173	LBS.	Upper Thigh Circumference		23 3/4
Height		70 7/8	Mid Thigh Circumference		21.0
Cervical Height		60 1/2	Lower Thigh Circumference		15 1/2
Mid Shoulder Height Right		59 7/8	Knee Circumference		15 1/8
Mid Shoulder Height Left		59 7/8	Calf Circumference		15
Shoulder Height Right		57 3/4	Lower Leg		9 1/8
Shoulder Height Left		57 3/4	Ankle Bone		10 1/4
Suprasternale Height		57 1/2	Scye Circumference Right		18 1/4
Nipple Height		51 3/4	Scye Circumference Left		18 1/2
Waist Height (Back)		43 1/4	Axillary Arm Circumference		12 7/8
Trochanteric Height		36 3/8	Biceps Flexed Circum.		13
Knee Cap		21 1/8	Elbow " "		12 3/4
Center Knee-Floor Height		20	Forearm Flexed Circum.		11
Crotch Height		33 1/2	Wrist Circumference		7
Shoulder-Elbow Length		14 1/8	Sleeve Inseam Right		19
Inter scye Breadth		14 3/4	Shoulder-Elbow Pivot		12 7/8
Biacromial Breadth		16 1/2	Elbow Pivot-Wrist		11 7/8
Shoulder Breadth		19 3/8	Wrist for Finger Tip		7 1/2
Chest Breadth		15	Vert Trunk Circ. Right		68
Waist Breadth		12 1/2	Waist, Front Length		15 1/2
Hip Breadth		13 3/8	Anterior Neck Length		4 1/2
Vert Trunk Dia. Right		25 7/8	Posterior Neck Length		4
Vert Trunk Dia. Left		25 1/2	Waist Back Length		18 5/8
Head Circumference		22 5/8	Gluteal Arc Length		10 1/2
Neck Circumference		15 1/2	Crotch Length		30
Shoulder Circumference		47	Span		71 5/8
Chest at scye		39 1/2	Span Free		—
Chest at nipple		38 1/2	Metacarple 2		8 1/2
Waist Circumference		34 1/2	Extended Arm Length	LEFT 76.7 / RIGHT 79.4	
Buttock Circumference		39	Mid-Shoulder/Top of Head		10 1/4

FOOT	Right	Left
Length	9 1/2	9
Instep Length	10	9 1/2
Width	B	B

WEARS B SHOE 9 1/2

Figure 7.19. A copy of the physical sizing data ILC's Richard Ellis gathered from Neil Armstrong on October 2, 1967. Ellis recorded sixty-six different measurements that ILC engineers used to make the patterns for the suit. Courtesy ILC Dover LP 2020.

AEROSPACE ENGINEERING
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From Apollo A7LB to Space Shuttle EMU

Apollo Custom Sized Suits

(Microgravity and Lunar Surface Operations, 1/6th g)

Current EMU's in use since 1981 (STS-1)

- <u>Zero G only</u>
- <u>Standard</u> Sizes
- Began with five Sizes, XS, S, M, L, XL
- Budget cut to 2, then back

SHUTTLE/ISS

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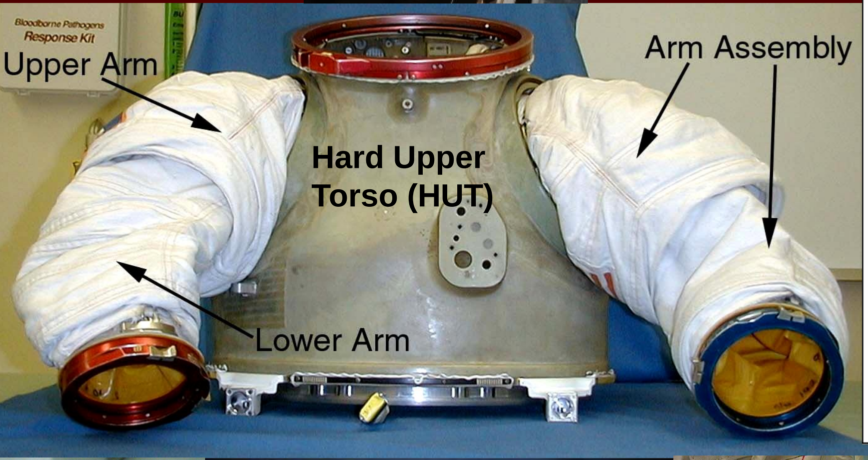
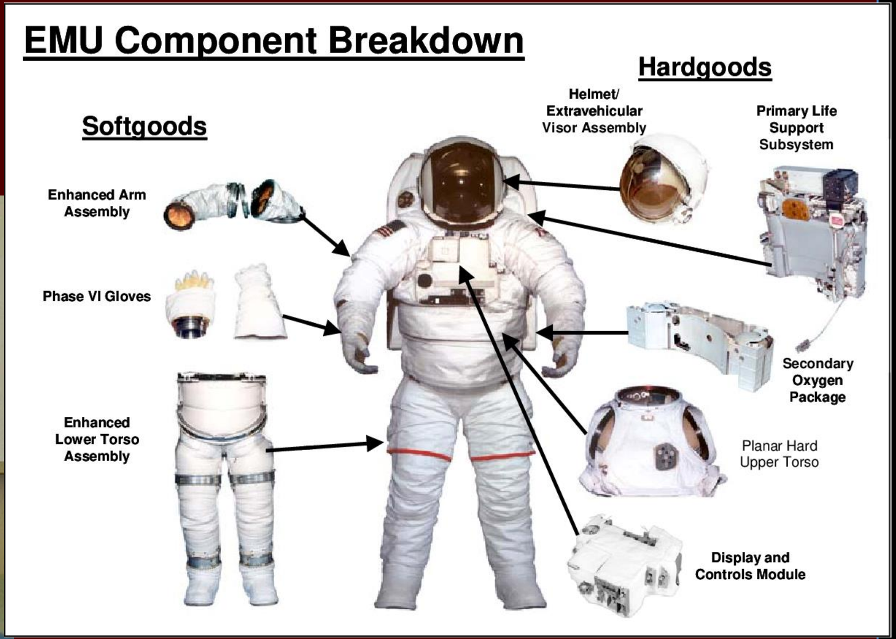
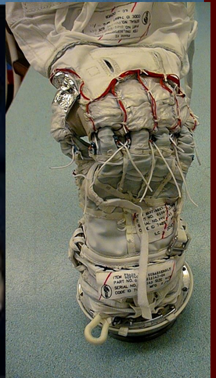
Space Shuttle/ISS EMU: 1978 – 2024 ++

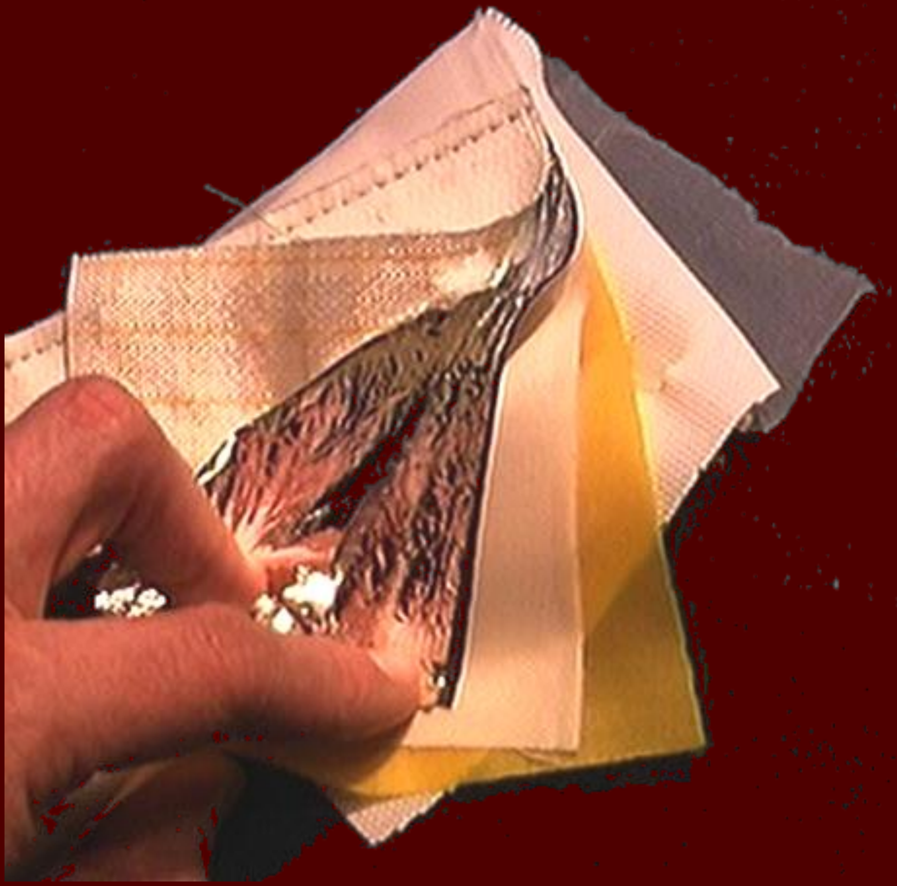


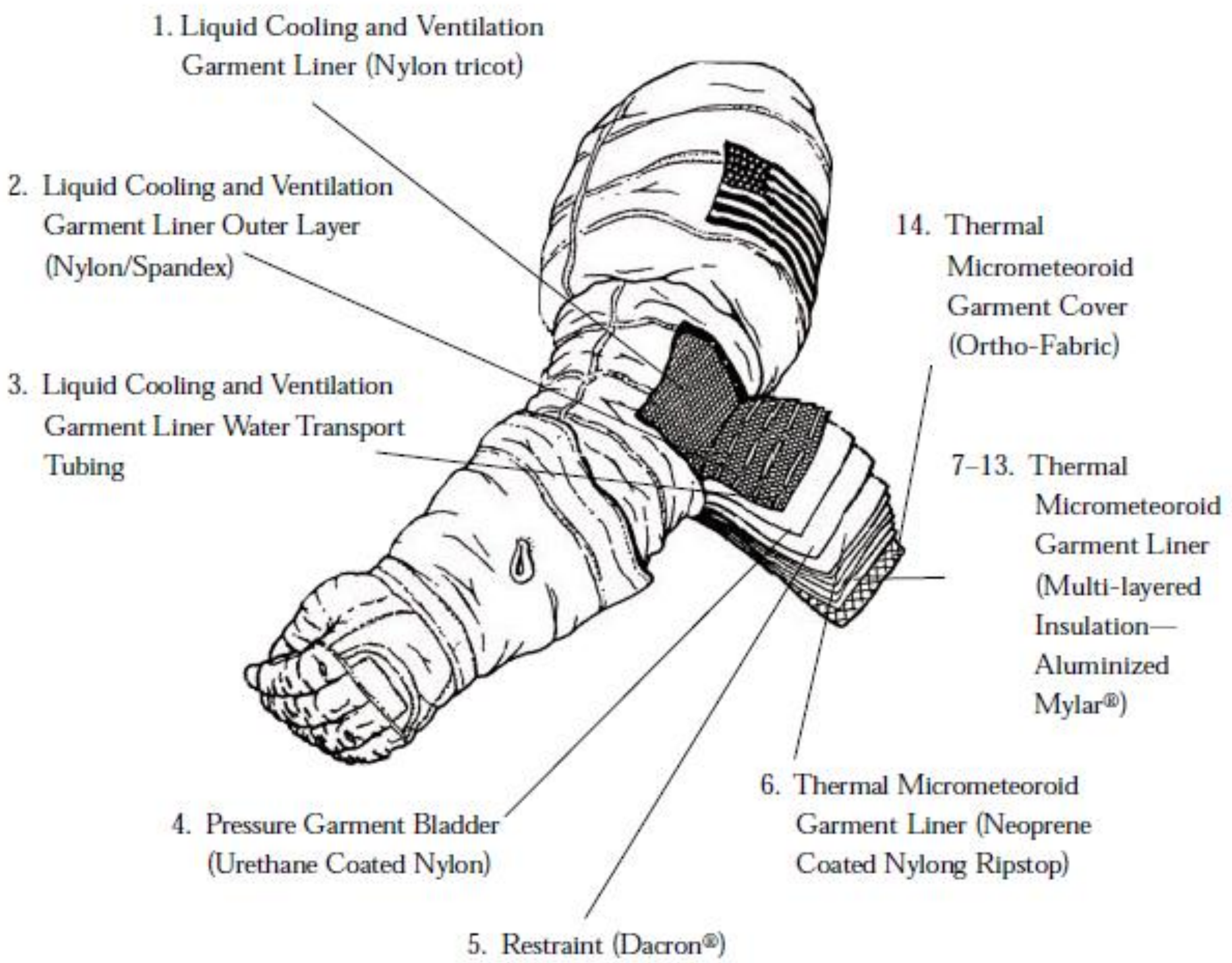




- **Space Shuttle Era Selection Criteria: 5th % Asian Female to 95th % Caucasian Male**
- Supported 135 Space Shuttle Flights: ~2 EVA crewmembers of 7 crewmembers per flight. Shuttle retired in 2011
- Supported ISS for more than 20 years: each crew member required to fit EVA suit.
- Began with 5 standard HUT Sizes
  - XS, S, M, L, XL
  - Budget cut to 2, then back to 3 (M, L, XL)
  - One Size Neck Ring
  - One size helmet (95th Percentile Male)
  - One Size Arm Diameter
  - One size leg diameter,
  - One size boot
- HUT size reduction in 2002 eliminated about 40% of existing astronaut corps, primarily smaller sizes
- Existing EVA Suit sizes changed the astronaut selection criteria when Shuttle retired in 2011

14 EMU Suit Layers

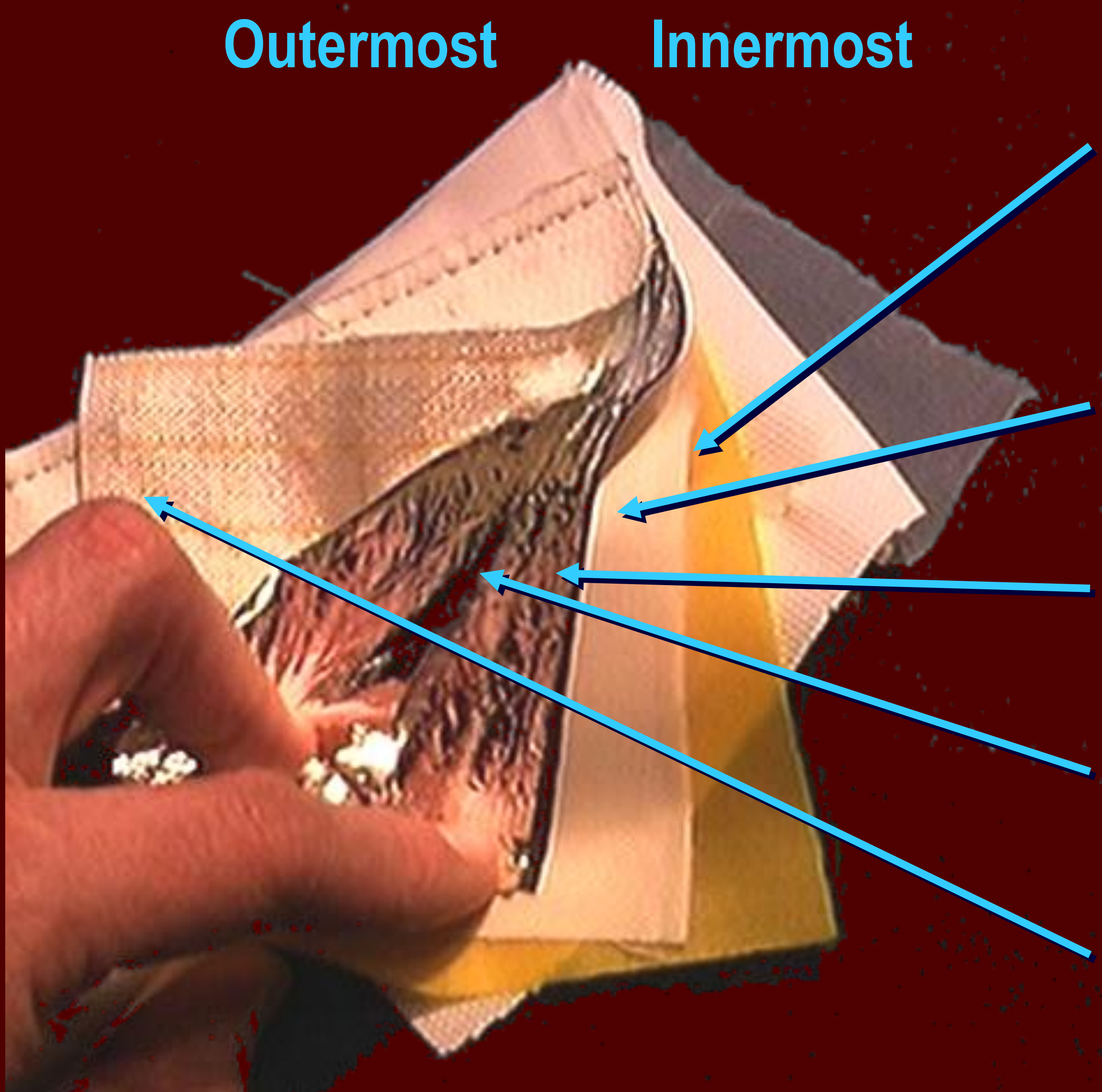




Liquid Cooling and Ventilation Garment (LCVG)

- Conformal garment to maintain body temperature with water
- Ethylene vinyl acetate tubing woven through spandex restraint cloth

EMU Suit Layers



- Pressure Garment Bladder – Urethane coated nylon oxford fabric
- Pressure Garment Cover Restraint – Dacron
- TMB Liner – Neoprene coated nylon ripstop
- TMG Insulation – 5-7 layers of aluminized mylar
- Thermal Micrometeoroid Garment (TMG) Cover

Helmet and Extravehicular Visor Assembly (EVVA)

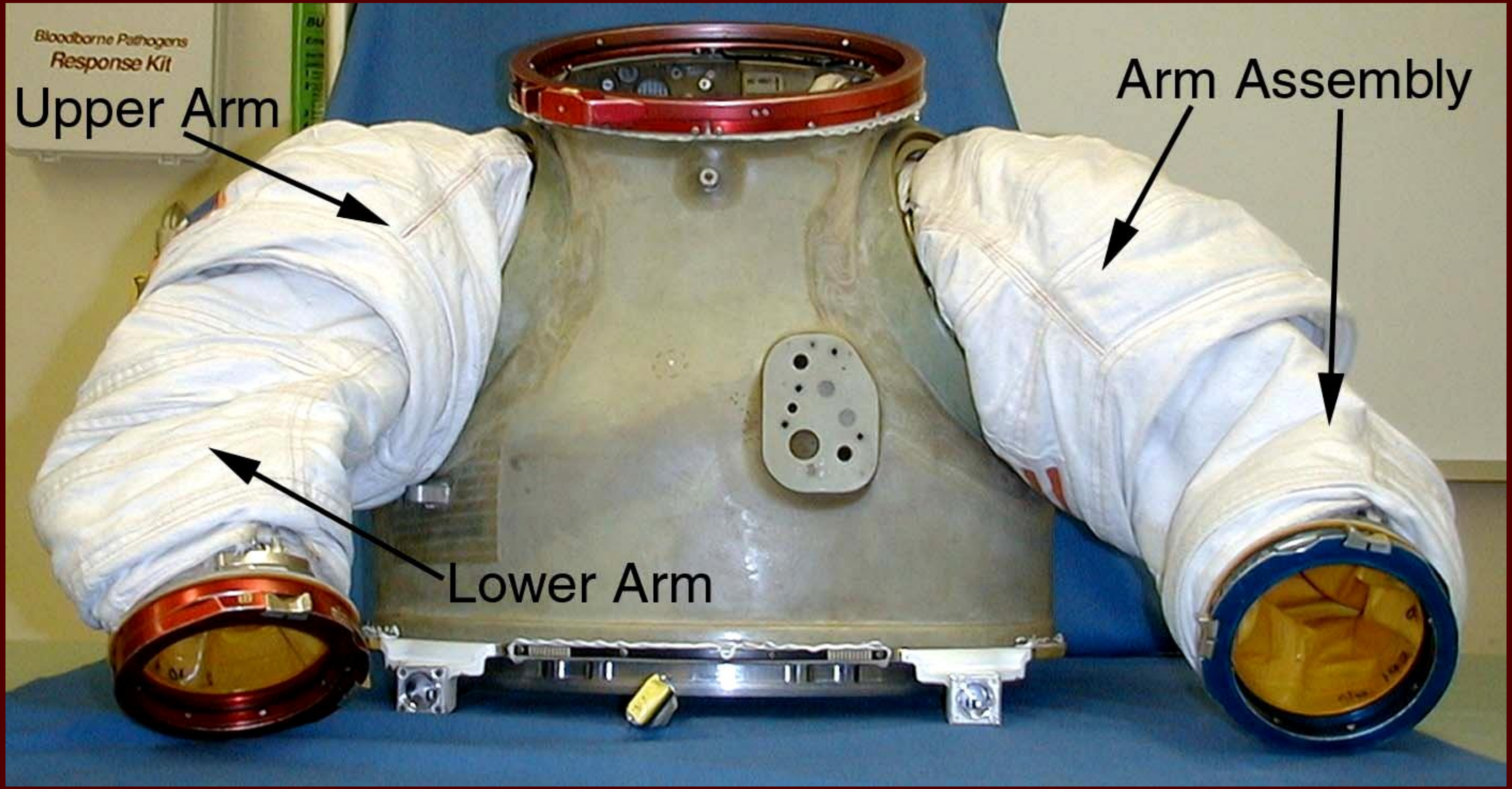
- **Pressure vessel for the head**
- **Visor provides visual, thermal, impact, and micrometeoroid protection in space**
- **One Size fits all: 3 sigma Caucasian male.**

Communications Carrier Assembly (CCA)

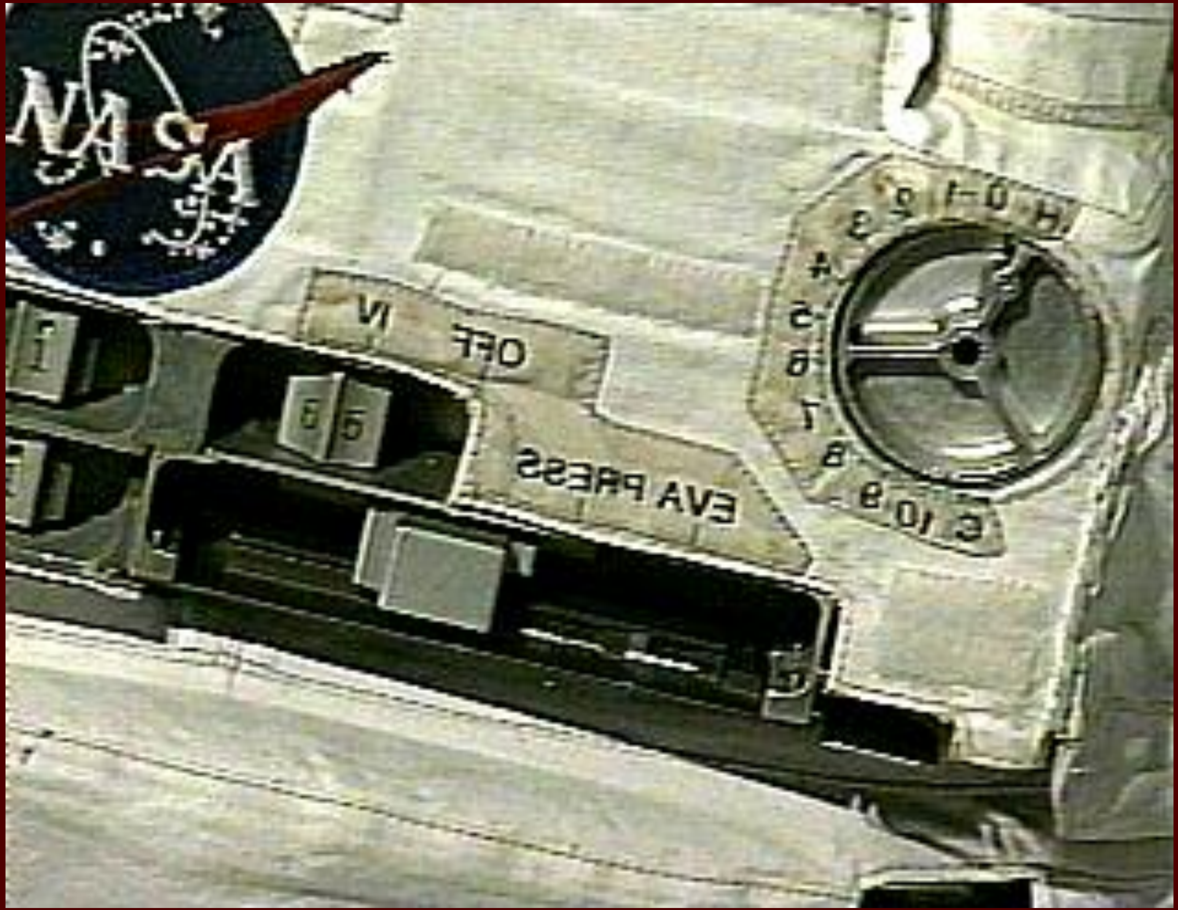
- Contains microphones and headphones for communication and caution and warning tones

Hard Upper Torso (HUT) and Arm Assembly

- Structural mounting interface
- Contains shoulder joints, upper arm bearings, elbow joints, and wrist bearings permitting joint mobility
- One Size Neck Ring, One Size Arm Assembly Diameter, Varieties of Arm Length



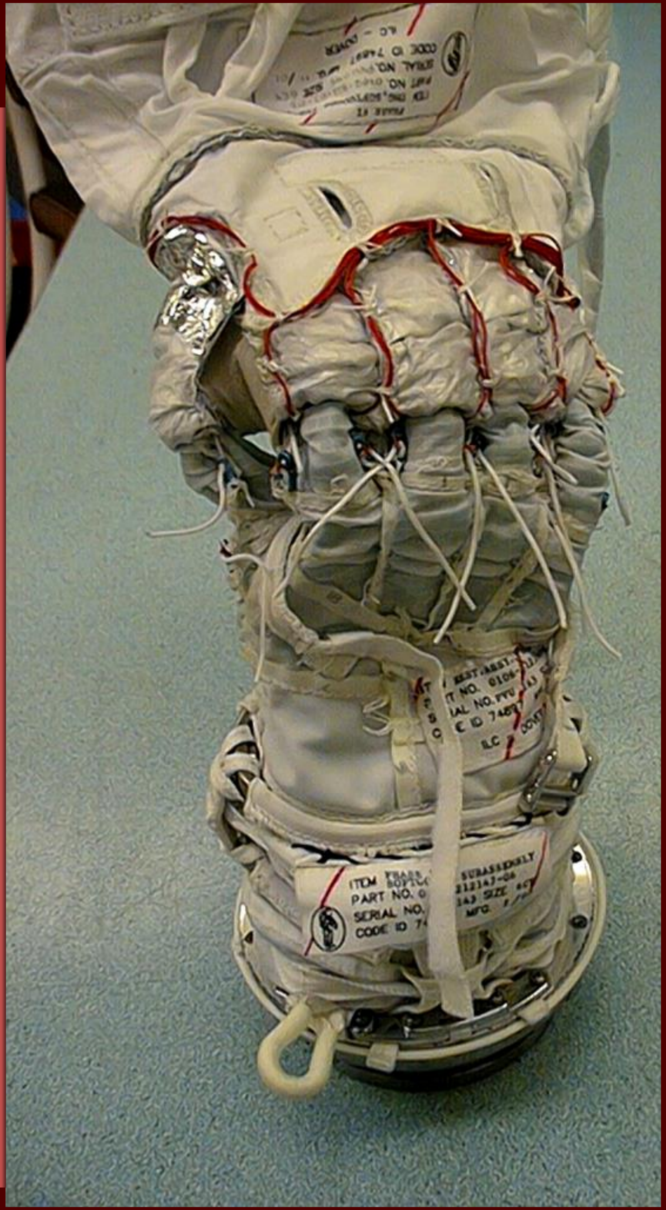
Display and Controls Module (DCM)



Lower Torso Assembly (LTA)

EVA Gloves

- Active interface between crewmember and work being performed



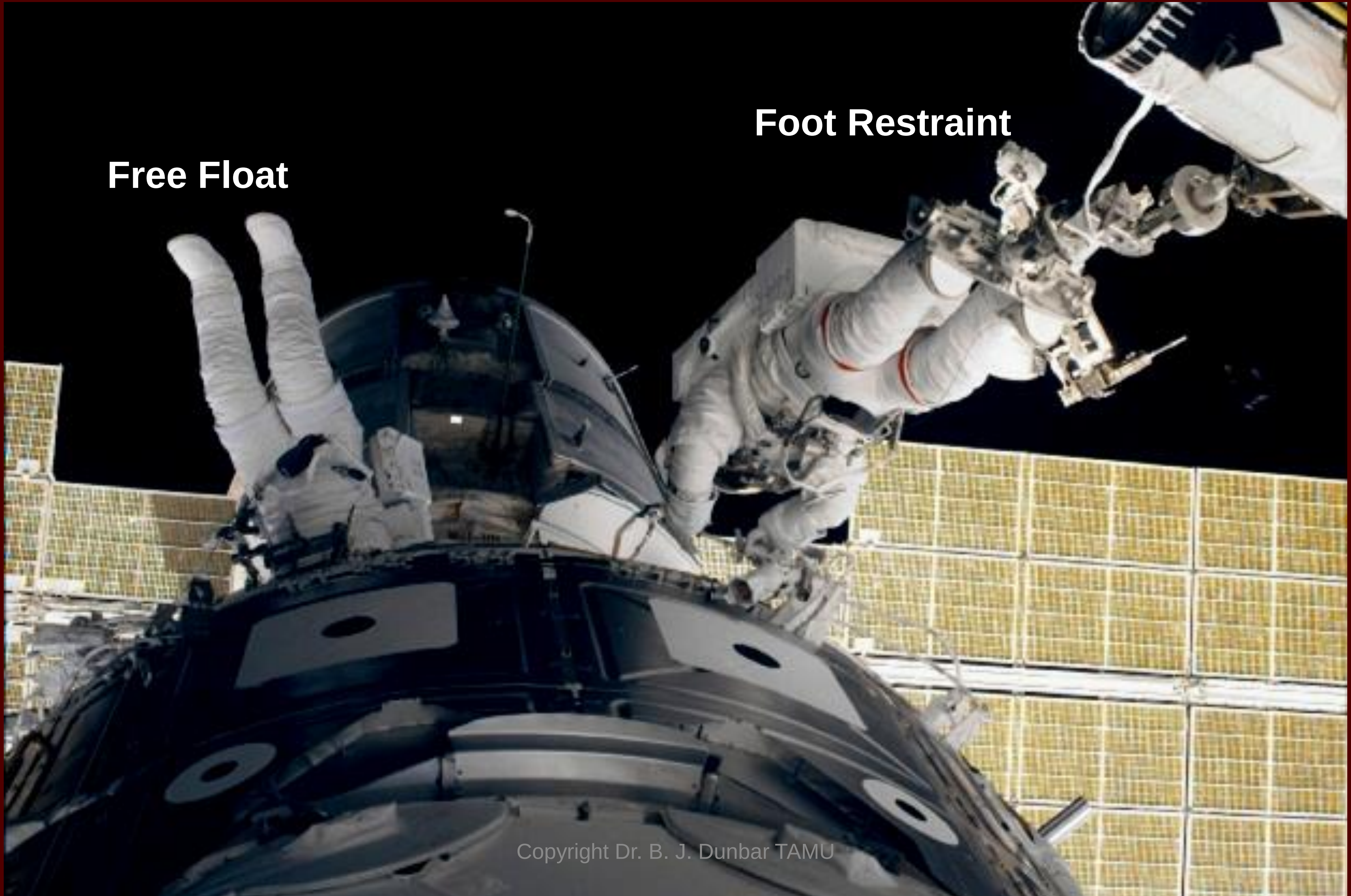
Boot and Sizing Insert

One Size
External Boot –
Change Insert

Boot Heel Clip

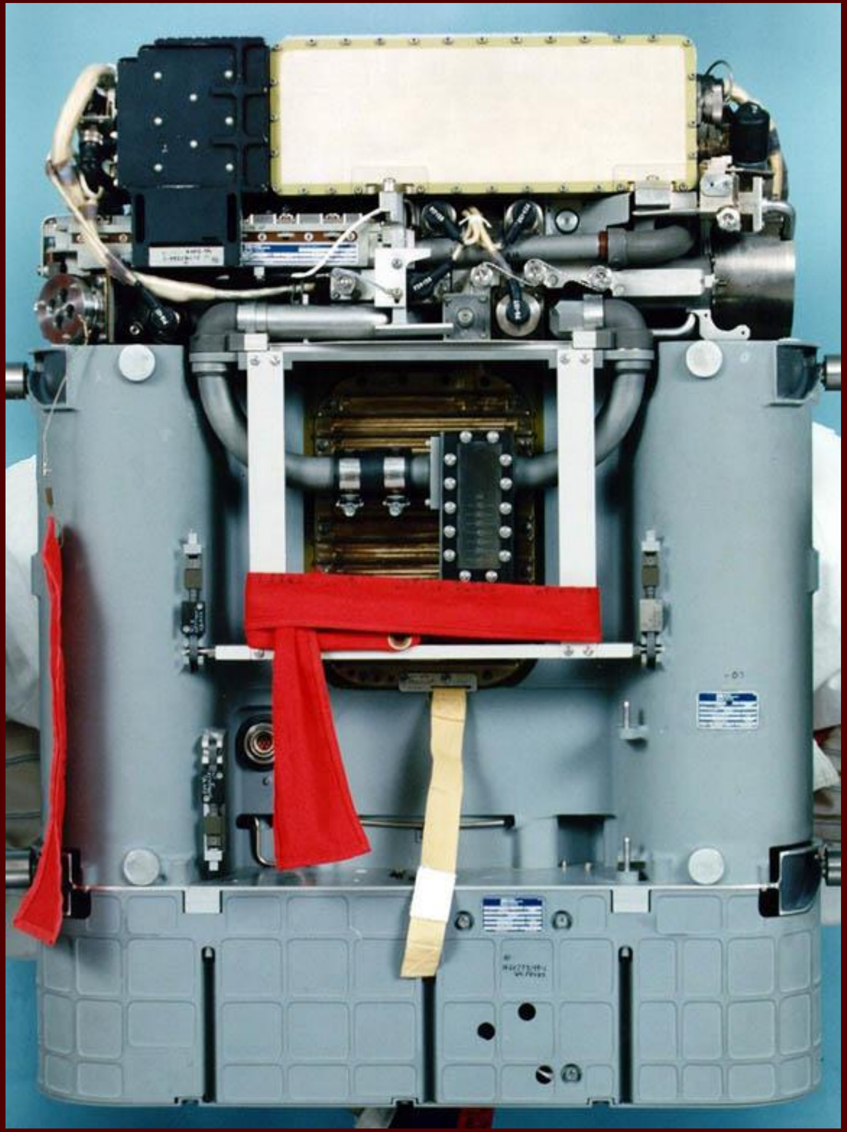
Foot Restraint

Extravehicular Activity (EVA): ISS



Portable Life Support System (PLSS)

- Provides primary and emergency oxygen
- Suit pressurization
- Carbon Dioxide removal
- Cooling Water/Thermal Control
- Power (battery)



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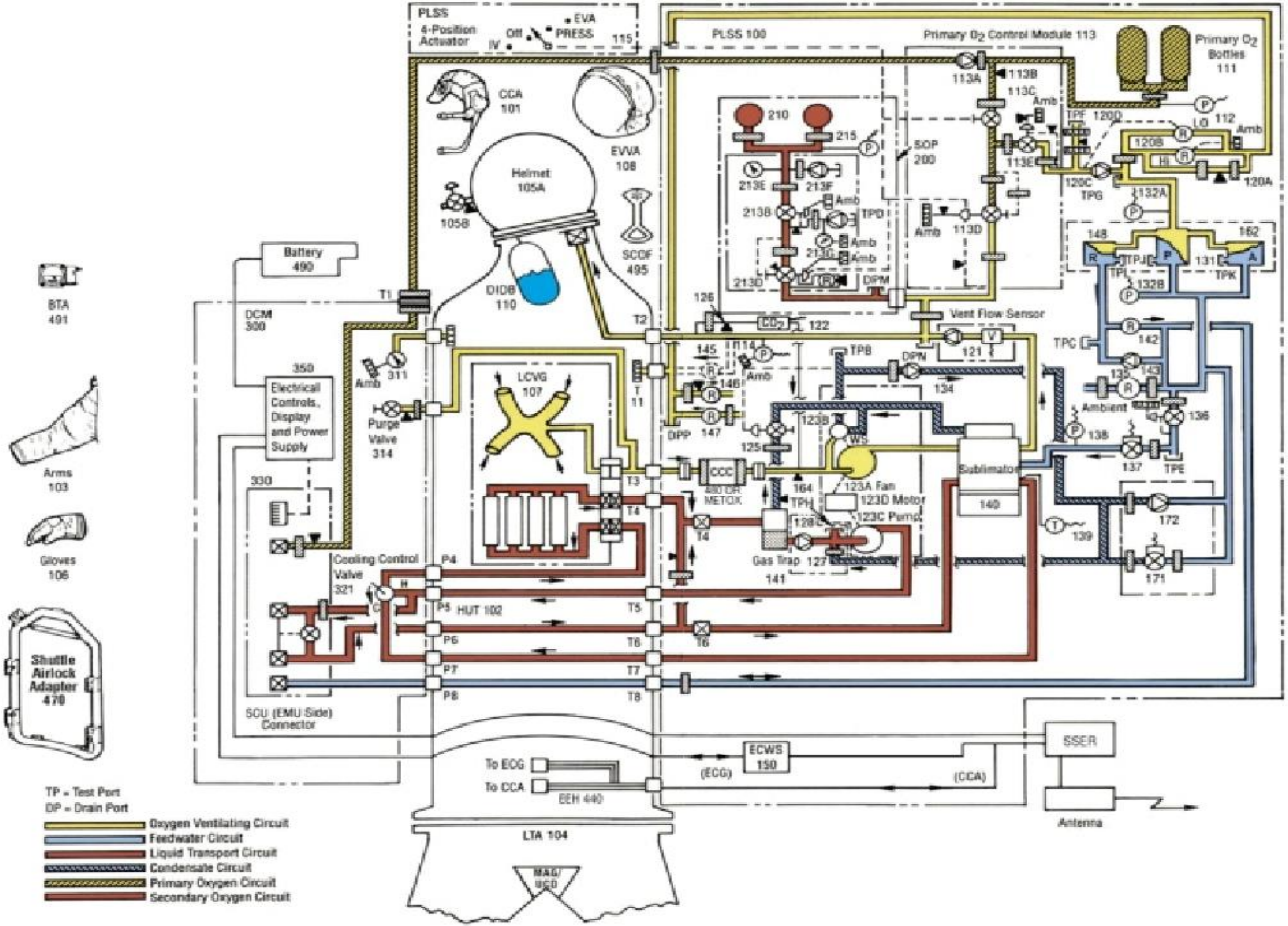
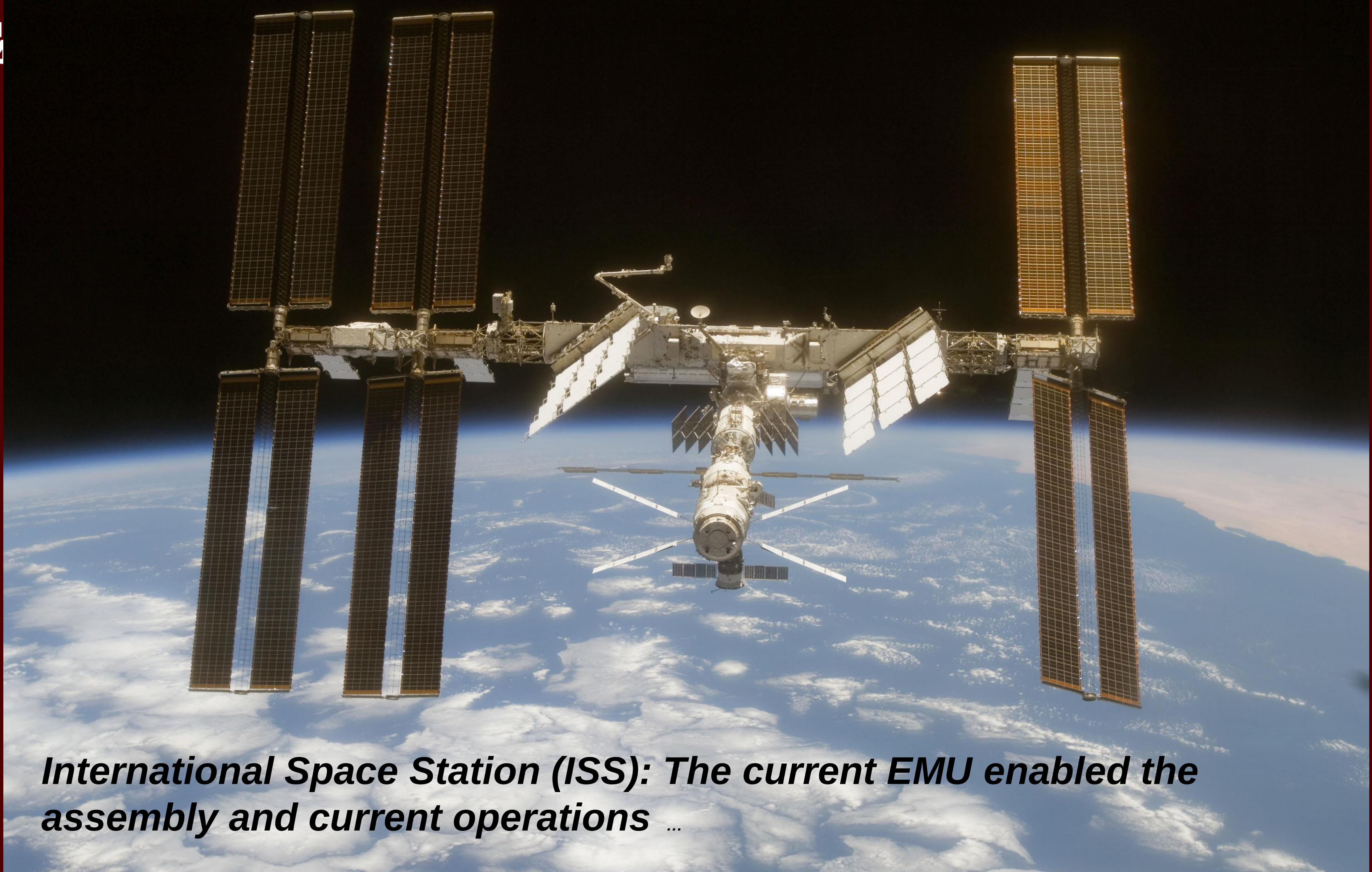
EVA Suit and PLSS Systems Drawing

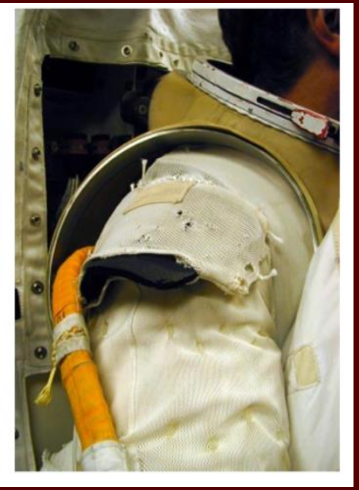




International Space Station (ISS): The current EMU enabled the assembly and current operations …

Suit Fit Injuries

- Suboptimal suit fit, in particular at the shoulders, has been identified as one of the predominant risk factors for shoulder injury while wearing a space suit.
  - Approximately, 64% of crewmembers experience shoulder pain after extravehicular (EVA) training in a suit*
  - Approximately, 14% of symptomatic crewmembers require surgical repair. *



Shoulder clearance between scye bearing and liquid cooling and ventilation garment.

Restricted shoulder motion by hard upper torso (HUT) assembly

Shoulder irritation immediately after extravehicular activity training

*Source: Williams & Johnson, 2003

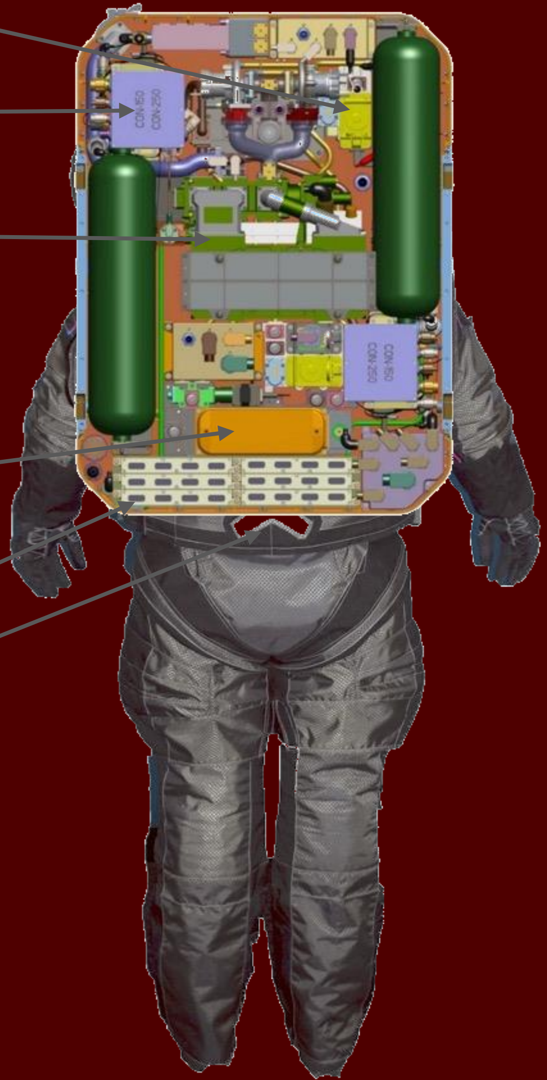
NEW EVA SUIT Design Initiatives

Current EVA Suit Status

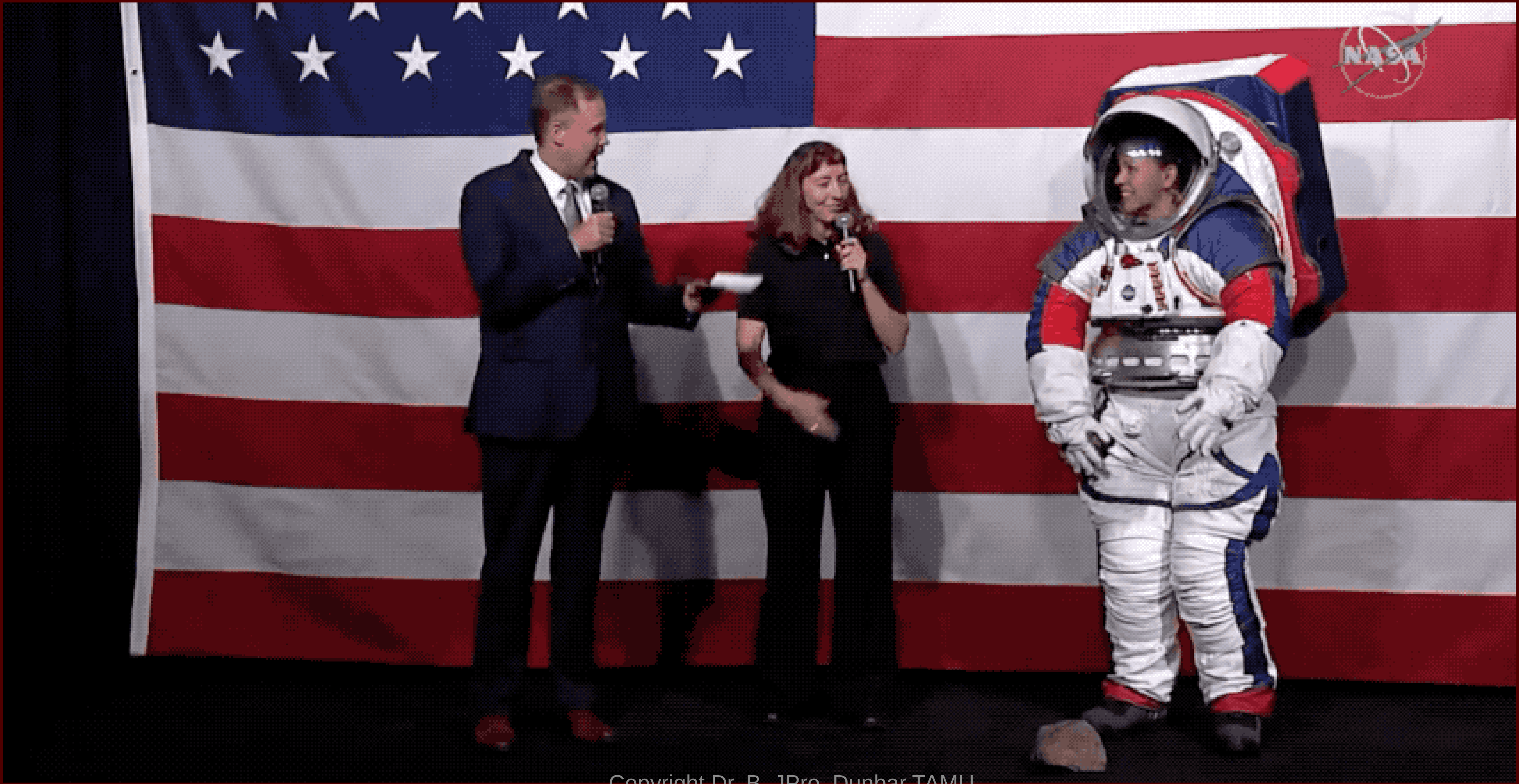
- Current Inventory of EMU EVA Suits is being reduced due to failures, lifetime issues, and lack of production line at ILC
  - EVA Astronauts are selected based on ability to fit into existing inventory using a static digital scan, and ability to operate in the Neutral Buoyancy Lab (NBL) with a “best fit” training suit.
- Collins Aerospace has contract to optimize current ISS EVA Suit, based on the EMU
- Axiom has Contract to construct the xEMU for Lunar Exploration (1% - 99%)
  - Note: one size Portable Life Support System, Back of suit entry

NASA Exploration xEMU Reference Architecture (1% - 99% population selections)

- **High Speed Data Comm.**
- 1 Hr. Emergency Return
- HD Video and Lights
- 4.3 – 8.2 psi Variable Pressure
- Informatics Display and Control
- Amine CO2 Removal Tech
- Integrated Communications
- Enhanced Upper Mobility
- Membrane Evaporation Cooling (SWME)
- Automated Suit Checkout
- Modular/ORU PLSS Design
- Rear Entry Ingress/Egress
- Planetary Mobility



xEMU Engineering Prototype for Artemis Lunar Mission (1% to 99% Male and Female Anthropometrics)



https://www.youtube.com/watch?v=QzyIiAeWEZA

New EVA Suit Strategies

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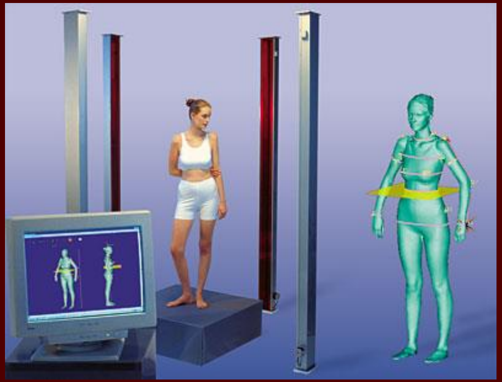
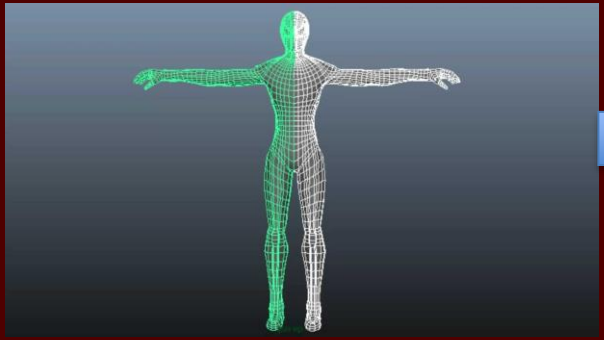
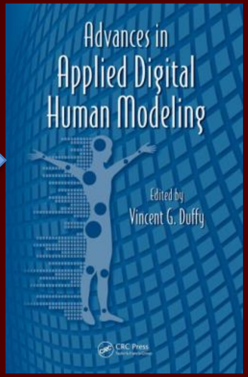
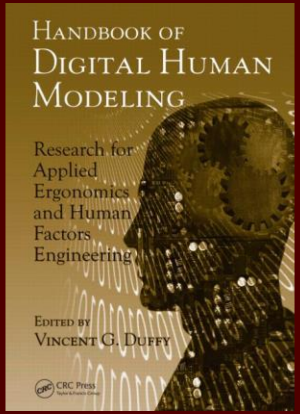
Future Vision:

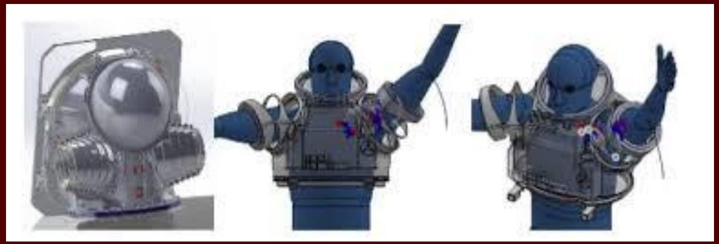
From Digital Human to Advanced and Additive/3D Manufacturing for Customized Pressurized Extreme Environment Personal Protection Equipment using Aerospace knowledge and tools with advanced materials, sensors and life support systems

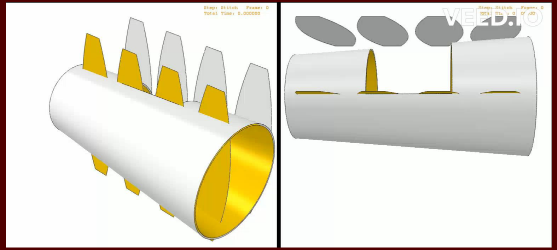












The Spacesuit Digital Thread: NIAC Phase I

4.0 Manufacture of Custom High Performance Spacesuits for the Exploration of Mars

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Texas A&M University
Director, AHSL
Astronaut, Ret.

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Mr. Dave Cadogan
President & Lead Design Engineer
Moonprint Solutions,

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(Human Systems Modeling)

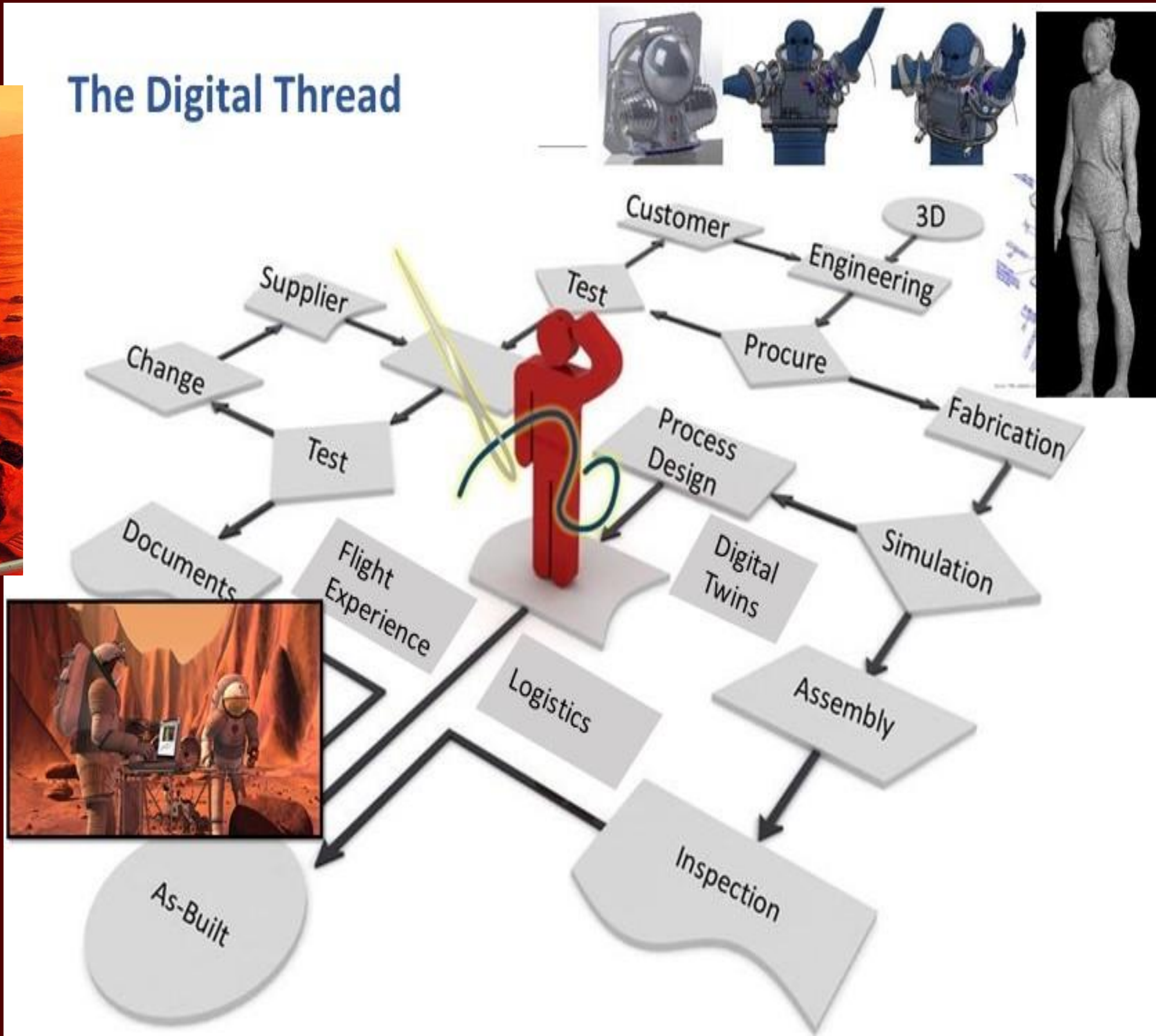
Mr. Dillon Hall
PhD Candidate
Aerospace Engineering
AHSL Texas A&M University and now employed by Axiom Aerospace

The Spacesuit Digital Thread:
4.0 Manufacture of Custom High Performance Spacesuits for the Exploration of Mars

The Vision

How do we get from………..To?

A notional Digital Thread
Beginning with a *Virtual Twin*



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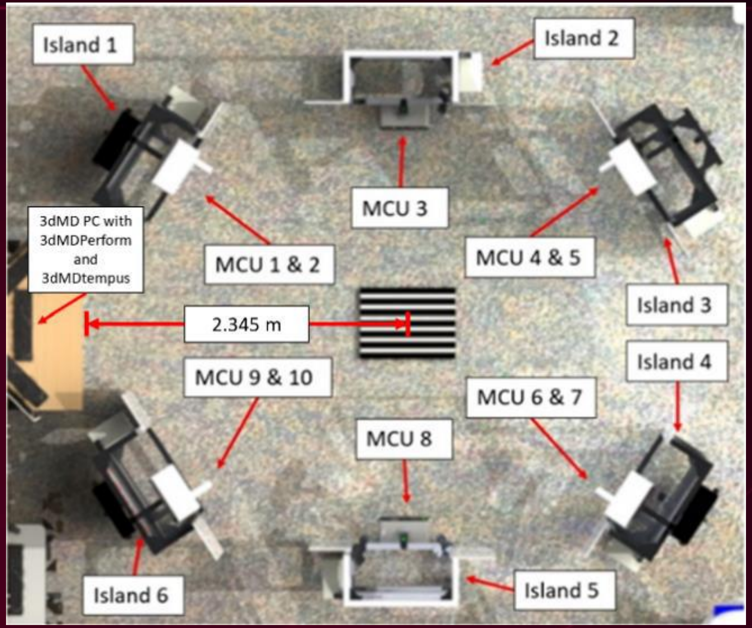
The 3dMD Full Body Motion Capture System

- Captures 20 seconds of motion per scan sequence at 10 Hz (i.e., 200 scans or “frames”).
- Consists of 10 modular camera units (MCUs)
  - Each MCU consists of 3 cameras and a speckle projector:
  - Two black and white cameras capture the surface distortion of the speckle projection to calculate 3D geometry
  - One color camera maps texture to the rendered 3D object.
- The 10 MCUs are positioned on 6 “islands” surrounding the subject.
- The 3dMD has been demonstrated to provide a surface accuracy of 1 mm and is used extensively in the medical industry.

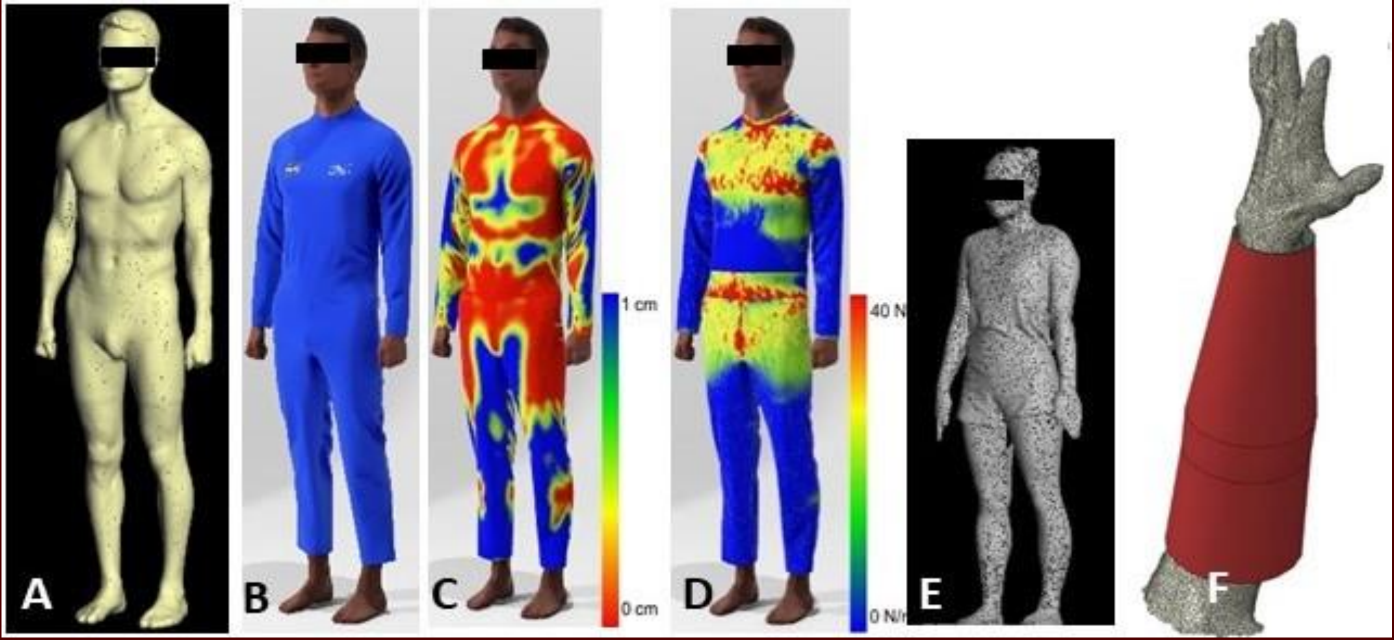


Configuration 3dMD Full Body Scanner with 6 Towers/Islands and 10 MCUs.

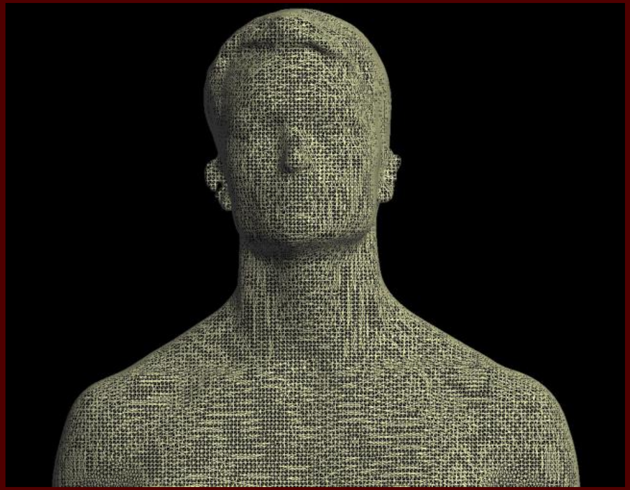
3dMD Motion Capture MCU Consisting of Two Black and White Cameras (A & B), One Color Camera (C), and a Speckle Pattern Projector (P).

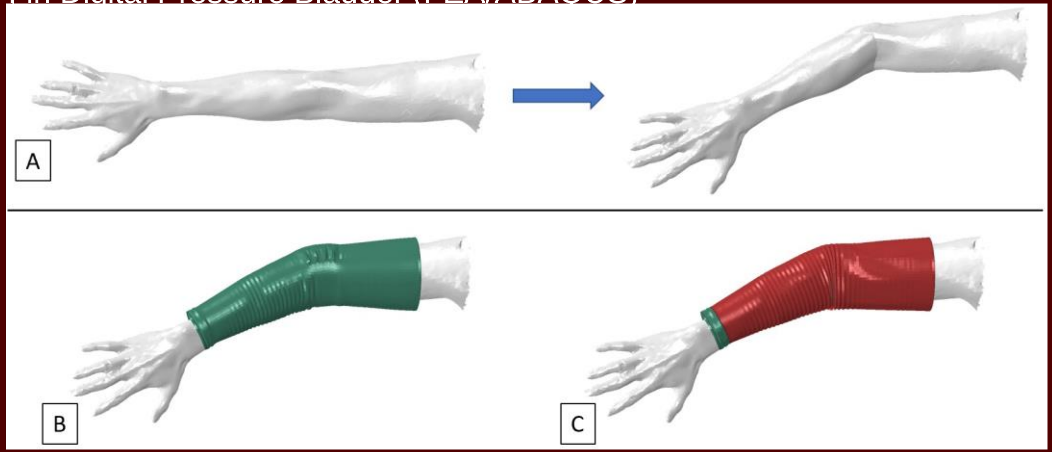
Preliminary Assessments: Human Scanning and Soft Goods FEA

- Vitronic **Vitus Laser Scanning** system is a world class facility which produces full body scans with 1 mm accuracy.
- The **CAD-VIDYA software** can simulate up to 20 different multi-layer materials on scanned subjects and calculate stresses, strains and “fit”, but the garments are not pressurized.
- **Finite Element Analysis (FEA) models** utilizing **pressure** garment and restraint materials coupled with kinematics of a human arm, in order to determine the sensitivity of elbow force and torque to both the suit arm design and the anthropometry of the astronaut.



A) Digital Scan of ~50th % American Male (~727K vertices); B) CAD/VIDYA Flight Suit; C) *Distance from Skin* Heat Map; D) *Material Stress* Heatmap; E) 10th % Asian Female Scan; F) Arm scan of “A”, in Digital Pressure Bladder (FEA/ABAQUS)

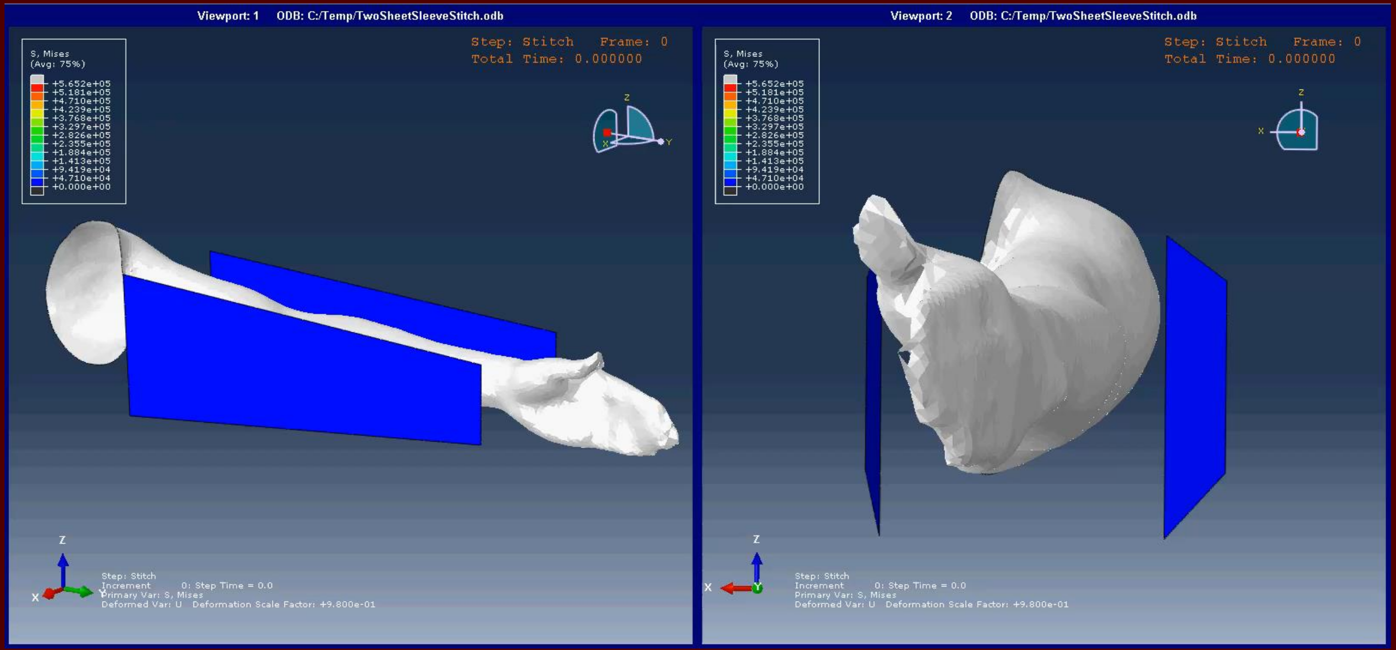


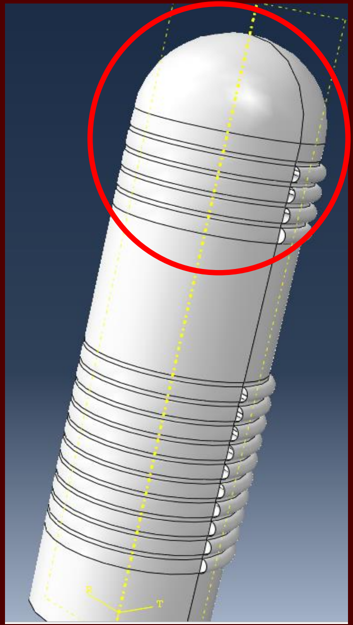


Digital Suit: Finite Element Mesh

Finite Element Analysis (FEA) of Pressurized Fabrics for EVA Suits – (ABAQUS)

Research Goal: To scan a subject, donned in an EVA or LEA suit, and then to digitally/quantitatively evaluate suit soft fabrics for mobility and fit after pressurization. (Graduate Students Dillon Hall and Patrick Chapates)

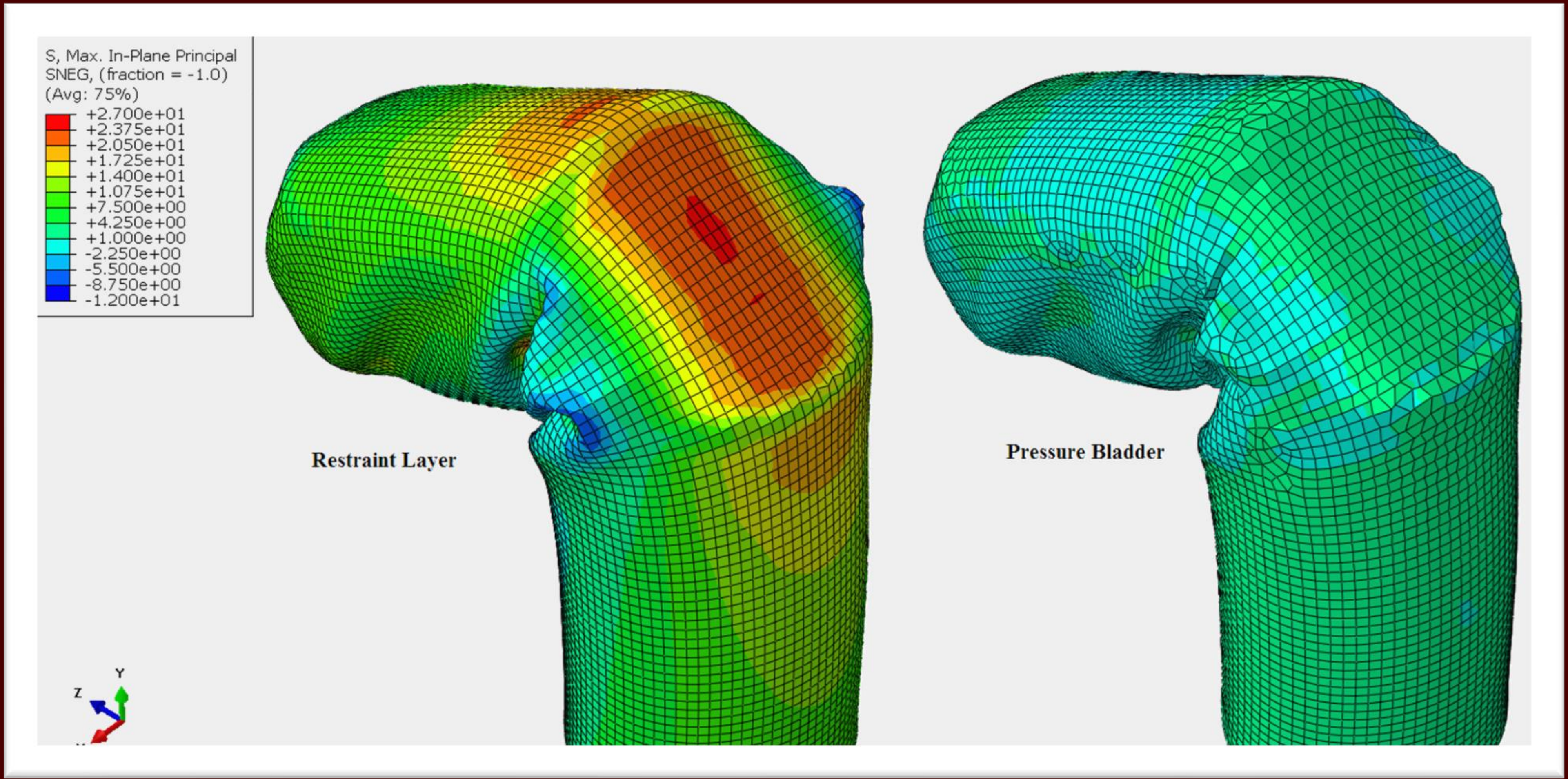




Dillon Hall

Patrick Chapates

Stress Distribution in Restraint Layer and Pressure Bladder

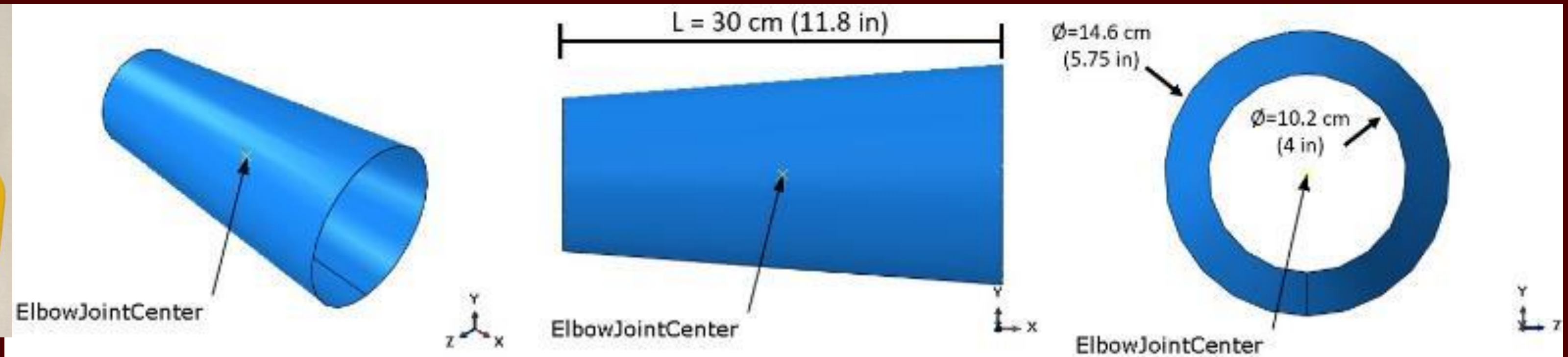


Majority of the load is carried by the restraint layer.

Methodology

- A baseline sleeve design model was introduced to serve as the foundation for adding additional features to analyze in subsequent design cases.
- For each case, an FEA solver pressurized and bent the lower arm assembly to determine the joint torque profile required to perform elbow flexion.
- Abaqus/Explicit 2021 was used for this analysis.

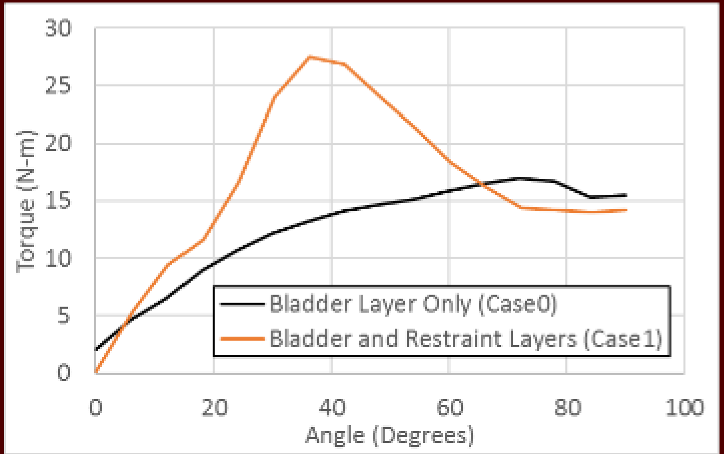
Size 04 EMU pressure garment elbow joint (left) from the inside and (right) from the outside



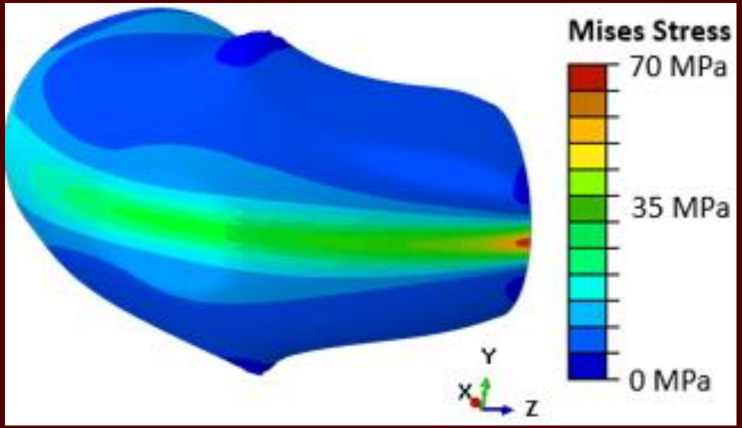
“Level-0” model of an EMU lower arm assembly design

Results – Effect of Restraint Layer

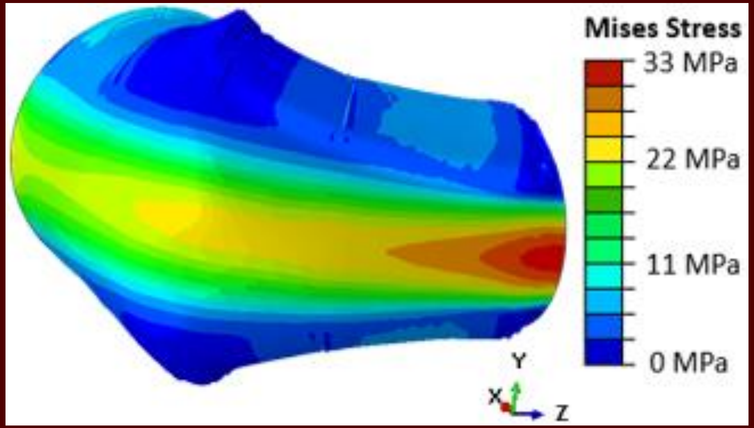
- Joint torque data suggests that adding a restraint layer increases bending resistance.
- Stress maps show max stress occurring on the lateral side of wrist cuff.
  - Adding a restraint layer reduces overall stress in the garment.



Effect of the restraint layer on the joint torque profile of a minimally designed lower arm assembly

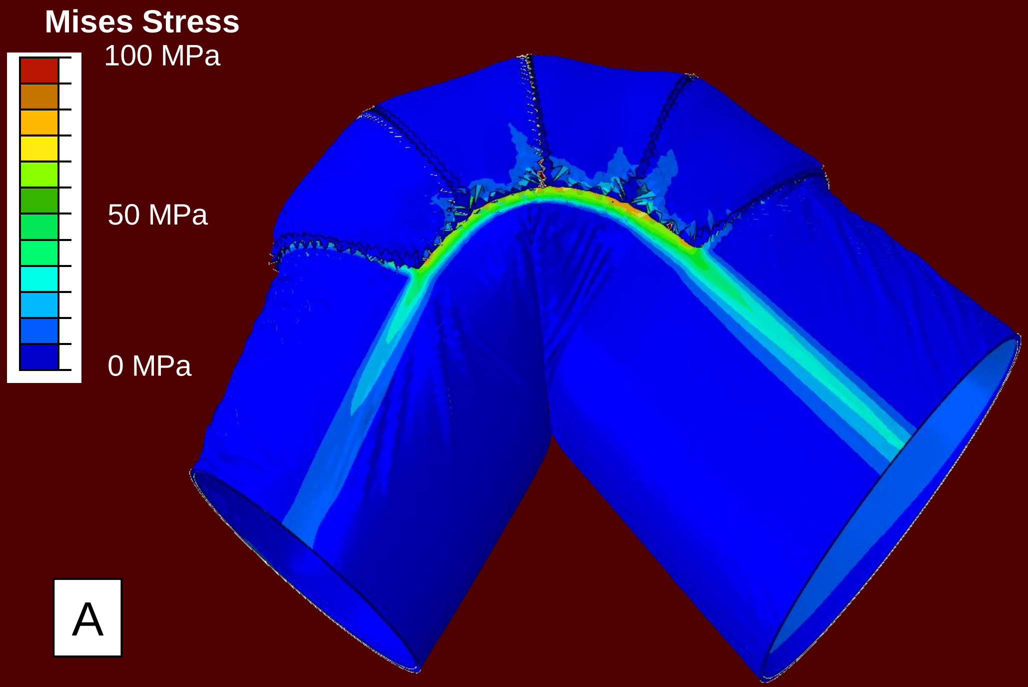


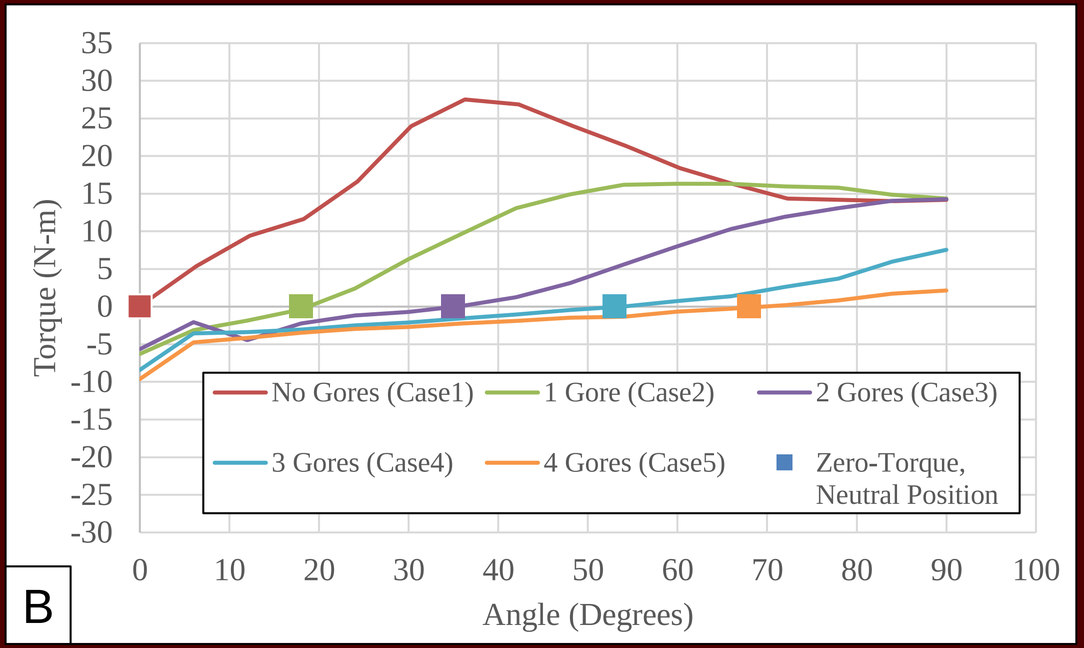
Stress Results
Bladder Only



Stress Results
Bladder and Restraint

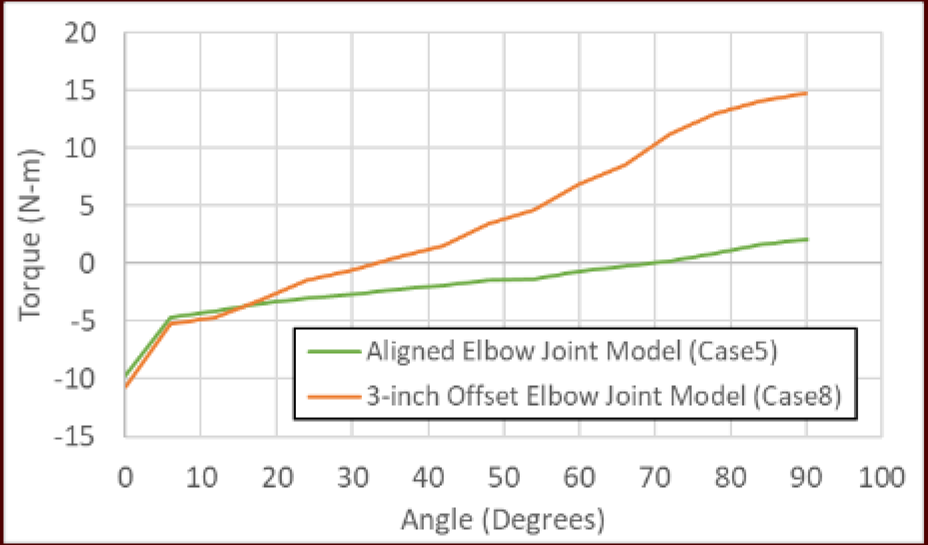
Elbow Torque as a Function of Number of Elbow Gores



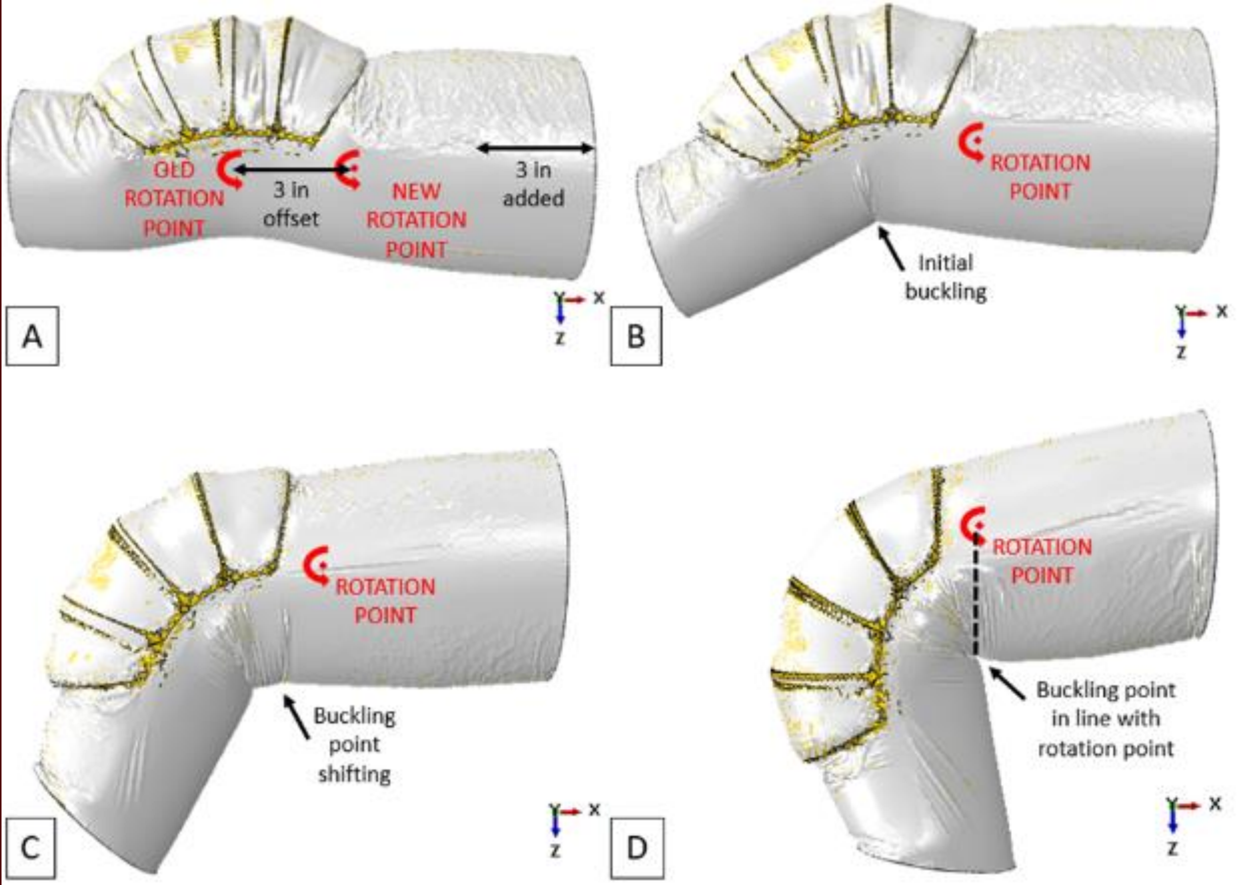


Results – Effect of 3-inch Elbow Joint Offset

- One additional case investigated the effect of a worst case, poorly sized lower arm assembly with a 3-inch offset applied to the bicep portion of the arm.
  - Simulates a crewmember elbow at a different position than the suit component elbow joint
- Results show a shifting breakpoint, higher torque slope, and higher max torque.

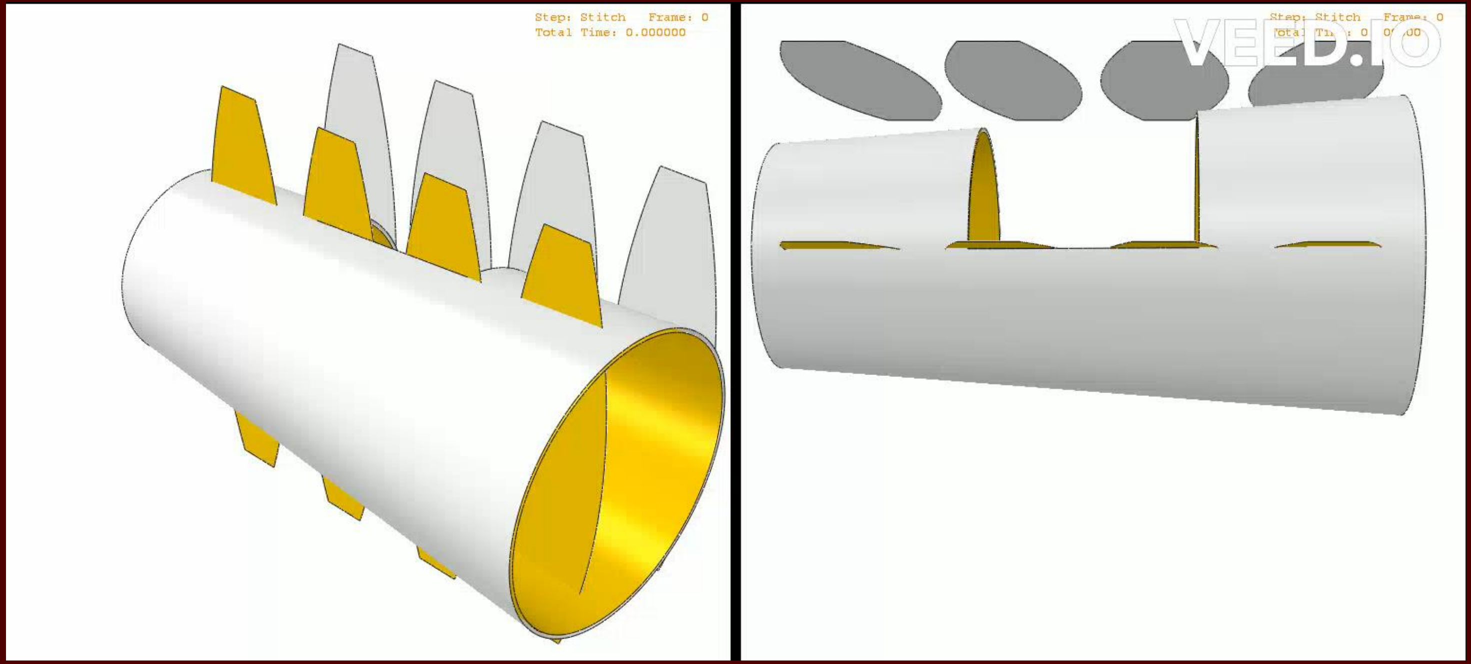


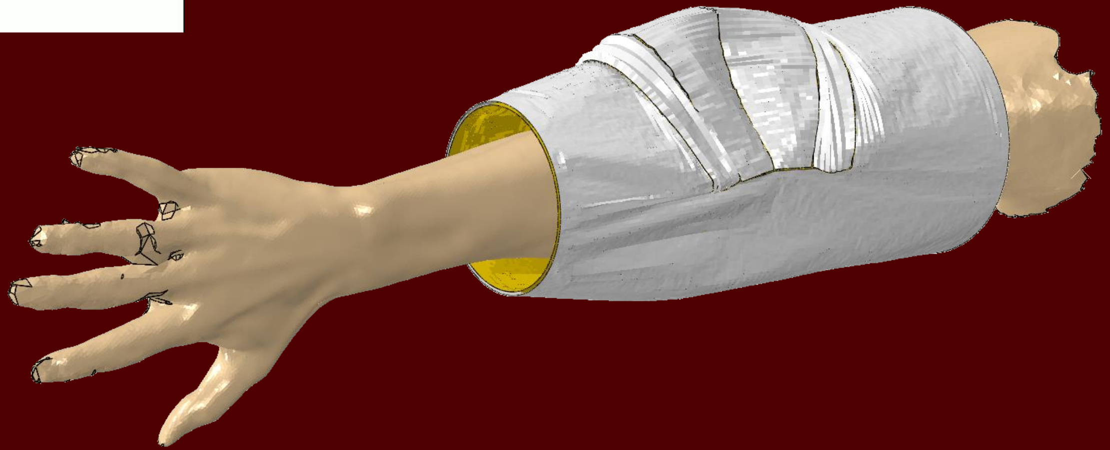
Effect of elbow offset on the joint torque profile of the lower arm assembly



Case 8, lower arm assembly with 3-inch elbow joint offset: A) overview of 3-inch offset, B) after initial buckling, C) buckling point shifting toward shoulder, and D) after 90° elbow rotation

Developing Virtual Twins with Human Scans In the Loop





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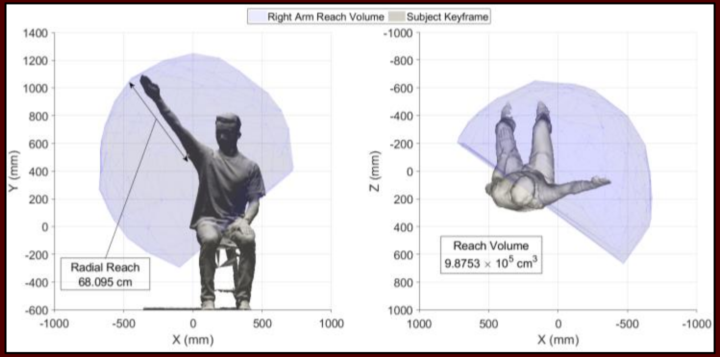
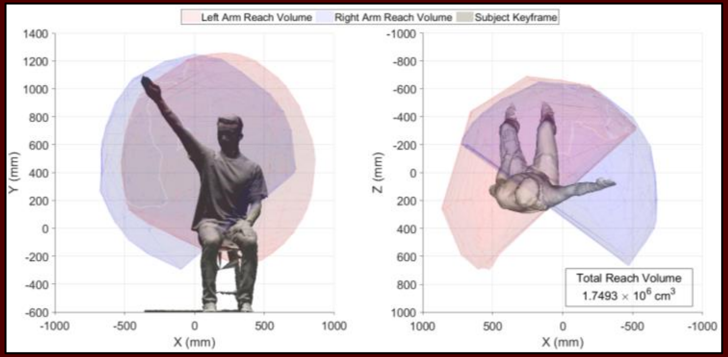
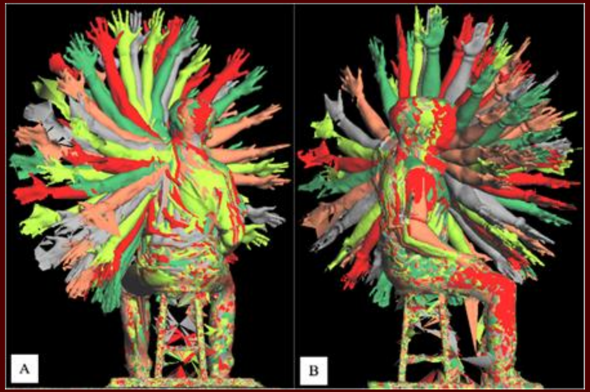
3D Motion Capture and Reach Envelope Analysis

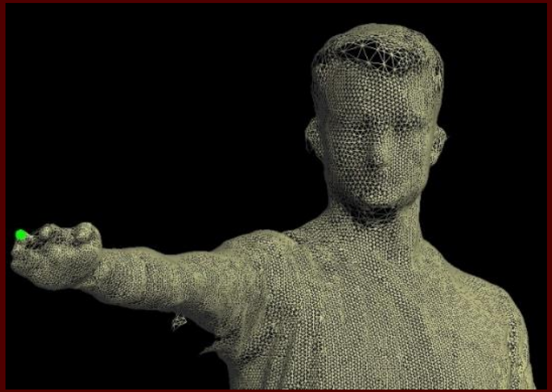


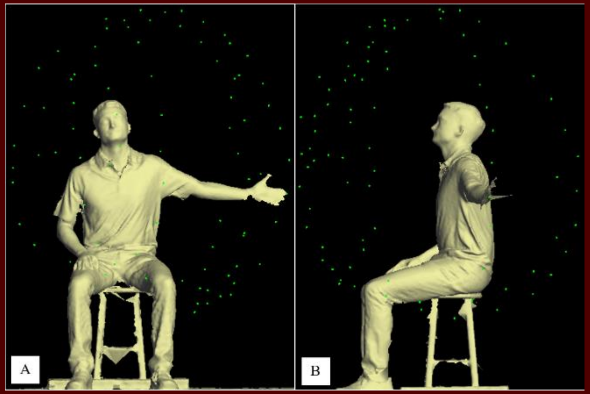
Using the 3dMD motion capture system, the AHSL team developed a method for computing the total reach volume and ROM for a subject in and out of a spacesuit.

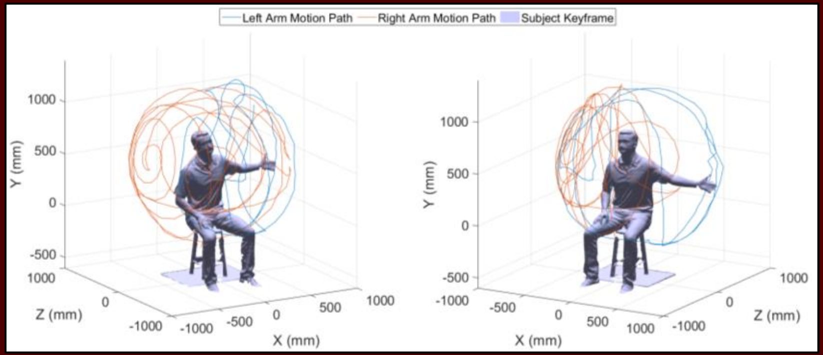
- Each frame of a 20 second (200 image) sequence is landmarked
- Paper Published: 2020 ICES Conference: Hall and Dunbar, "Range of Motion (ROM) Analysis for Pressure Garments (EVA and LES) using 3D Photogrammetric Motion Capture,"

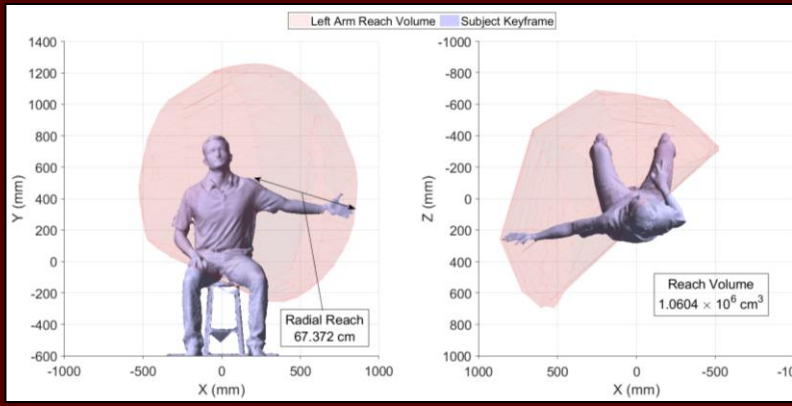




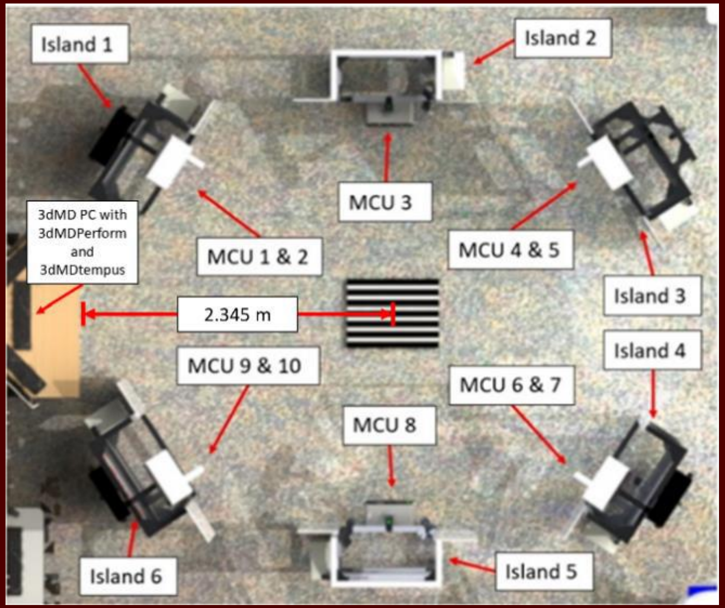


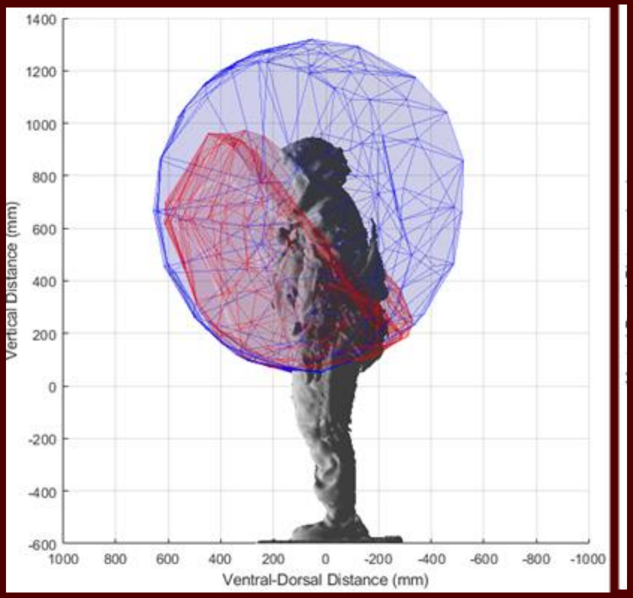






3dMD Full Body Motion Capture (Photogrammetric Scanning, 1mm Accuracy)





Example of Pressurized Suit Impact: Range of Motion (ROM) (in this case, unpressurized vs unsuited)

Methodology: Unsuited vs Suited-Unpressurized ROM

- The 400-frame, Abercromby motion path was executed to evaluate the difference in unsuited vs. suited ROM and Reach.
- The subject was selected who best matched the Sokol suit measurements

Unsuited Motion, Abercromby Path
(Horizontal Component)

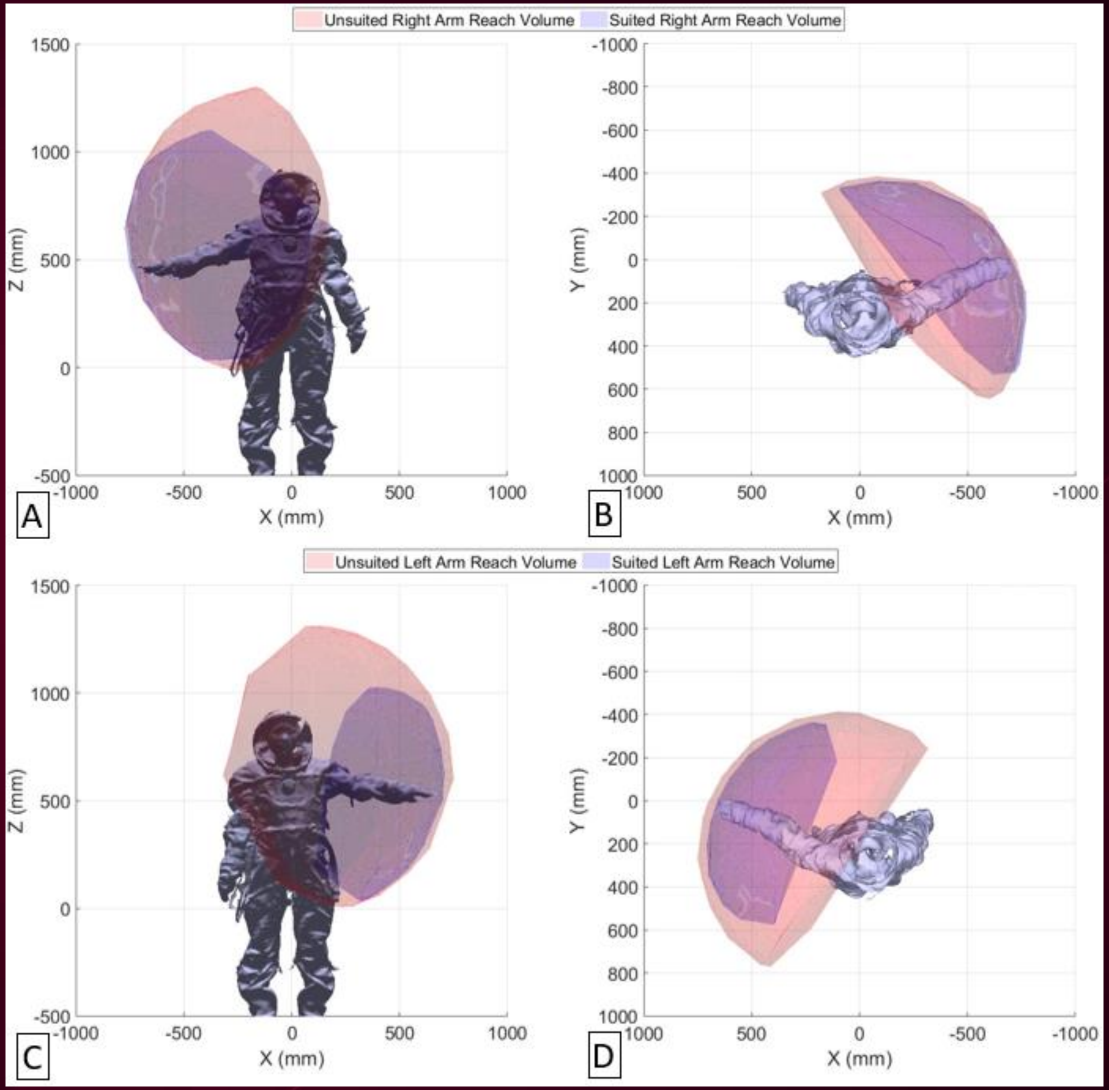
Suited Motion, Abercromby Path
(Horizontal Component)

Suited Motion, Abercromby Path
(Vertical Component)

Results: Unsuited vs. Suited-Unpressurized Comparison

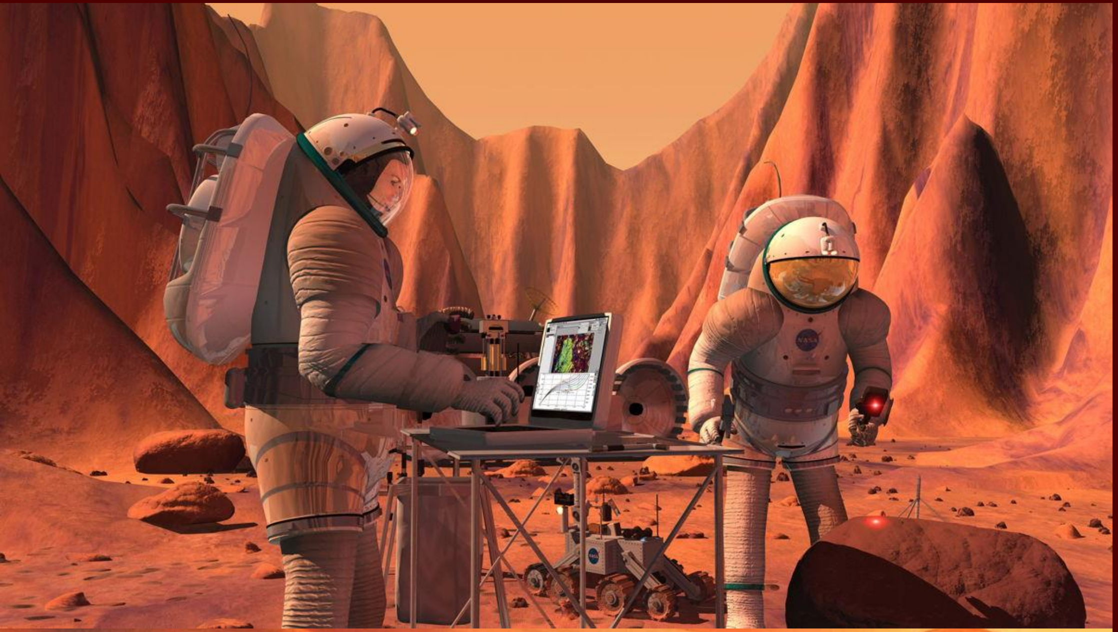
- Superimposed ROM envelopes show significant degradation in some directions (e.g., reaching overhead) in the unpressurized Sokol
  - Red bubble: Unsuited reach envelope
  - Blue/Purple bubble: Suited reach envelope

- ROM volumes decreased for each suited case:
  - Left Arm: 79% volume reduction
  - Right Arm: 72% volume reduction



Comparison of Unsuited (red) and SOKOL-Suited-Unpressurized (blue) ROM Envelopes for Right Arm Motion, A) Front View and B) Top View and Left Arm Motion C) Front View and D) Top View

IMPORTANCE OF RESEARCH

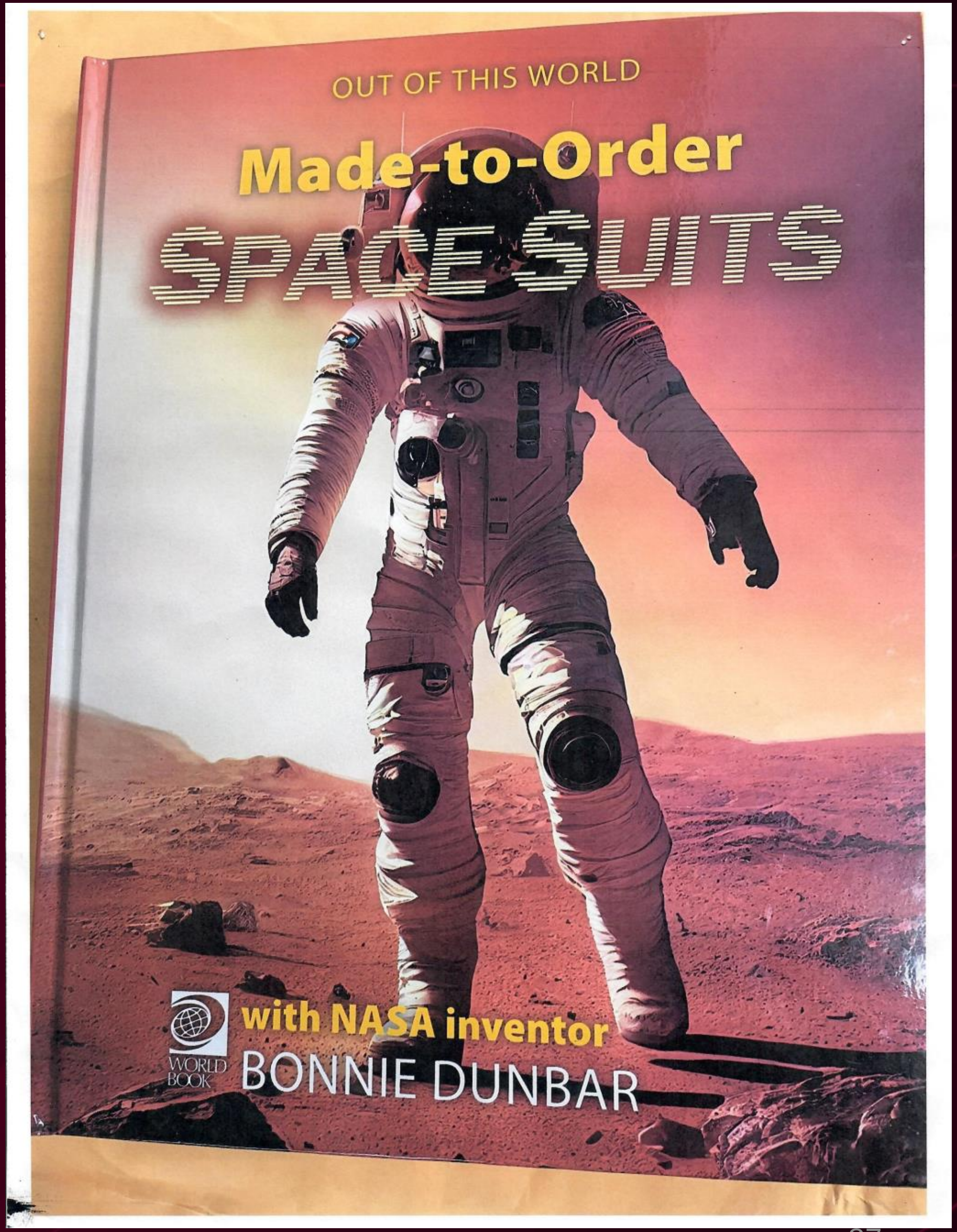


- Connects analyses of manufacturing, mass trades, calculated risk, failure probabilities, logistical requirements, opportunities for in situ repair, potential for replacing EVA suit components with re-purposed in-situ materials/
- Has the potential to reduce life cycle costs and time to manufacture.
- Customized EVA suit design will improve astronaut performance, minimize crew injuries and ensure a properly fitting suit for all crewmembers, regardless of size and shape
- Customized EVA suits have the potential to increase Mars surface EVA science and engineering productivity.
- Extensible to future Lunar Exploration Missions
- Will benefit commercial spaceflight participants and others who operate in extreme environments requiring rapidly manufactured, well fitting protective garments, such as first responders, individuals working with infectious diseases, and our military, regardless of "size" and "body shape".

Proposing 21st Century EVA Suits

- Customize the EVA Suit to the Individual (Apollo Approach with 21st Century Digital Engineering Tools)
  - Design for Operational Success

- Develop a Virtual Twin Prior to manufacture
  - Digital Scans and DHM integrated with CAD Designs
  - Utilize FEA to optimize and perform sensitivity testing



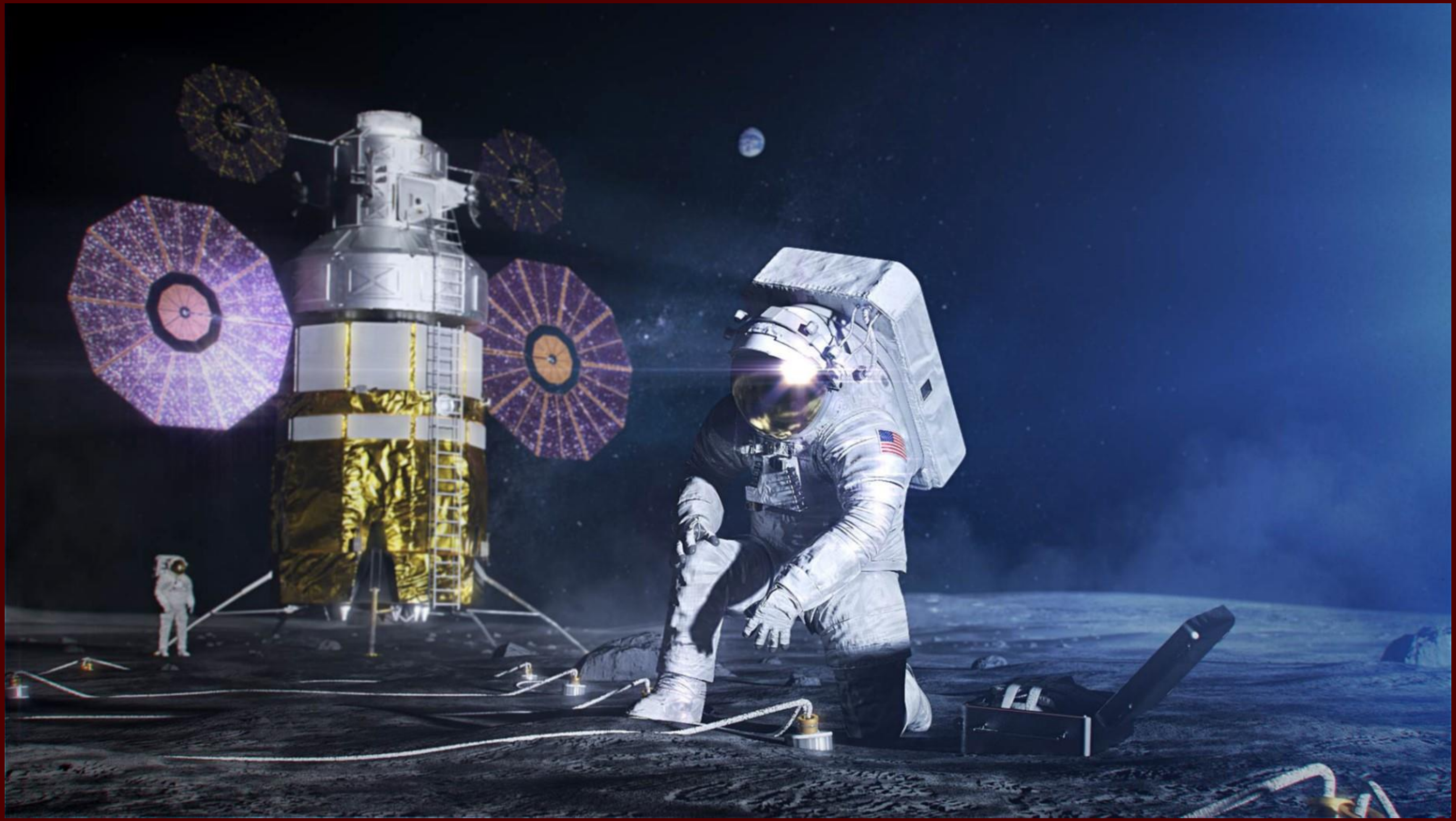
- **Goal of integrating HSI, Digital Engineering, Bioastronautics, DHM, and space human factors for EVA Suits**

  - *Place the highly variable human body within these restrictive physical environments to ensure that the entire anticipated population is safe and can function in the extreme environment of space*

National Aeronautics and Space Administration

The Aerospace Engineering Vision

OR A future when spacesuits are engineered for any human shape, are operationally transparent, and will support survival in any extreme environment



QUESTIONS?

Impacts of Crew Size and Suit "Fit" Problems

- Mercury, Gemini, Apollo and Skylab (Custom Suits)
  - Males from Test Flight School and Science Astronauts
  - Selected as small as possible for mass

- Space Shuttle Program
  - Males and Females
  - Selected 5th Percentile Asian Female to 95th Percentile Caucasian Male
  - Custom T-38 Flight Suits
  - Customized Shuttle IVA Flight Clothing 1981-1986
  - EVA Suits: 1981 to Present
    - 5 sizes of Hard Upper Torso (HUT) (reduced to 3)
    - Mix and match arms and legs
      - Change Length, Circumference Constant
    - One Size Helmet fits all
    - One Size Boot with sized inserts
    - Best fit Glove in most cases
      - Only custom when required
    - Last Size reduction eliminated ~40% of astronaut corps from ISS Flight Selection