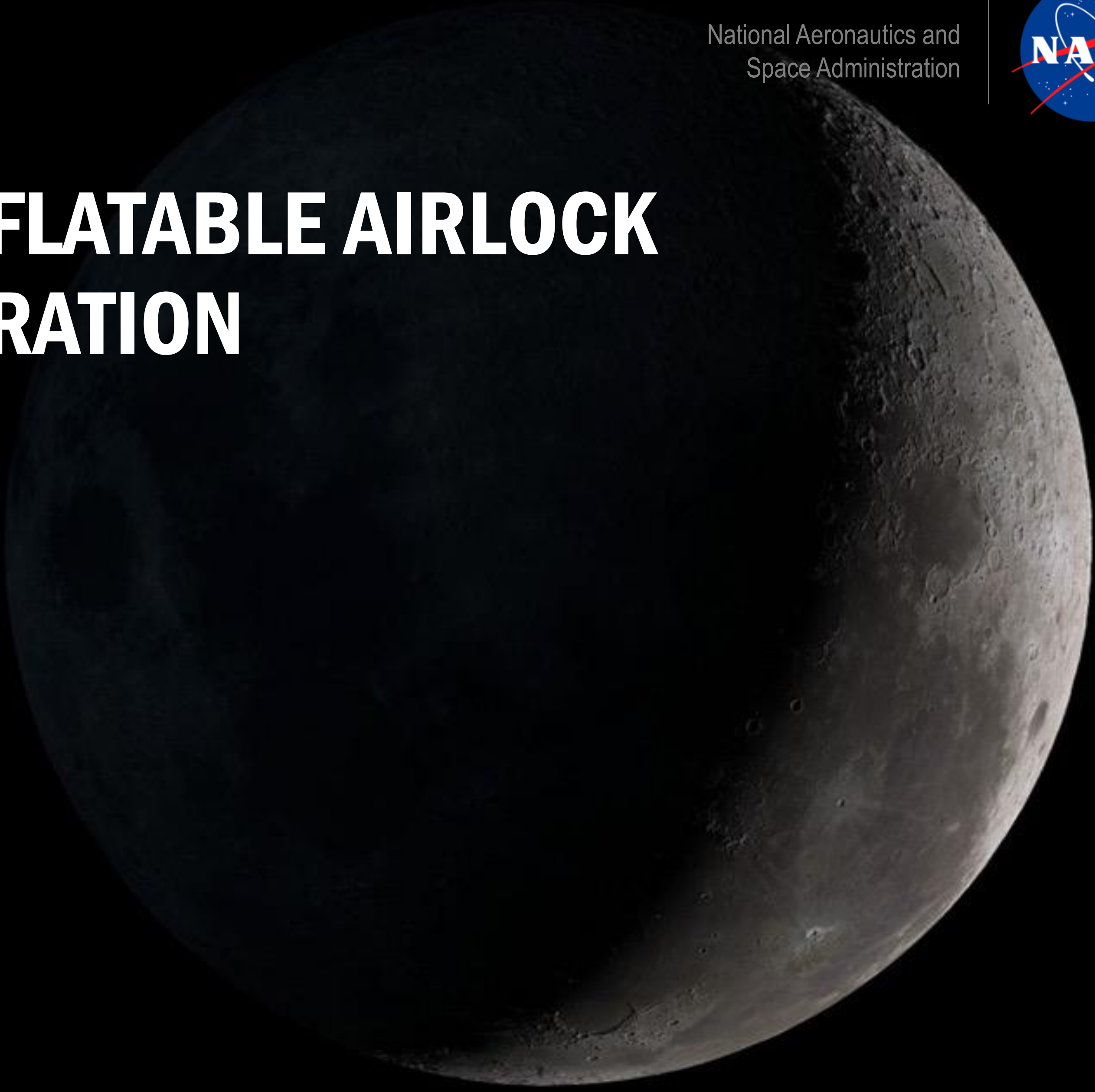
National Aeronautics and
Space Administration

DEVELOPMENT OF AN INFLATABLE AIRLOCK FOR DEEP SPACE EXPLORATION



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AIAA SPACE Forum
Orlando, Florida
September 18, 2018

OUTLINE

- Introduction
- History of Inflatable Airlock Development
- Design Considerations for Inflatable Airlocks
  - Generic Airlock Considerations for Space Applications
  - Inflatable Airlock Specific Considerations
- Conclusions and Future Work

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INTRODUCTION

- Airlocks have been used for EVAs (extravehicular activities) since 1965
- Airlock designs including integrated, single, and dual-chamber, along with various volumes and hatch shapes have been used

In Service From	To	Name	Type /Chamber	Dimensions L x D (ft)	Volume (ft^3)	Mass (lbm)	EVA Hatch Shape	Opening (in)
1965	1965	Voskhod 2 Volga	Inflatable	8.2 x 3.9	88.3	551	Circular	26
1965	1966	Gemini Capsule	Integral	19.0 x 9.8	90	8490	Trapezoid	15 x 51 x 37
1969	1972	Apollo Ascent Module	Integral	3.5 x 7.7	159	4740	Square	32 x 32
1973	1974	Skylab Airlock	Single	12.8 x 5.4	322	16936	Trapezoid	15 x 51 x 37
1983	2011	Shuttle Airlock	Single	6.9 x 5.3	150	827	D-Shape	40
1989	2001	Mir Kvant Airlock	Single	19.0 x 13.1	1413	21164	Circular	39
2001	Present	ISS Pirs Airlock	Single	16.1 x 8.4	460	7892	Circular	39
2001	Present	ISS Quest Airlock	Dual	18.0 x 13.1	1200	21896	D-Shape	40

INTRODUCTION

- Dual-chamber airlocks using an “Equipment Lock” and “Crew Lock” minimize the evacuated volume, separate the electronics and hardware, and provide redundancy in the event of a hatch failure
- While dual-chamber airlocks are recommended, they limit the launch volume available with a metallic structure design
- The use of an inflatable soft goods structure as a Crew Lock would provide valuable launch volume savings
- Inflatable soft goods have been studied since the 1950’s as habitable space structures that offer large deployed volumes in a compact stowed launch package
- They utilize high strength fabrics and internal pressure to create a stiffened vessel that can replace traditional metallic or composite shell structures
- The soft goods shell is comparable in mass to a metallic vessel, but due to the packaged configuration, reduce the required launch volume and dynamics

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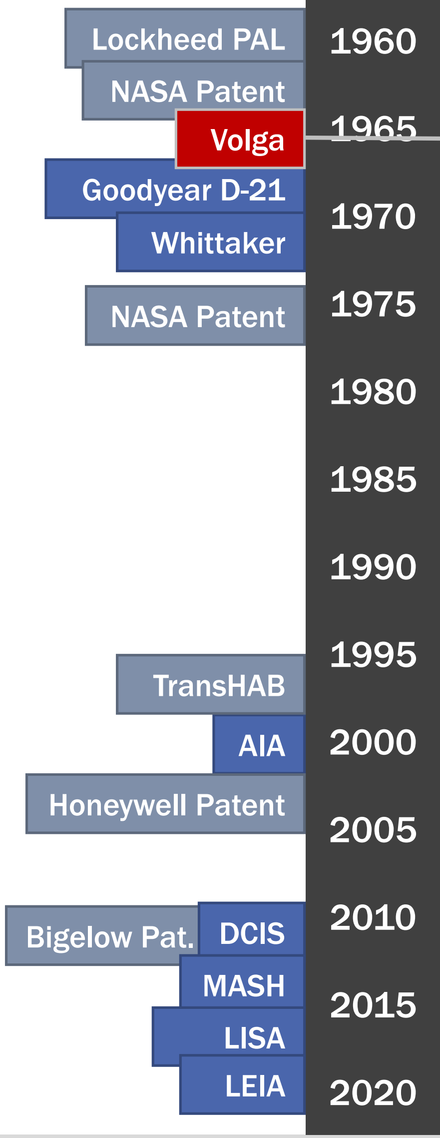
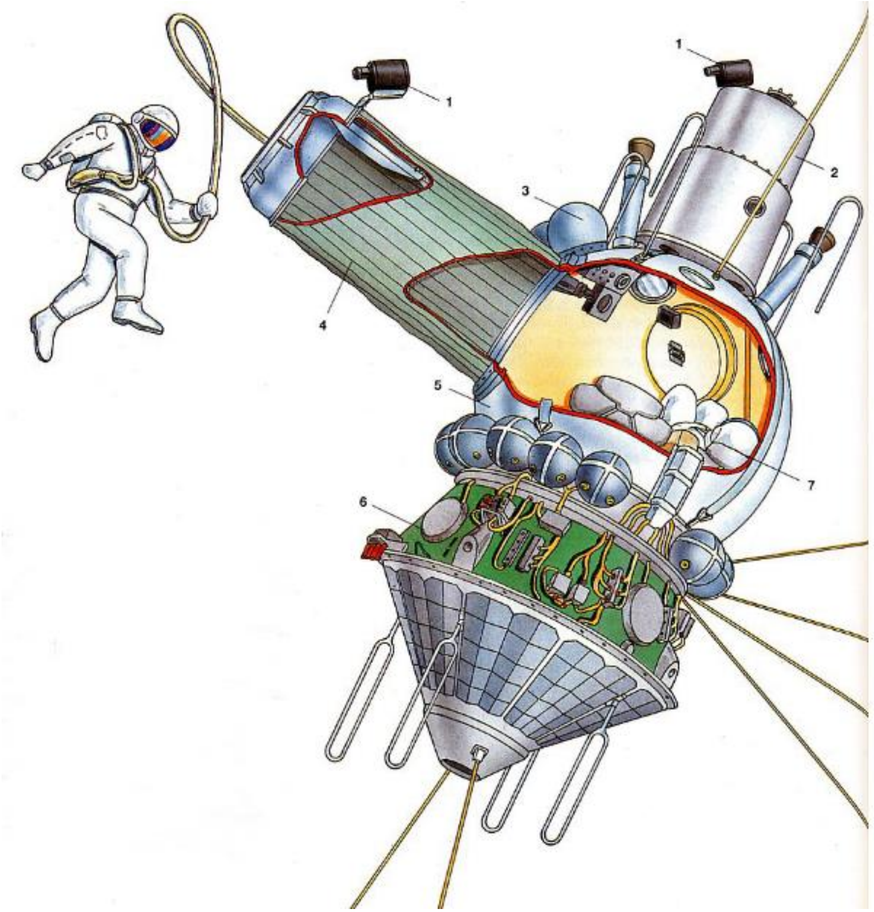
Volga Inflatable Airlock – Voskhod 2

- Developed by USSR in 1965
- Dimensions:
  - Packed: 2.5 ft long x 3.9 ft wide
  - Expanded: 8.2 ft long x 3.9 ft wide; 88.3 ft^3 internal
  - Hatch: 26 in diameter
- First ever EVA was conducted from the Volga airlock on the Voskhod 2 mission by Alexei Leonov in 1965
- Designed out of necessity because Voskhod capsule could not be depressurized
- Cylindrical in shape, utilized rubber air-booms around the circumference to maintain shape
- Airlock deployed nominally to 5.8 psia, used for a single crew member, and jettisoned after use



Volga Inflatable Airlock – Voskhod 2



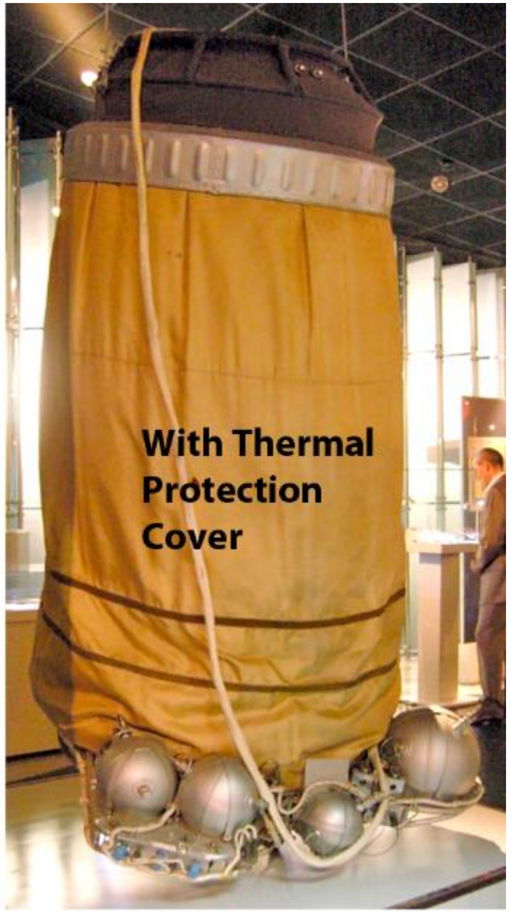


Image Source: [3]

Lockheed PAL	1960
NASA Patent	
Volga	1965
Goodyear D-21	
Whittaker	1970
NASA Patent	1975
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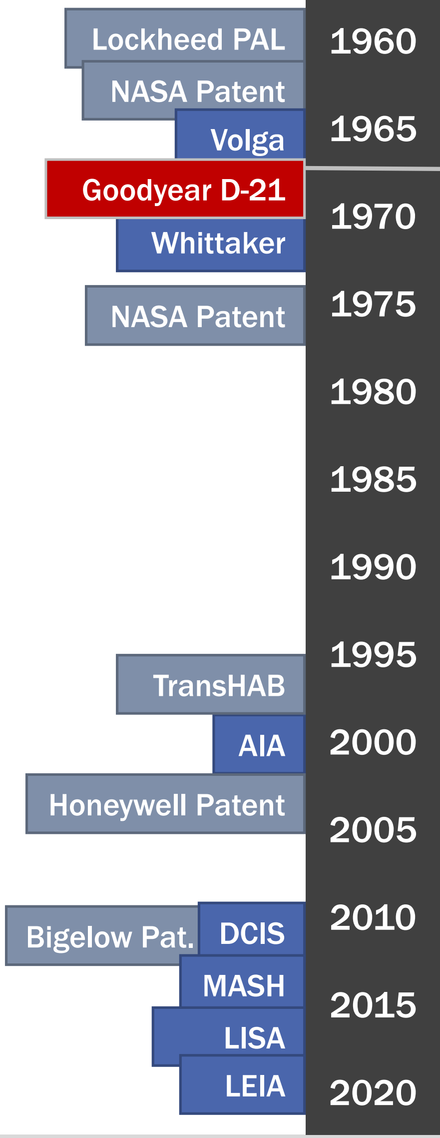
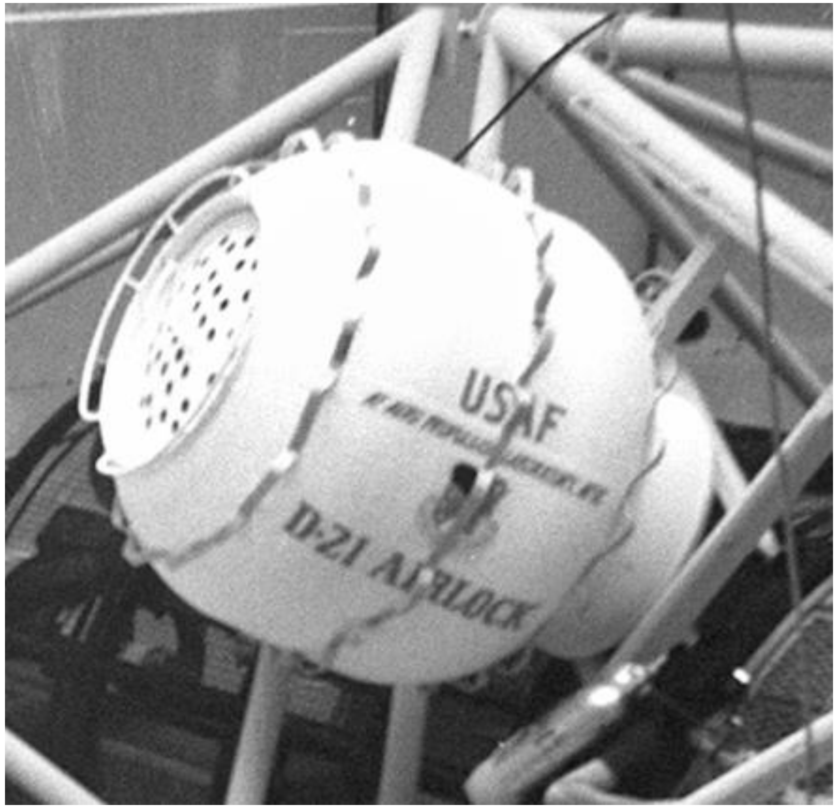
	1985
	1990
	1995
TransHAB	
AIA	2000
Honeywell Patent	
	2005
Bigelow Pat., DCIS	2010
MASH	
LISA	2015
LEIA	2020

D-21 – Goodyear Inflatable Airlock

- Built by Goodyear Aerospace Corporation in the 1960’s
- Dimensions:
  - Packed: 2.5 ft long x 4 ft wide
  - Expanded: 5.4 ft long x 5 ft wide; 78 ft^3 internal
  - Hatch: 34 in diameter
- Developed with Air Force and designed to fly on Skylab with a single crew member, but was dropped from mission suite
- Design pressure of 3.5 psia, made of nylon/foam/foil bladder, stainless steel/Taslan yarn, filament-wound structural layer, and polyurethane foam for MMOD (micrometeoroid and orbital debris) and thermal protection
- Extensive ground testing demonstrated structural capability and cold temperature deployment test proved the need for additional thermal protection layers and fire resistant materials



D-21 – Goodyear Inflatable Airlock



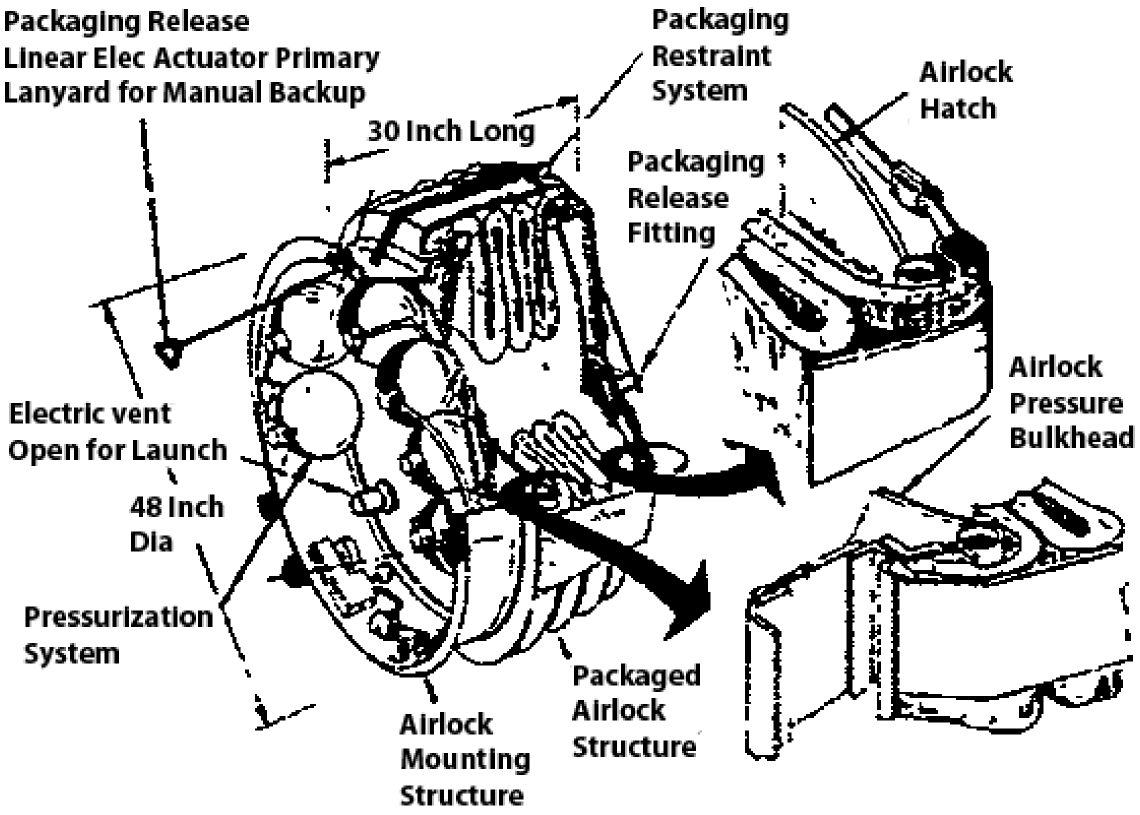
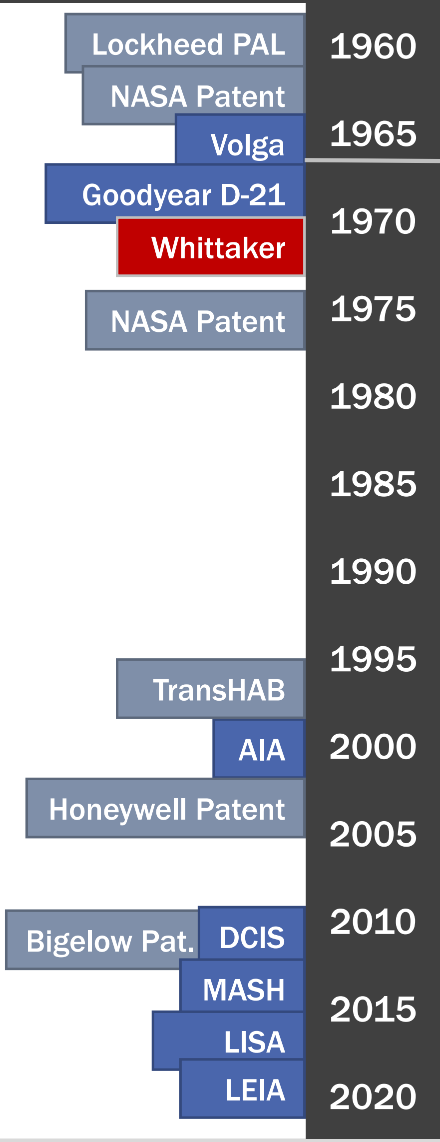


Image Source: [6]

HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

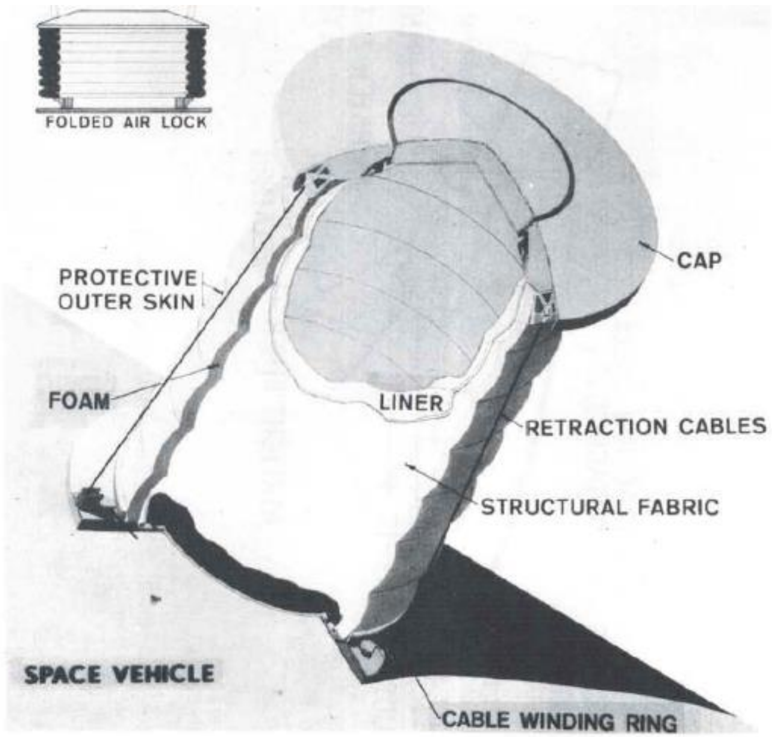
Whittaker Inflatable Airlock

- Developed by Whittaker Corporation in 1965
- Dimensions:
  - Expanded: 7 ft long x 4 ft wide; 87 ft^3 internal
  - Hatch: 30 in diameter
- Developed under a research grant with NASA
- Design pressure of 10 psia, made of a thick vinyl bladder, isotensoid filamentary restraint layer in a knitted material, polyester foam for MMOD and an outer thermal coating for temperature control, sized for a single crew member
- Multiple design iterations were evaluated, including an inner airlock and packaging trials that identified the benefit of rigid (metallic) hoop bands in the structural shell to induce fold lines and resist loads



HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Whittaker Inflatable Airlock



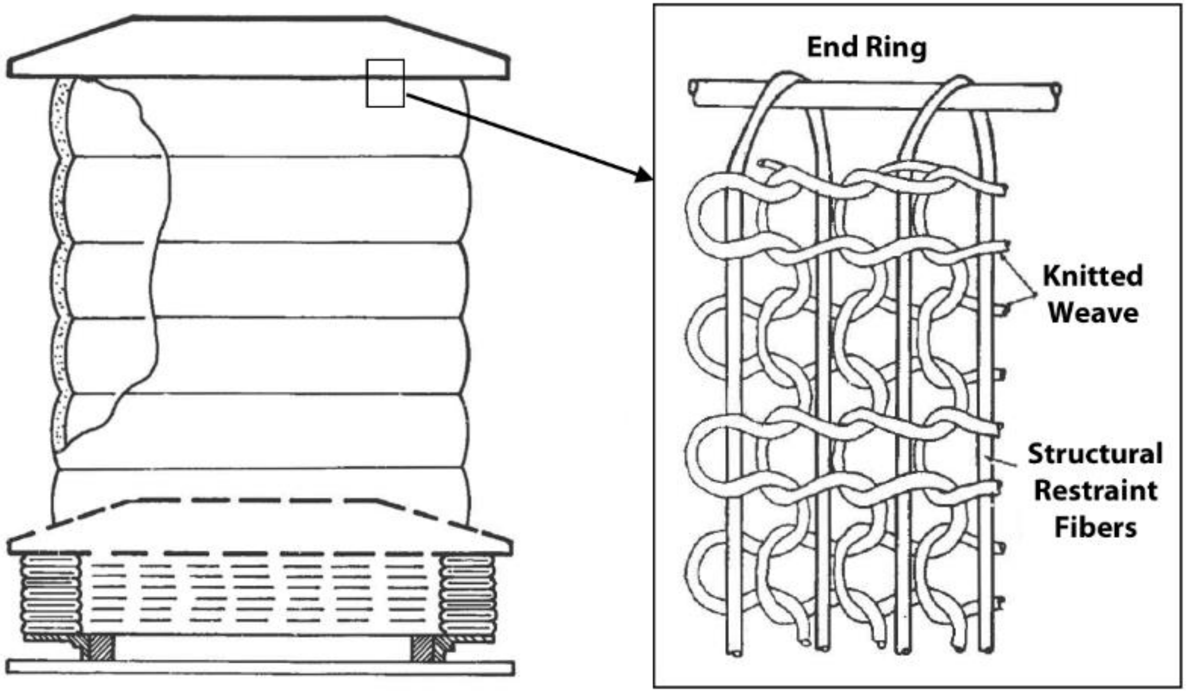


Image Source: [10]

Lockheed PAL	1960
NASA Patent	
Volga	1965
Goodyear D-21	
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NASA Patent	1975
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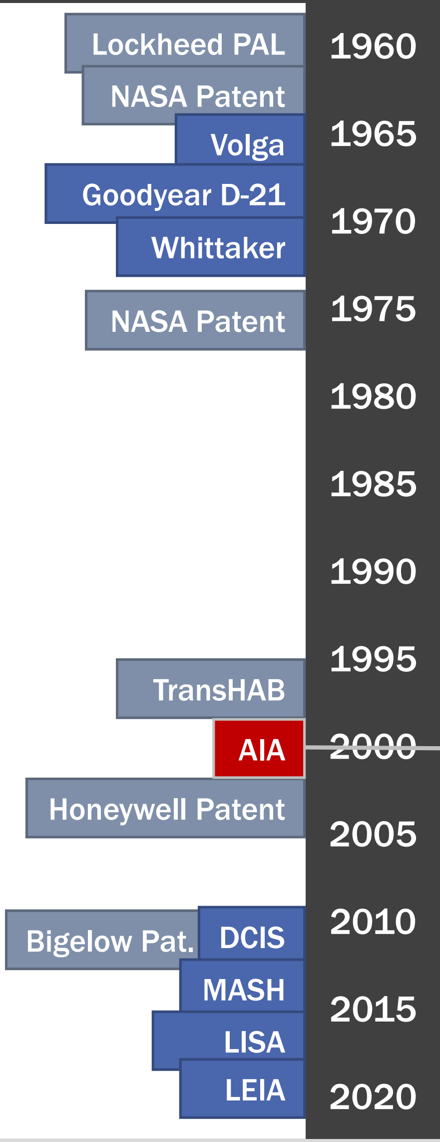
HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

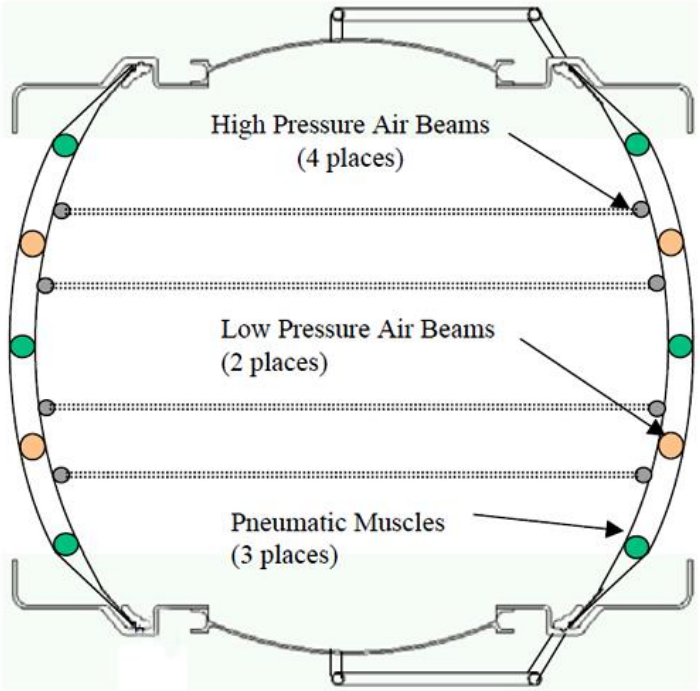
Advanced Inflatable Airlock (AIA)

- Developed by Honeywell International, A&P, FTL Design Engineering, Clemson University and NASA in 2001-2003
- Dimensions:
  - Expanded: 8 ft long x 7 ft wide; 226 ft^3 internal
  - Hatch: 40 in diameter
- Built upon TransHAB technology for soft airlock to fit any platform or vehicle needing EVA capability with two crew members
- Design pressure of 14.7 psia, made of a nylon bladder, Vectran restraint layer, Nextel MMOD layer, MLI (multi-layer insulation) thermal blanket and Beta cloth outer layer
- Work focused on restraint layer, a single wide-angle braided Vectran tube, and a deployment/retraction system using linear actuators, air-beams, and pneumatic muscles



HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Advanced Inflatable Airlock (AIA)



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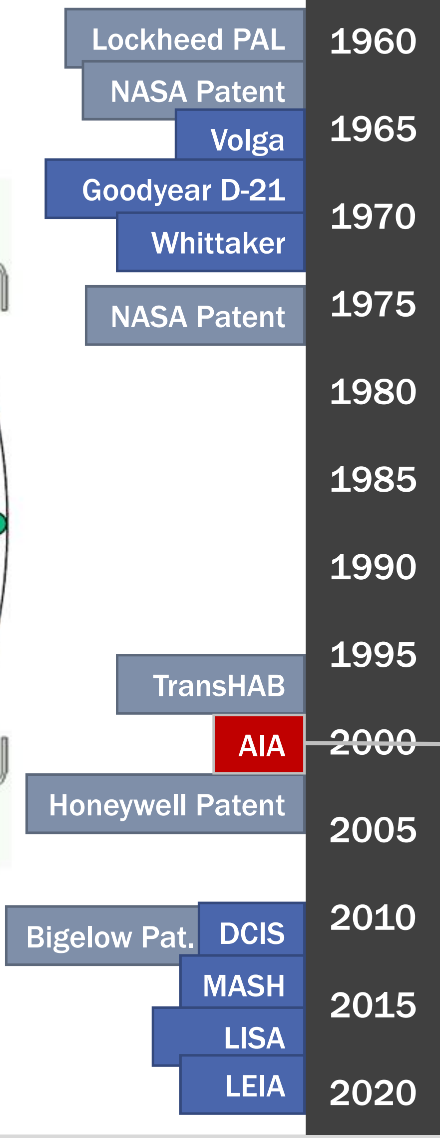
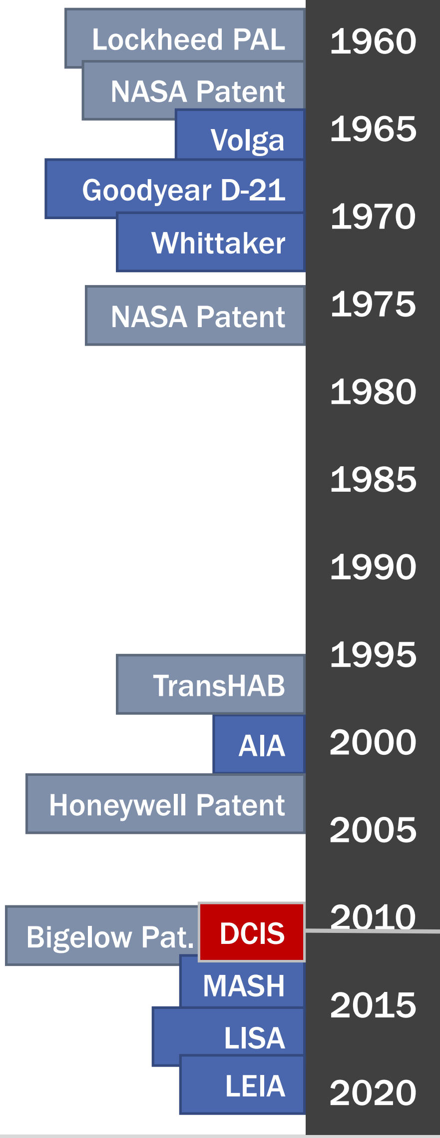


HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

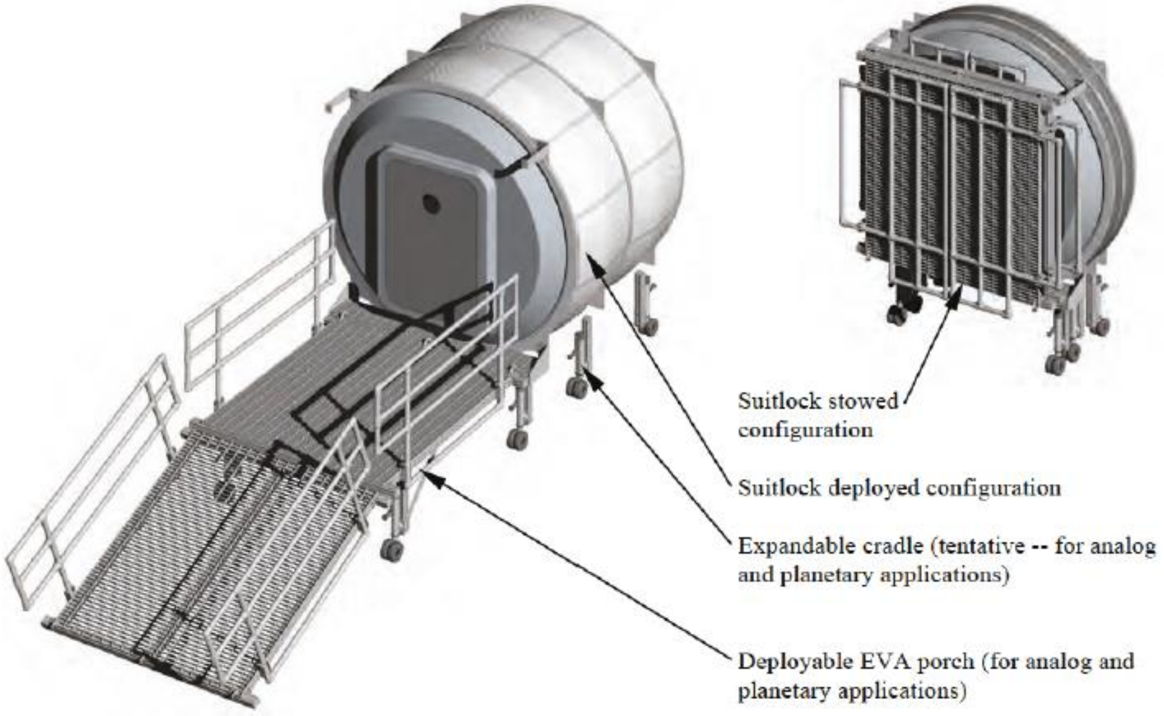
Dual-Chamber Hybrid Inflatable Suitlock (DCIS)

- Developed by NASA JSC and JPL in 2011
- Dimensions:
  - Expanded: 24.2 ft long x 9.2 ft wide; 470.1 ft^3 internal
  - Hatch: Surface door-type hatch
- Developed for the Lunar Surface Systems project under the Constellation Program
- Design pressure of 8.2 psia, made of three metallic bulkheads separated by fabric tunnels, creates a dual-chamber airlock that can be collapsed and moved on demand
- Operational testing was completed in a simulated surface mission with focus on suitport integration, dust mitigation, and a porch used for easier surface ingress/egress



HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Dual-Chamber Hybrid Inflatable Suitlock (DCIS)



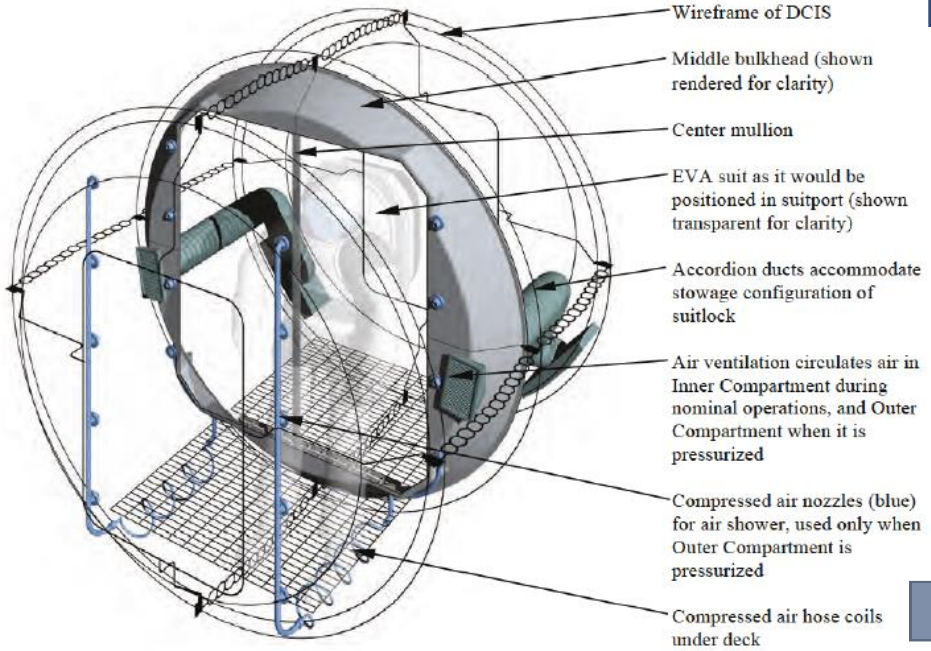


Image Source: [15]

Lockheed PAL
NASA Patent
Volga
Goodyear D-21
Whittaker
NASA Patent
TransHAB
AIA
Honeywell Patent
Bigelow Pat.
DCIS
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1960
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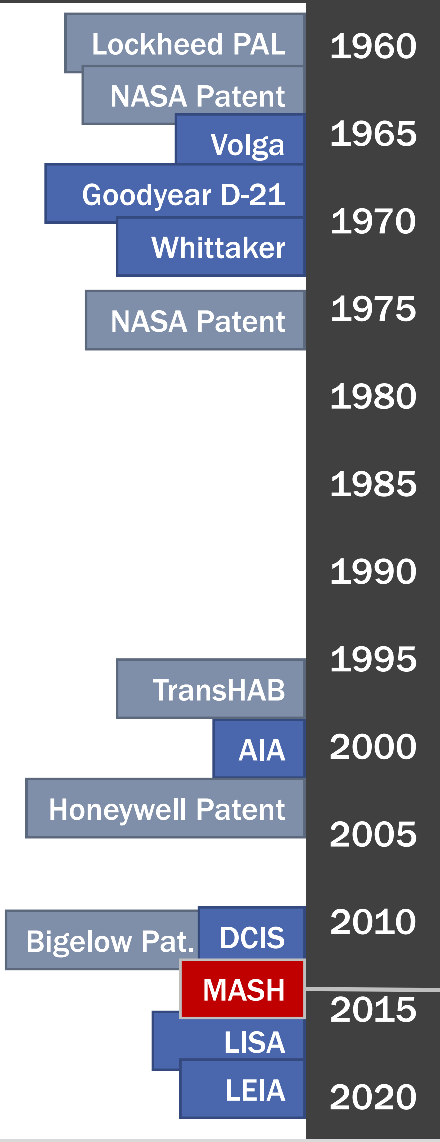
HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Minimalistic Advanced Soft Hatch (MASH)

- Developed by NASA LaRC in 2014-2016
- Dimensions:
  - Expanded: 14.7 ft long x 6.5 ft wide; 356 ft^3 internal
  - Hatch: Integrated linear hatch
- Goal to significantly reduce weight of airlock hatch by integrating a soft hatch into a soft goods airlock structure
- Design pressure of 15.2 psia using a non-axisymmetric shape with lobed areas that provide low hoop stress zones, made of urethane coated nylon bladder, Vectran fabric and cordage restraint layer, designed for two crew members
- Structural testing completed on the non-axisymmetric shape and linear seal integration showed proof of concept for soft hatch in a unique design



HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Minimalistic Advanced Soft Hatch (MASH)

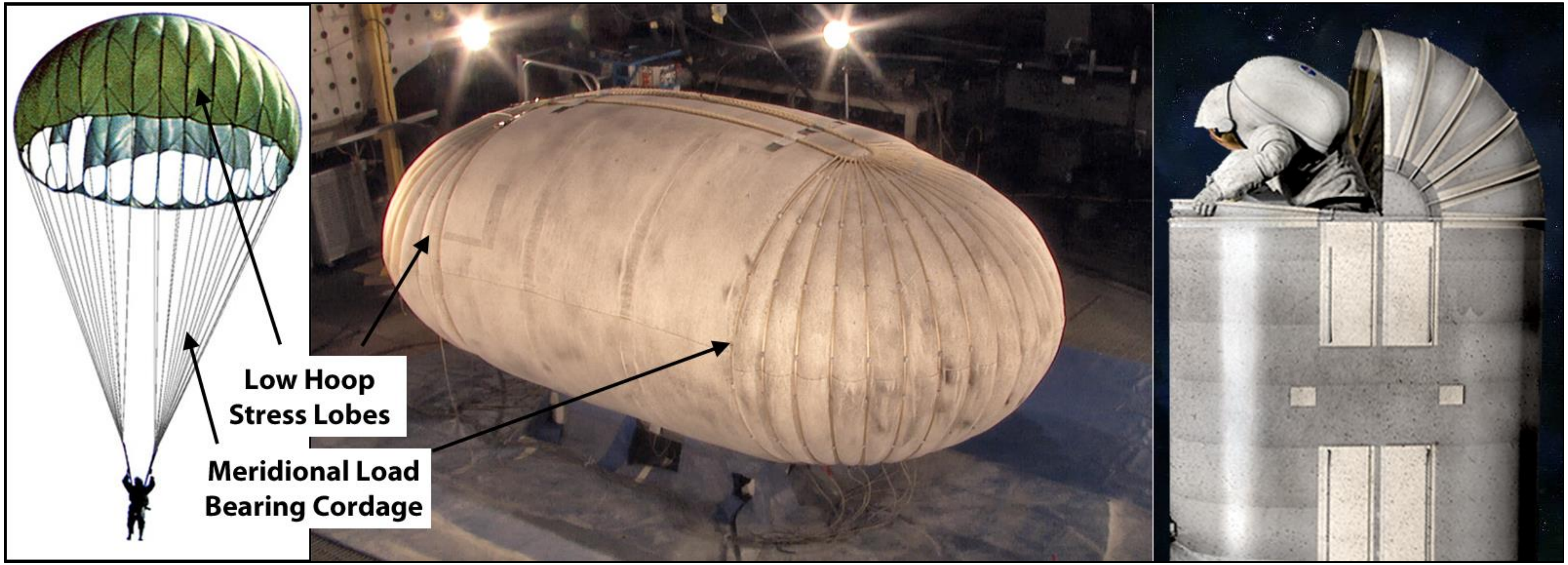


Image Source: [18]

Lockheed PAL	1960
NASA Patent	
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Goodyear D-21	
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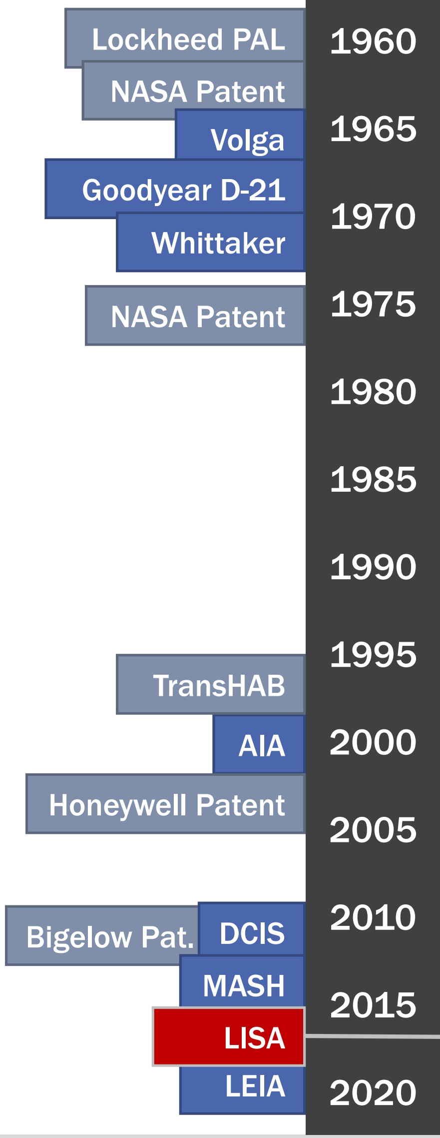
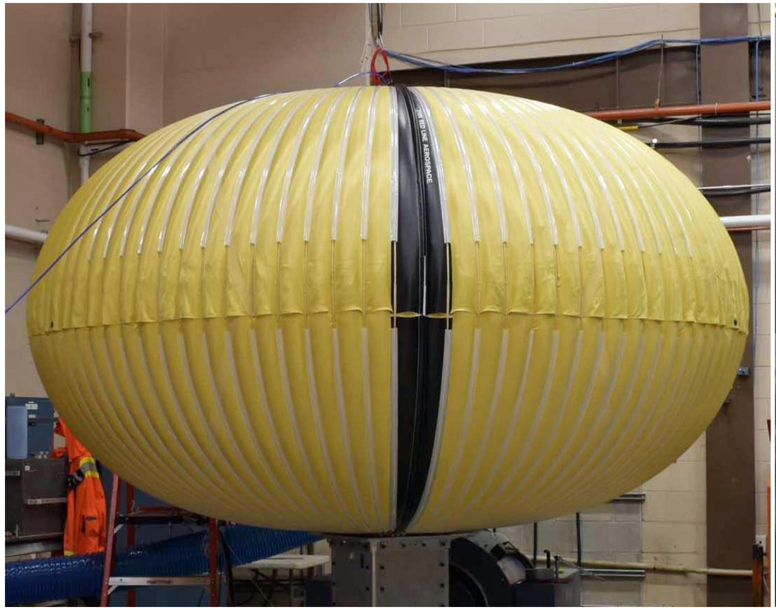
HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

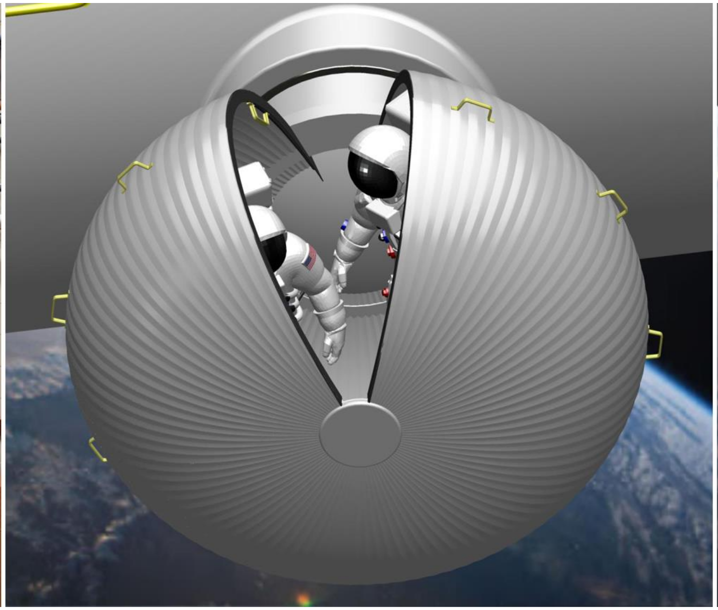
Lightweight Inflatable Structural Airlock (LISA)

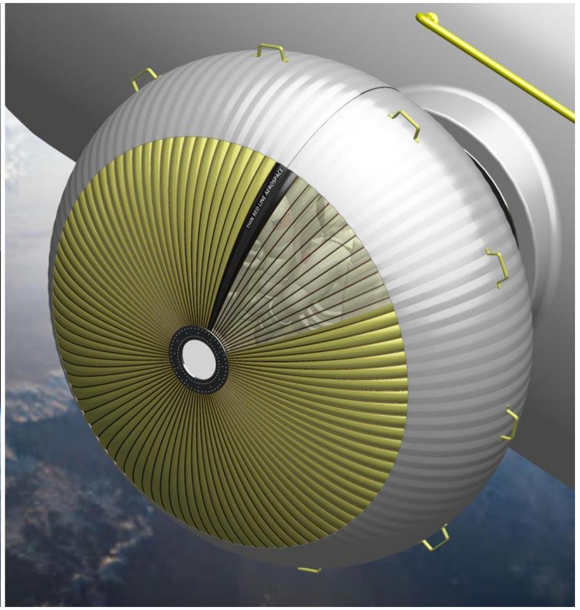
- Developed by Thin Red Line Aerospace and Computational Fluid Dynamics Research Company in 2016-2018
- Dimensions:
  - Expanded: 5.9 ft long x 9.8 ft wide; 327 ft^3 internal
  - Hatch: Integrated linear hatch
- Developed under an SBIR with NASA
- Design pressure of 15.2 psia, utilizing a Ultra High Performance Vessel and proprietary linear seal, made of a urethane coated nylon bladder, Kevlar fabric and Vectran cordage, designed for two crew members
- Structural testing with an integrated linear seal was completed, advancing the state of the art and showing additional feasibility for a soft hatch airlock



Lightweight Inflatable Structural Airlock (LISA)







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Honeywell Patent	2005
Bigelow Pat. / DCIS	2010
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LISA	
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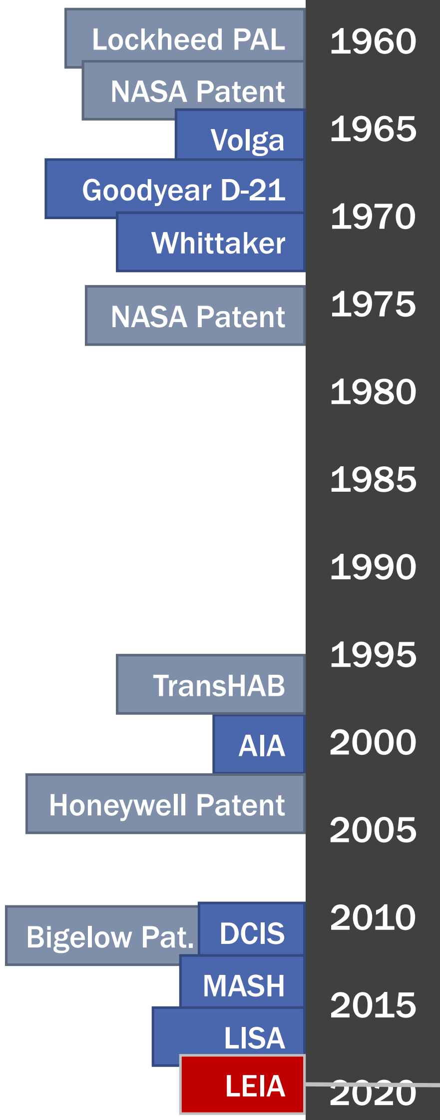
HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

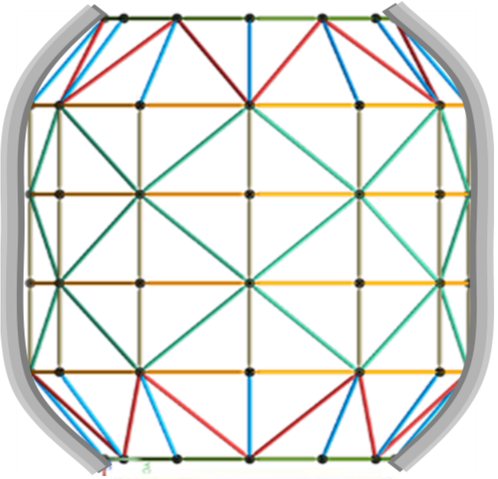
Lightweight External Inflatable Airlock (LEIA)

- Developed by NASA JSC in 2017-2019
- Dimensions:
  - Expanded: 13 ft long x 10.5 ft wide; 565 ft^3 internal
  - Hatch: 40 in diameter
- Design pressure of 14.7 psia, sized for two crew members, with focus on internal sub-structure and crew interfaces
- Iterated on two concepts for internal structure including an inflatable truss (made of Kevlar fabric) and an erectable truss (made of carbon fiber tubes)
- Conducted full scale mobility testing with micro-gravity simulation, developed soft handrails, and completed structural burst testing of an inflatable truss design



HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Lightweight External Inflatable Airlock (LEIA)



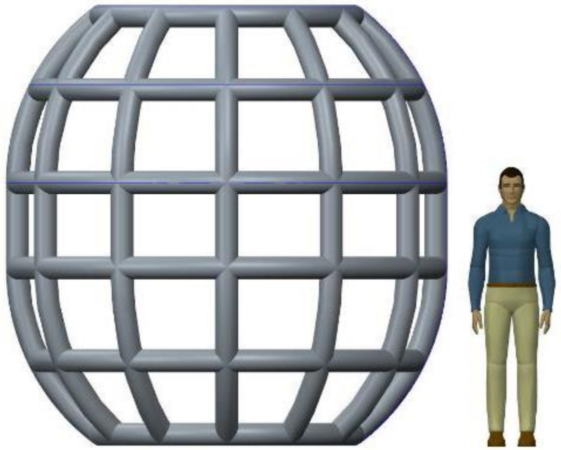


Image Source: NASA

1960	Lockheed PAL
	NASA Patent
1965	Volga
	Goodyear D-21
1970	Whittaker
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1980	
1985	
1990	
1995	TransHAB
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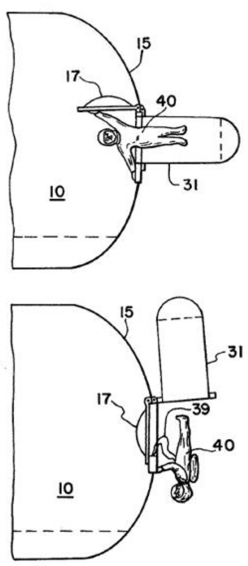
2010	Bigelow Pat.
2010	DCIS
2015	MASH
	LISA
2020	LEIA

HISTORY OF INFLATABLE AIRLOCK DEVELOPMENT

Other Concepts and Patents

1. NASA patent (1968) – single hatch with moveable airlock
2. NASA patent (1976) – flexible, deployable tunnel
3. Honeywell patent (2002) – deployable and retractable, flexible airlock
4. Lockheed Martin Portable Air Lock (PAL) (1963) – airlock concept shown in local newspaper
5. Bigelow Aerospace patent (2012) – inflatable airlock with exterior longerons



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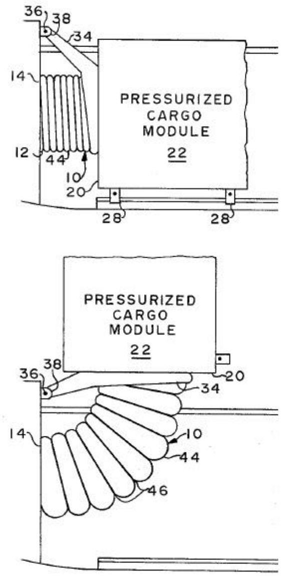

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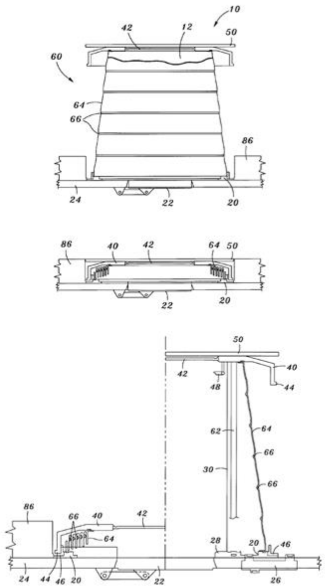

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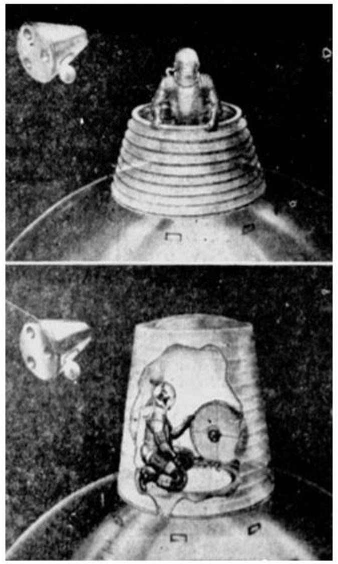

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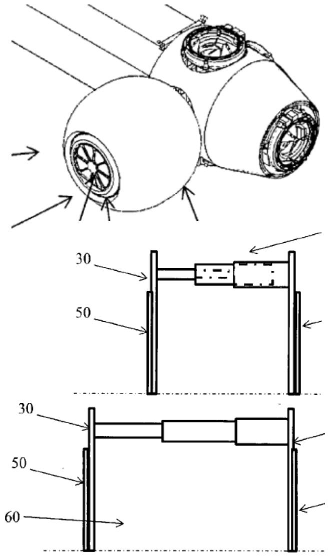

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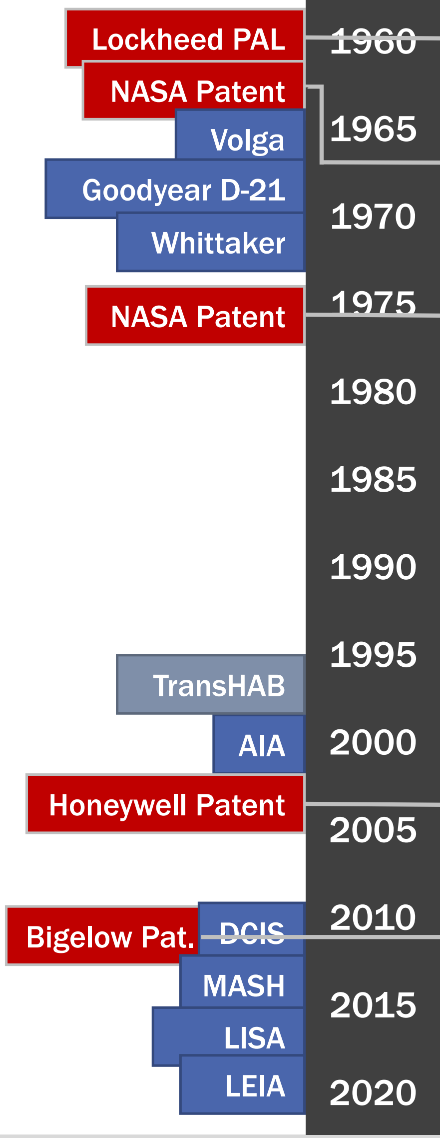

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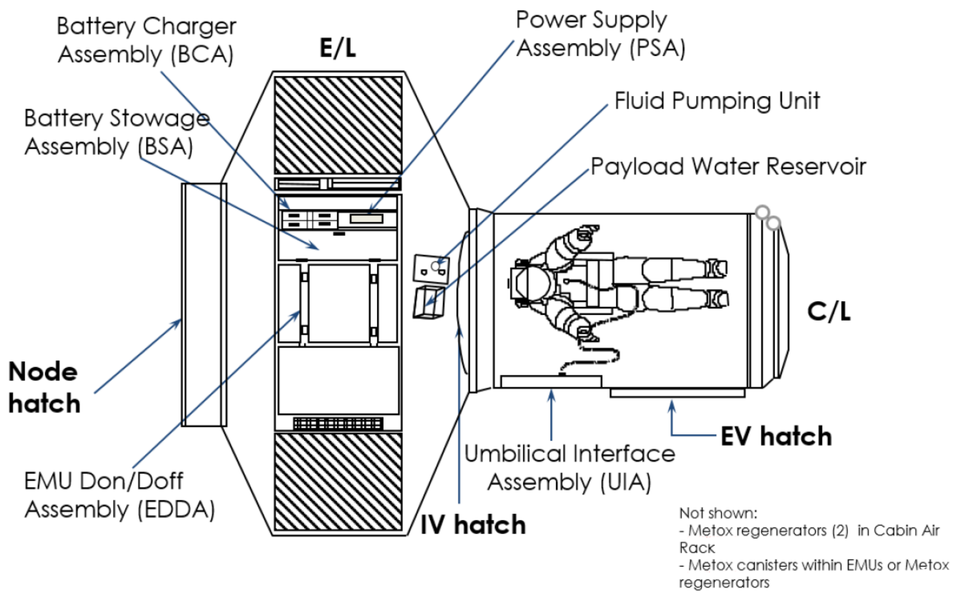
GENERIC AIRLOCK CONSIDERATIONS

- Dual vs Single Chamber Design
  - ISS airlock uses a dual-chamber design
  - Dual-chamber designs provide redundancy in the event of a failure, eliminate the need for hardware and electronics to be vacuum compatible, and minimize gas loss during a depress/repress cycle
  - EVA community assumes future airlocks provide at least a secondary ingress capability as a backup option in the event of a failure



ISS Quest Airlock Diagram, Image Source: [1]

- EV Hatch
  - Sized for crew members and payloads to pass through
  - Typically EV hatches are pressure-assisted and inward opening
  - Mounted on side of Crew Lock on ISS because of mobility issues with a suited crew member
    - They can only use their hands/arms in front of their chest, so hatch placement and operation should be accommodating to these constraints
  - Exploration guidelines designate a hatch should have ≥ 39 in diameter opening

GENERIC AIRLOCK CONSIDERATIONS

- Internal Volume
  - Need volume for suit don/doff, suit maintenance, suit servicing equipment, logistics, tools, and payloads, which are typically housed in an Equipment Lock, but could be part of an integrated habitat or utility module
  - The Crew Lock is often the smallest volume and only requires room for two suited crew members to be able to translate and operate the hatch
- Suit Interfaces
  - Suits must be able to interface with the airlock to recharge consumables and be repaired/maintained
  - Most of the servicing equipment is located in the Equipment Lock with a suit umbilical interface in the Crew Lock
- Handrails/Tethers
  - Crew members translate through the airlock and onto the exterior of the spacecraft using handrails, handholds, and tether attach points
  - Rigid translation aids are required for all expected translation paths, these are typically composed of metallic tubing that is designed for crew member tether and translation loads
  - ISS translation aids use a specific cross-sectional shape that is designed to interface with the suit gloves and prevent inadvertent damage

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INFLATABLE AIRLOCK CONSIDERATIONS

- Dual vs Single Chamber Design
  - Inflatables achieve full structural capability once pressurized, so an inflatable Equipment Lock is not recommended because of the rigid equipment needed
  - An inflatable Crew Lock, however, offers EVA capability in a small launch package
  - Additionally, a dual-chamber design provides redundancy in the airlock
- Deployment/Folding
  - Soft goods airlock should be packaged as small as possible on the ground, while not damaging the fabric layer
  - Deployment method should provide initial expansion in a controlled and predictable manner using internal pressure and an internal/external deployment mechanism
- Environmental Protection
  - Airlock must protect against the space environment, like a metallic airlock, but special considerations should be made for low temperature effects on polymer materials, radiation exposure to fabrics, and dust degradation on a surface airlock

INFLATABLE AIRLOCK CONSIDERATIONS

- EV Hatch
  - Soft hatches are still a low TRL and continue to be pursued by NASA and industry
  - Integrating a traditional, rigid hatch into a soft goods airlock provides the most heritage and flight history for EVA ingress/egress
- Mobility/Handrails
  - Crew members will require handholds, foot restraints, and tether attach points to move around the vehicle in micro-gravity
  - Handholds could be made from soft goods and be foldable/expandable as long as they provide the required stiffness and rotational control
  - Railing and attach points will also be required on surface missions to assist in crew mobility
- Internal Secondary Structure
  - When the airlock is depressurized, a secondary structure is needed to maintain the module's stiffness and provide a framework for crew handholds and tethers
  - This structure can be integrated into the fabric layers and be used on both the inside and the outside of the soft goods airlock

INFLATABLE AIRLOCK CONSIDERATIONS

Consideration	In-Space LEO/Interplanetary Vehicle	Moon/Mars Surface Surface Outpost/Mobile Vehicle
Gravity	Micro-gravity	Reduced gravity
Thermal	LEO: Cyclic, day/night; Interplanetary: Constant extreme cold	Location dependent, Constant shadows, Long/regular day/night cycles; Mars: Atmosphere and seasons; Moon: Abrupt day/night transitions
Radiation	LEO: Low risk; Interplanetary: Higher risk with GCR and SPE	Higher risk with more common EVAs, longer distance from SPE shelters, long term GCR
Atmosphere	None, clean, hard vacuum	Low to zero; Abrasive, magnetic, fine dust; Mars: High speed, low pressure wind
MMOD	LEO: High risk (orbital debris); Interplanetary: Lower risk (micrometeoroids)	Medium to low risk (long exposure)
Crew Restraint	Handholds, handrails, foot restraints; Tether attachments required	Handrails, Rigid floor, Fewer mobility restraints
Crew Movement	Cable and clip tether, Maneuvering unit	Self-powered, Walk, Hop, Climbing

INFLATABLE AIRLOCK CONSIDERATIONS

Consideration	In-Space LEO/Interplanetary Vehicle	Moon/Mars Surface Surface Outpost/Mobile Vehicle
EVA Suits	Limited range of motion, Fewer requirements than surface suits	Lightweight, Higher mobility, Robust to environment/dust, Need more maintenance
Consumables	Possibility of venting air on each EVA, Primary vessel can provide contingency air and egress volume	Must recycle/recapture air, *Mobile:* Additional contingencies needed due to risk
Extra Equipment	EVA tools, Repair units, Upgrade supplies	*Outpost:* EVA surface tools; *Mobile:* Equipment may need to be accessed through external hatch
EVA Frequency	Infrequent, Typically for repairs	Common, Potentially daily, Surface exploration
Hatch	Circular or heritage D-shape with ≥ 39 in diameter opening	Taller and larger hatch for easier access and more common entrance/exit in gravity
Volume	Min. volume/mass for consumables, Based on two EVA suited crew members	Min. volume/mass needed for planetary missions, Based on at least two EVA suited crew members
Pressure	Mission dependent, Typically 14.7 psia habitat pressure	Mission dependent, Potentially 8.2 psia suitport and exploration pressure

INFLATABLE AIRLOCK CONSIDERATIONS

Consideration	In-Space LEO/Interplanetary Vehicle	Moon/Mars Surface Surface Outpost/Mobile Vehicle
Deployment	One time deployment with secondary or habitat consumables	Deployment with outpost consumables and retractability for modularity and mobile use
Depressurized Stability	Needs lightweight deployable or erectable internal and external structure including handrails and attachment points	Needs lightweight deployable or erectable internal and external structure including handrails, equipment stowage and floors
Redundancy	Dual or single chamber with multiple seal lines, Needs contingency for failed hatch	*Outpost:* Multiple elements and contingency airlocks available; *Mobile:* Dual hatches
Maintainability	Vehicle relatively easy to access in micro-g during EVA with translation aids, Long term missions should carry replacement hardware and design for repairs	Habitats harder to access with gravity, Long term missions should carry replacement hardware and design for repairs, Dusty surface environments require maintenance of seals and electronics
Modularity	Mission dependent, Not required	Mission dependent, Likely reusable/common elements for repair and replace in space, Design for multi-use on Moon and Mars

OUTLINE

- Introduction
- History of Inflatable Airlock Development
- Design Considerations for Inflatable Airlocks
  - Generic Airlock Considerations for Space Applications
  - Inflatable Airlock Specific Considerations
- Conclusions and Future Work

CONCLUSIONS AND FUTURE WORK

- A rigid Equipment Lock with an inflatable Crew Lock is the most feasible near-term integration approach for a Gateway airlock
- An inflatable Crew Lock provides several advantages over a metallic structure:
  - Reduced launch volume can offer increased habitat volume
  - Dual-chamber airlock offers contingency with little additional volume
  - Secondary inflatable can be used to capture and reuse gas
  - Soft goods materials have excellent impact resistance for MMOD protection
  - Ability to deploy and retract and can be modular for multiple uses
- Developmental work continues at NASA to further develop:
  - IVA/EVA outfitting and soft handholds
  - Lightweight hatch developments
  - Air circulation and ventilation integration
  - Rigid hatch to soft goods seals
  - Cold temperature materials testing
  - Long term creep materials testing

QUESTIONS?

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