Defining Operational Space Suit Requirements for Commercial Orbital Spaceflight

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As the commercial spaceflight industry transitions from suborbital brevity to orbital outposts, spacewalking will become a major consideration for tourists, scientists, and hardware providers. The challenge exists to develop a space suit designed for the orbital commercial spaceflight industry. The unique needs and requirements of this industry will drive space suit designs and costs that are unlike any existing product. Commercial space tourists will pay for the experience of a lifetime, while scientists may not be able to rely on robotics for all operations and external hardware repairs. This study was aimed at defining space suit operational and functional needs across the spectrum of spacewalk elements, identifying technical design drivers and establishing appropriate options. Recommendations from the analysis are offered for consideration.

Nomenclature

g = gravitational acceleration

I. Introduction

EVERY space suit is be designed with a set of goals and requirements in mind. My insight and understanding into the current world of space suits at the National Aeronautics and Space Administration's Johnson Space Center (NASA JSC), complemented by my studies in commercial spaceflight operations at the University of Colorado Boulder allow me to develop recommendations based on the perceived goals and requirements of the commercial spaceflight industry. A considerable amount of space suit information is publicly available from government, academia, and private companies, but little of this information has been leveraged with commercial spaceflight in mind. The Federal Aviation Administration (FAA) Office of Commercial Space Transportation has not provided detail on commercial space suit and spacewalk legislation.

The process of defining commercial space suit operational requirements was completed using various engineering methods. The majority of the analysis will be performing trade studies of space suit systems. Other methods of analysis included comparing/contrasting aspects of past and present space suits, previous space suit designs that never left the conceptual stage, future space suit designs that are currently being developed, and launch and entry suits. Finally, some analysis was completed on the non-engineering aspects, such as financial evaluations and market research on the interest of doing a spacewalk during an orbital commercial spaceflight.

II. Background

Considering that the launch, ascent, abort, and re-entry phases of flight will likely be conducted while wearing a pressure garment to accommodate potential emergency scenarios, the chronological starting point for defining operational requirements actually begins on the pad. Given that some form of protection will be necessary for the commercial space tourist to operate in each environment, numerous configurations can be considered. This study involved developing a process for defining space suit functional requirements based on specific safety needs, activities, and commercial spaceflight experiences as a means of setting up a weighted trade study to evaluate alternative architectures.

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The results of a feasibility study of commercial space suit concepts are summarized here. The objective was to identify an appropriate suit system and architecture concept options for independent commercial spaceflight companies and provide these as a baseline recommendation to the FAA Office of Commercial Space Transportation for the next revision of their “Established Practices for Human Space Flight Occupant Safety” document.[1]

III. Suited Operational Scenarios

By decomposing the various phases of flight into individual elements, a framework is presented for identifying common suit requirements across various phases. The results are useful for weighing the common requirements higher than others when developing various suit component combinations.

Each mission element in Fig. 1 defines a unique environment in which a passenger will have different space suit requirements.

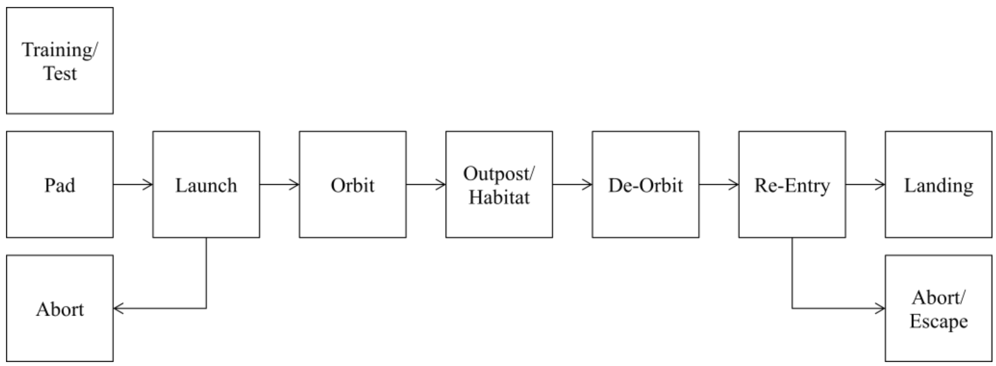


Figure 1. Mission Elements Modified for Commercial Spaceflight Purposes[2]

IV. Suited Environment Characteristics

Mission elements were assessed for commonalities in the suited environment such as gravitational, thermal, radiative, and atmospheric (pressure and composition) properties, as summarized in Table 1 and Fig. 2-4, respectively.

A. Gravitational Environment

Gravitational environments change throughout mission phases, and different mobility requirements exist for these phases. In a weightless environment, a majority of the spacewalk work is completed. Commercial space customers will spend time spacewalking, repairing external payloads, and will spacewalk for extended durations. During this time, the space suit should allow for maximum comfort, ease of mobility, a large field of view, and ability to apply necessary forces into tools and structures. While on the launch pad, mobility will be limited, so it is imperative that the space suit provides necessary consumables, communications, and allows for visibility and enough arm mobility to reach controls (buttons, switches, etc.) In the event of a launch pad emergency, the space suit needs to be light enough that its user can evacuate in a 1-g environment. This also holds true during abort during ascent and re-entry environments, when the space suit will be under high-g loads.

Table 1. Gravitational Environments

Mission Element	Gravitational, g		
	0	1	>1
Earth/Pad		✓	
Launch/Re-entry			✓
Orbit/De-Orbit	✓		
Outpost	✓		
Abort/Escape			✓

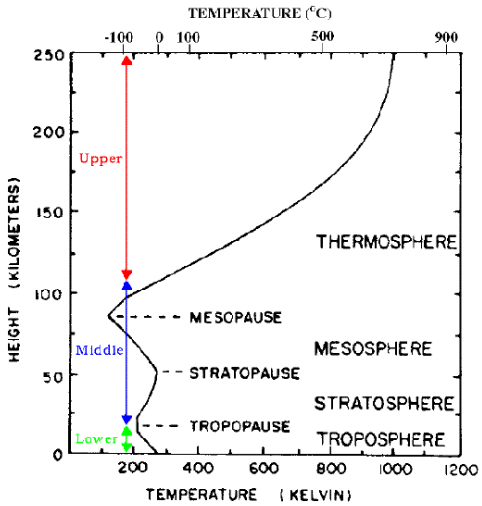


Figure 2. Thermal Environments.[4] *Daytime thermal environment of Earth's atmosphere up to 250 km.*

B. Thermal Environment

When continuously orbiting the sun in low earth orbit, some bare metals can reach temperatures above 260 degrees Celsius. These extremely hot temperatures can be hazardous to spacewalkers. To reduce the temperature hazards, cautionary measures typically tend to keep "touch temperatures" between 120 degrees Celsius and -129 degrees Celsius.[3] The thermal environment varies largely at different altitudes of Earth's atmosphere, especially once reaching the upper atmosphere (Thermosphere) where commercial orbital outposts are located. In addition to solar energy, other thermal environmental factors are geothermal heating - the Earth gives off enough heat for it to impact the atmosphere, orbital inclinations, spacecraft attitudes, and more. As stated earlier, a space tourist that is on a spacewalk that may last up to 6 hours or more needs to be comfortable - thermally and otherwise.

C. Radiative Environment

Radiation is a major concern for deep space travel, but while in low-Earth orbit, solar radiation helps protect from galactic cosmic rays, and passing behind the Earth protects from solar radiation for roughly half of every orbit. The closer the spacecraft's orbit takes it to the poles of the Earth will provide higher radiation doses.[5] For these reasons, the biggest concerns with radiation are long-term health effects. Designs of each commercial orbital outpost can provide some radiation protection, but the current space suit designs to not provide any significant radiation protection. Advancing technology has presented potential solutions.

> This combination of highly protective materials, medical grade compression, sensory, and muscular activation techniques, will address the initial need at NASA for improved astronaut health and mobility. Each suit panel is comprised of non-terminating yarns. The support areas of the fabric consist of several textile stitch areas of gradient levels of stretch elements, flex, rigid, and restrictive elements, which are integrated into the fabric by mapping the appropriate levels of motion or protection required.[6]

This potential solution also outlines the need to develop advanced undergarments for space suits as much as the external or exposed hardware. The entire space suit system has to work together to provide the best product possible for the consumer.

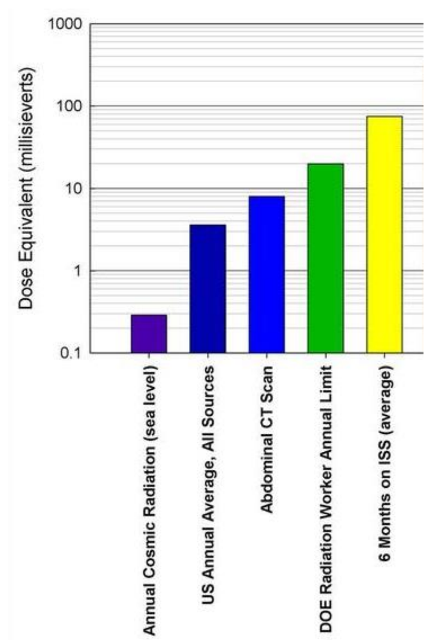
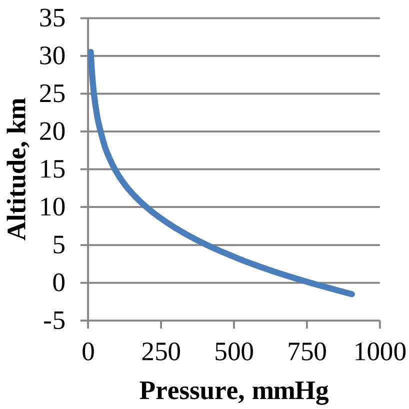


Figure 3. Radiative Environments.[7] *Human radiation exposure comparisons.*

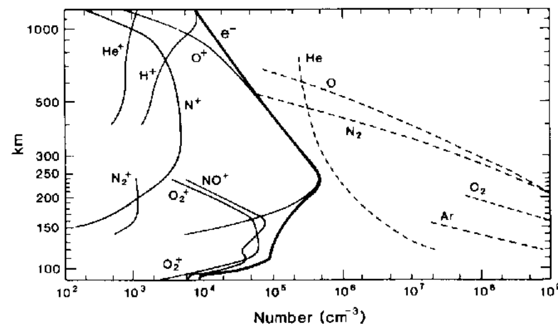
D. Atmospheric Environment

The external atmosphere of the space suit drives different functional requirements as well. A low pressure environment, such as at high Earth altitude or the surface of Mars requires different types of hardware and processes than a near vacuum, such as in low-Earth orbit. During launch, including ascent and orbital insertion, the atmospheric pressure dissipates quickly. If the spacecraft cabin pressure is unable to hold, the space suit must be able to sustain the passenger as well as allow the individual to perform all necessary functions to ensure the safety of everyone onboard. Likewise, during re-entry into the atmosphere, pressure builds up quickly, and the spacecraft drag on the atmosphere creates heat. The local environment around a spacecraft during re-entry is a dangerous one which the space suit is the last line of defense for the passenger in the event of a failure.

Aside from the pressure of the atmospheric environment, one must account for the composition of elements and ions, particularly from a materials standpoint. Any reactivity of the space suit with the atmospheric composition should be avoided by selecting proper materials, or applying necessary covers or coatings on materials that have a higher likelihood of reactivity with the environment at a given altitude.



a.) Pressure.[8] *Pressure is negligible above 30 km, therefore is not shown.*



b.) Composition.[9] *International quiet solar year daytime ionospheric and atmospheric composition based on mass spectrometer measurements.*

Figure 4. Atmospheric Environments

V. Space Suit Functional Decomposition

To define functional requirements for the space suit, the system was broken down into supporting functions, in this case utilizing a tree structure starting with the complete space suit system and decomposing it down to a more basic level.

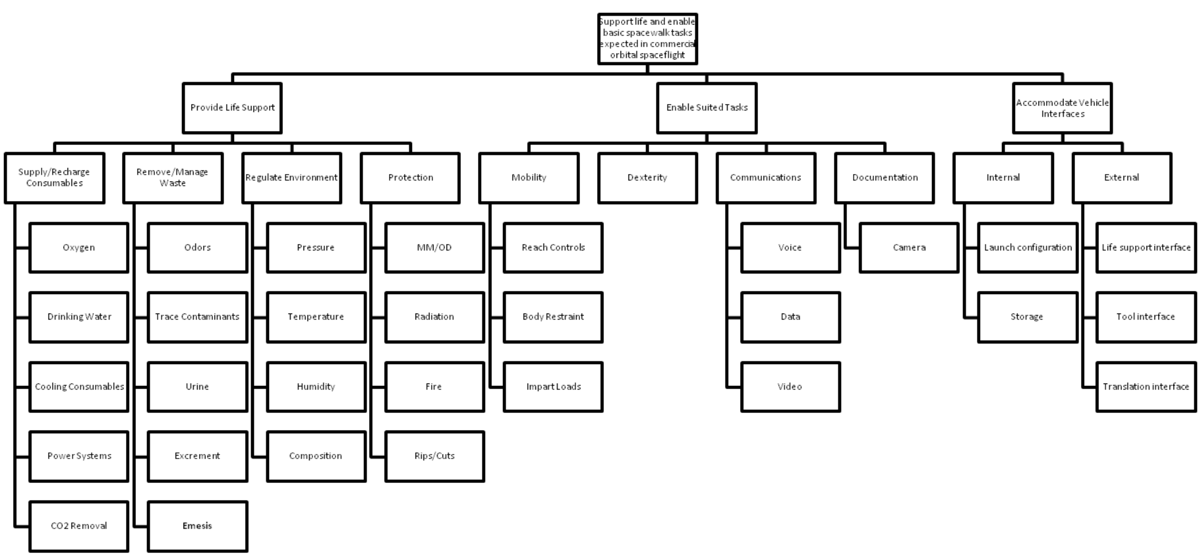


Figure 5. Space Suit Functional Decomposition for Commercial Spaceflight. *For clarity, the decomposition is only shown to the fourth level.*

Notably, the differences between a space suit for commercial spaceflight are minimal compared to what exists between multiple current space suits. The key for commercial requirements is to find an elegant, cost-effective, and safe solution to combine these functions into a single, reliable space suit for all phases of flight.

VI. Derived Design Requirements

Requirements for this analysis were derived from the perceived needs of commercial spaceflight as it progresses to orbital missions based on suit functional requirements to provide the customer protection, mobility, and facilitate interaction with various internal and external vehicle interfaces. Environmental requirements must address gravitational, thermal, radiative, and atmospheric exposure. The functions were examined to determine where overlaps exist between all mission elements.

VII. Assumptions

A number of assumptions about technology, operations, environmental and financial factors were established in order to assess the tradeoffs.

1) At least one company, Virgin Galactic has changed its mind and does not currently plan to use space suits for the launch and entry phase of flight. All considerations will assume each space suit shall support all phases of flight.[10]
2) Only technologies considered have already been currently demonstrated, are within 5 years of a demonstration flight or otherwise noted. No completely new technology will be implemented.
3) Commercial space tourists will not be relied upon to execute emergency repair spacewalks.
4) Common component interfaces will be used for all commercial vehicles.
5) There will be coming interfaces for the Life Support System and space suit assembly.
6) Repair and replacement of space suit components on orbit is not required. For commercial spaceflight, the assumption is there will be regular rotations of crew, and suits can be swapped between launches.

VIII. Results

Evaluation of the derived design requirements was performed and weighted using two methods. The first is a binary method comparing each criterion with each of the others, then adding these individual comparison scores together for an individual criterion for a total score to be evaluated against the others. The second method is a weighting method, where the total weight of all factors equal 100, and each individual factor accounts for a fraction of that total, but not all factors account for the same fraction. Examples of the methods are included in Tables 2-3.

Table 2. Binary Weighting Method

Criteria	Technical Feasibility	Operational Performance	Cost	Tourist Experience	**Score**
Technical Feasibility		1	1	1	**3**
Operational Performance	0		1	1	**2**
Cost	0	0		1	**1**
Tourist Experience	0	0	0		**0**

Table 3. Fractional Weighting Method

Criteria	**Weight**
Technical Feasibility	45
Operational Performance	20
Cost	20
Tourist Experience	15
Total	**100**

Once each individual method of weighting factors was identified, overall results were averaged to deduce the final weighting factors to be used in the evaluation of results. An example for the overall results is included in Table 4, using the example weighting methods in Tables 2 and 3.

Technical feasibility was considered the most important criteria, as commercial spaceflight companies need a reliable space suit to train and use as soon as they are flying tourist into low-Earth orbit. Any delays would significantly impact schedule and budget, therefore increasing risk of losing customers and flights.

Suit designs being evaluated initially fall into two categories of an outer layer garment: gas counter-pressure (GCP) and mechanical counter-pressure suits (MCP). GCP suits are single- or double- layer pressure garments that resemble all the current space suits being utilized by NASA, RSA, and China. These suits are sizeable to a large section of individuals, may or may not contain bearings and composite materials, and introduce tradeoffs between decompression sickness (DCS) risk and mobility. MCP suits are an evolving technology that many manufacturers initially developed to increase hand mobility in the gloves. Enterprises, such as MIT's Man Vehicle Lab have taken the MCP approach to the entire space suit design.[11] These suits are interesting enough to be included in this study, though their technology is barely matured enough to be considered according to Assumption 2. An MCP suit allows extensive mobility, basically to the limits of the human body and also provides the sleek look that many commercial spaceflight companies are interested in. Aside from the outer garment, sub categories include, but are not limited to, single- or multi-compositional breathing gas,[12] passive- or active- limb compression,[13] and spherical or elongated helmets[14] (no viable technical alternative to the helmet bubble has been found). An example of the specific trade studies performed is detailed in Tables 5, while the rest of the trade studies can be found in Appendices 4-10. Results of all the trade studies are shown in Table 6.

Table 4. Final Weighting Factors

Criteria\Method	Binary	Fract.	**Final**
Technical Feasibility	50	45	**47.5**
Operational Performance	33	20	**26.5**
Cost	17	20	**18.5**
Tourist Experience	0	15	**7.5**

Table 5. Gas Counter-Pressure Suit vs. Mechanical Counter-Pressure Suit Trade Study

Tech Feasibility	GCP	MCP	**Score**
GCP		1	**1**
MCP	0		**0**

Ops Performance	GCP	MCP	**Score**
GCP		0	**0**
MCP	1		**1**

Cost	GCP	MCP	**Score**
GCP		1	**1**
MCP	0		**0**

Tourist Experience	GCP	MCP	**Score**
GCP		0	**0**
MCP	1		**1**

Criteria	**Weight**	**GCP**	**MCP**
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	0.0	26.5
Cost	18.5	18.5	0.0
Tourist Experience	7.5	0.0	7.5
Totals	**100.0**	**66.0**	**34.0**

Table 6. Trade Study Results

First Choice	Second Choice	Point Differential
Single-Gas Breathing System	Multi-Gas Breathing System	85
Higher Suit Pressure	Lower Suit Pressure	47
Suit with No Bearings	Suit with Bearings	47
Single-Layer Pressure Garment	Double-Layer Pressure Garment	47
Spherical Helmet Bubble	Elongated Helmet Bubble	32
No Use of Composites	Use of Composites	32
Passive Limb Compression	Active Limb Compression	32
Gas Counter-Pressure Suit	Mechanical Counter-Pressure Suit	32

IX. Conclusion

Results of the trade study suggest that the ideal space suit for commercial orbital spaceflight, to be worn throughout all phases of the flight is a very boring space suit. A single-gas breathing system reduces cost and complexity while increases reliability. The detriment to using a single-gas breathing system, oxygen, is that spacewalkers need to denitrogenate via some prebreathe method.[15] Independently, the trade study determined a higher pressure suit is preferred to a lower pressure suit, but this trade also compliments the single-gas breathing system, since a higher suit pressure will reduce the prebreathe times required by using a single-gas breathing system. A suit without bearings is preferred because it will improve performance during the Launch and Re-entry phases, although it will reduce mobility during the microgravity spacewalk. A single-layer pressure garment is preferred over a double-layer simply to reduce costs and complexity of the system. While a single-layer pressure garment requires more frequent repairs, Assumption 6 explains why this concern would be mitigated. While the trade study prefers a spherical helmet bubble over an elongated helmet bubble due to the manufacturing history and flight history, an individual commercial spaceflight company might recognize this trade once where they can stand out and improve the tourist experience with an elongated helmet bubble. A wider field of view would provide the panorama of unobstructed space that a spacewalking tourist is paying millions of dollars to view. Likewise, the trade study prefers not to use composite materials, particularly due to the complexity and costs, although this is another area where a commercial company may choose to stand out. Passive limb compression is reduces cost and complexity. The GCP was preferred over the MCP, but this is another area that would be very interesting if the MCP suit technology matures over the next few years.

E. Alternative Suit Evaluation Criteria

The suit evaluation can be expanded upon by an individual commercial spaceflight company for their specific needs. The following items should also be taken into account.

1) Mass: each trade should consider the overall mass and volume impacts to the launch vehicle and total mission design. A change in mass to a space suit system over 100 kg can impact costs and margin to accommodate other mission systems.
2) Volume: each trade should consider the overall volume impacts to the launch vehicle and total mission design. Each crew cabin has limited volume, and while trades should impact volume as much as changes to mass, it also plays into the tourist experience, and how much cabin space is available for the passengers to experience weightlessness.
3) Logistics: it has been discussed in the Conclusion and Assumption 6 some baseline logistics assumptions that individual commercial spaceflight companies might approach differently to their mission design depending on how each company plans to handle maintainability affecting reliability.

F. Effects of Technology on Suit Architecture Preference

As discussed in multiple sections of this research, trade studies avoided any technology that was more than 5 years away from a demonstration of flight worthiness. As technology improves, the following areas are identified as areas that would affect future trade study results.

1) Heads-Up Display technology for space suit helmets
2) Wearable technologies
3) Exoskeleton technology (specifically for the space suit glove, but eventually for the entire space suit system)
4) Carbon nanotube technology (building off composite improvements)
5) Prebreathe optimization for length and effectiveness
6) Advanced cabin atmosphere compositions
7) Haptic air-typing space suit glove technology

G. Recommendations

To complete this trade study for an individual commercial spaceflight company designing a space suit, it is recommended to expand upon the initial trade studies outlined, including company-specific alternative suit evaluation criteria and incorporating any new technologies that have developed further or that the individual company decides to develop in house and take on that risk.

Appendix

Appendix 1. Previous and Current US Operational Space Suits

Suit	Vendor	Attributes
Mercury	US Navy and B.F. Goodrich Company	Modified version of a pressurized flight suit, 20 pounds, operated with pure oxygen at 5.0 psi (Swenson et al., 1989). Worn unpressurized and served as a backup for spacecraft pressure loss, which never occurred (Hoffman, 2004).
Gemini	David Clark Co.	Also served as a cabin pressure backup, but had an added abort requirement to function appropriately in the event of ejection using the capsule ejection seats. In 1965, the first U.S. EVA was accomplished in this suit using a spacecraft umbilical. Suit pressure had been reduced to 3.7 psi (Johnston et al., 1966).
Apollo EMU	Hamilton Standard (PLSS) and ILC Dover (Pressure Garment)	Designed for intravehicular, 0-g and lunar surface operations (Hoffman, 2004). Two different basic Pressure Garment Assembly (PGA) configurations were employed, one for the command module pilot and the other for the commander and lunar module pilot. The commander and lunar module pilot PGA allowed interface with the Portable Life Support System (PLSS) for pressurization, temperature control, ventilation and communication during lunar EVA. The EMU operated at 3.75 psi. Supplemental equipment such as EVA gloves, visor assemblies and lunar boots allowed the suits to be better customized for the lunar environment (Gibson, 1971).
Skylab EMU	Hamilton Standard and ILC Dover	Simplified version of the Apollo suit, no longer included capability for attachment to the PLSS, supported by umbilical tether. Originally, EVA was only intended to service solar physics experiments at intervals throughout the mission, but additional experiments added later required EVA tasks (NASA, 1974). Skylab astronauts spent 17.5 hours conducting planned EVA's and 65 hours conducting unplanned EVA's.
Shuttle EMU	Hamilton Standard and ILC Dover	Similar to suits used during Apollo and Skylab, but emphasizes improved reliability while minimizing maintenance and pre-EVA checkout requirements (NASA, 1983). Operates at 4.3 psi and has a fully charged mass of 117 kg (NASA, 1983).
ISS EMU	Hamilton Sunstrand and ILC Dover	Based on the Shuttle EMU, but imposed two additional requirements - extended storage duration and additional time between refurbishment (Wilde, 1995).
Shuttle Launch & Entry Suit	David Clark Co.	Partial pressure suit that allowed for survival of cabin depressurization up to altitudes of 30 km and provided insulation from cold air and water that may be encountered. Incorporated g-suit to reduce blood pooling in the legs during reentry (Barry, 1995).
Advanced Crew Escape Suit	David Clark Co.	ACES Model S1035 first flown on STS-64, resembles the LES but utilizes an outer shell constructed of Gore-Tex™ and is a full pressure suit (Lee et al., 2004). Used for launch and entry operations and employs g-suit functionality (Barry, 1995).

Appendix 2. Previous and Current Soviet/Russian and Chinese Operational Space Suits

Suit	Vendor	Attributes
Vostok Sokol	Zvezda	The first Soviet space flight utilized the SK-1, full pressure suit, allowed 5 hour open loop operation in a depressurized cabin using onboard compressed air. Mass ~23 kg, designed for cosmonaut ejection at 8 km and 12 hours of survival in cold water or 3 days at -15 deg C (Skoog et al., 2002). The SK-2 suit was developed specifically for Valentina Tereshkova, the first female cosmonaut, differed mainly in gender form fit.
Voskhod Berkut	Zvezda	Modified Vostok Sokol suit worn during the first Soviet EVA in 1965, functioned at 5.88 psi or 3.97 psi, designed to protect crew from cabin depress and for EVA with an added life support pack to provide 45 minutes of oxygen and cooling (Hoffman, 2004). Removable helmet, two-layer sliding visor and light filter (Skoog et al., 2002)..
Yastreb	Zvezda	Full pressure EVA suit, nominally used during Soyuz 4/5. Life support system allowed 2.5 hours of activity. Backpack life support baselined, but, due to size relative to the Soyuz hatch, the life support system was strapped to the legs (Skoog et al., 2002).
Orlan Series	Zvezda	Derived from the Krechet space suit intended for moon landings. Orlan-D, DM, DMA, and M models used throughout the Soviet/Russian programs. Semi-rigid Orlan suit operates at 5.8 psi requiring an oxygen pre-breathe period of only 30 minutes. The Orlan-DM featured improvements such as head lights, improved controls, sturdier construction and increased mobility. Orlan-DMA introduced in 1988 with improved gloves and life support system, and lighter, tougher, more flexible composite fabric in the arms and legs. The Orlan-DMA empty mass is 90 kg (Hoffman, 2004).
Sokol	Zvezda	Based on SK-1 and SK-2 designs, improvements made to the field of view, joints and gloves, worn for launch, entry and IVA, mass of ~10 kg (Abramov and Skoog, 2003).

Appendix 3. Tested Advanced Suits and Select Future Concepts

Suit	Vendor	Attributes
D-suit	David Clark Co.	Technology demonstrator used in mobility system testing and evaluation. Based on Shuttle ACES, operates at 3.75 psi. Designed as a predominantly fabric suit incorporating minimal bearings. Current prototype mass is 12 kg (Hoffman, 2004).
I-Suit	ILC Dover	All soft, multi-bearing EVA suit proposed for multiple mission phases. Evaluated as advanced technology, work conducted on a second generation I-Suit and Small I-Suit (Graziosi and Lee, 2003). I-Suit development unit has been tested in various lab environments at JSC, on parabolic flights, and in the Mojave Desert.
H-Suit (MK series)	NASA	Designed as demonstrator models of zero pre-breathe functionality at 8.3 psia, mass is ~ 54 kg (Hoffman, 2004). The MK III version incorporates soft and hard elements, with the torso, brief, and hip areas made of a graphite/epoxy composite construction, and the legs/boots made of fabric. Donning accomplished via a rear entry closure, PLSS can be directly mounted or integrated into the H-suit structure (Harris, 2001).
AX Series	NASA	All hard construction utilizing aluminum alloy and stainless steel, first to demonstrate multiple-bearing technology. Design goals similar to the MK series, such as zero pre-breathe (8.3 psi), easy don/doff, and adequate mobility (Klaus and West, 1989).
Chameleon	Hamilton Sundstrand	Concept suit, distributes life support processes throughout suit itself (Hodgson, 2003). Proposes use of integrated materials to transport heat and metabolic waste out and provide energy, with the ability to change shape, thermal properties, optical properties, pore size or chemical activity. Micro-electro-mechanical systems (MEMS) technologies embedded into the suit material. Projected availability in 10-40 years.
PLEAS	Hamilton Sundstrand	The Planetary EVA Architecture System is suggested to provide a 'one suit solution' for all VSE mission phases. Analysis into the use of a top entry design allowing for suit donning through the helmet opening is currently being conducted (Wilde et al., 2004). Key elements of the PLEAS concept have been field tested in the Arctic.
Bio-Suit	MIT	Proposes mechanical counter-pressure in lieu of pressurized gas volume. Concept allows for incorporation of wearable technologies, external layer proposed to be installed by "spray on" or "shrink wrap" means (Pitts et al., 2001). Proposes self-repair at localized sites, while reducing EVA workload and increasing mobility.
ESSS	Dornier	Initiated as part of the cancelled Hermes program, the European Space Suit System was proposed as an advanced hybrid EVA suit comprised of a hard torso and brief with soft waist, arm, and leg joints. Developed as demonstrator, pressure 7.2 psi with 95 percent oxygen (Harris, 2001). Unassisted don/ doff, rear entry system.
EVA Suit 2000	Dornier, Zvezda	Begun as a European-Russian partnership before cancellation of ESSS, for use on Hermes, Mir 2, Buran, and ESA ISS contribution (Harris, 2001). SS-2000 was semi-rigid construction and utilized rear hatch entry (Abramov and Skoog, 2003), operating pressure was 5.8 psi. Joint effort ended in 1994, Russians evolved into the Orlan-M.

Appendix 4. Bearing vs. No-Bearing Pressure Garments Trade Study

Tech Feasibility	Bearing	Non	**Score**
Bearing		0	**0**
No-Bearing	1		**1**

Ops Performance	Bearing	Non	**Score**
Bearing		1	**1**
No-Bearing	0		**0**

Cost	Bearing	Non	**Score**
Bearing		0	**0**
No-Bearing	1		**1**

Tourist Experience	Bearing	Non	**Score**
Bearing		0	**0**
No-Bearing	1		**1**

Criteria	**Weight**	**Bearing**	**Non-Bearing**
Technical Feasibility	47.5	0.0	47.5
Operational Performance	26.5	26.5	0.0
Cost	18.5	0.0	18.5
Tourist Experience	7.5	0.0	7.5
Totals	**100**	**26.5**	**73.5**

Appendix 5. Single-Layer vs. Double-Layer Pressure Garments Trade Study

Tech Feasibility	Single	Double	Score
Single-Layer		1	**1**
Double-Layer	0		**0**

Ops Performance	Single	Double	Score
Single-Layer		0	**0**
Double-Layer	1		**1**

Cost	Single	Double	Score
Single-Layer		1	**1**
Double-Layer	0		**0**

Tourist Experience	Single	Double	Score
Single-Layer		1	**1**
Double-Layer	0		**0**

Criteria	Weight	Single-Layer	Double-Layer
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	0.0	26.5
Cost	18.5	18.5	0.0
Tourist Experience	7.5	7.5	0.0
Totals	**100**	**73.5**	**26.5**

Appendix 6. Utilizing Composite Materials vs. Not Trade Study

Tech Feasibility	Composite	Non	Score
Composite		0	**0**
Non-Composite	1		**1**

Ops Performance	Composite	Non	Score
Composite		1	**1**
Non-Composite	0		**0**

Cost	Composite	Non	Score
Composite		0	**0**
Non-Composite	1		**1**

Tourist Experience	Composite	Non	Score
Composite		1	**1**
Non-Composite	0		**0**

Criteria	Weight	Composite	Non-Composite
Technical Feasibility	47.5	0.0	47.5
Operational Performance	26.5	26.5	0.0
Cost	18.5	0.0	18.5
Tourist Experience	7.5	7.5	0.0
Totals	**100**	**34.0**	**66.0**

Appendix 7. Single-Gas vs. Multi-Gas Breathing System Trade Study

Tech Feasibility	Single	Multi	Score
Single-Gas		1	**1**
Multi-Gas	0		**0**

Ops Performance	Single	Multi	Score
Single-Gas		1	**1**
Multi-Gas	0		**0**

Cost	Single	Multi	Score
Single-Gas		1	**1**
Multi-Gas	0		**0**

Tourist Experience	Single	Multi	Score
Single-Gas		0	**0**
Multi-Gas	1		**1**

Criteria	Weight	Single-Gas	Multi-Gas
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	26.5	0.0
Cost	18.5	18.5	0.0
Tourist Experience	7.5	0.0	7.5
Totals	**100**	**92.5**	**7.5**

Appendix 8. Higher Suit Pressure (Lower DCS Risk, Less Mobility) vs. Lower Suit Pressure (Higher DCS Risk, More Mobility) Trade Study

Tech Feasibility	Hi Suit P	Lo Suit P	**Score**
Higher Suit P		1	**1**
Lower Suit P	0		**0**

Ops Performance	Hi Suit P	Lo Suit P	**Score**
Higher Suit P		0	**0**
Lower Suit P	1		**1**

Cost	Hi Suit P	Lo Suit P	**Score**
Higher Suit P		1	**1**
Lower Suit P	0		**0**

Tourist Experience	Hi Suit P	Lo Suit P	**Score**
Higher Suit P		1	**1**
Lower Suit P	0		**0**

Criteria	**Weight**	**Hi Suit P**	**Lo Suit P**
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	0.0	26.5
Cost	18.5	18.5	0.0
Tourist Experience	7.5	7.5	0.0
Totals	**100**	**73.5**	**26.5**

Appendix 9. Passive vs. Active Limb Compression Trade Study

Tech Feasibility	Passive	Active	**Score**
Passive		1	**1**
Active	0		**0**

Ops Performance	Passive	Active	**Score**
Passive		0	**0**
Active	1		**1**

Cost	Passive	Active	**Score**
Passive		1	**1**
Active	0		**0**

Tourist Experience	Passive	Active	**Score**
Passive		0	**0**
Active	1		**1**

Criteria	**Weight**	**Passive**	**Active**
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	0.0	26.5
Cost	18.5	18.5	0.0
Tourist Experience	7.5	0.0	7.5
Totals	**100**	**66.0**	**34.0**

Appendix 10. Spherical vs. Elongated Helmet Bubble Design Trade Study

Tech Feasibility	Spherical	Elongated	**Score**
Spherical		1	**1**
Elongated	0		**0**

Ops Performance	Spherical	Elongated	**Score**
Spherical		0	**0**
Elongated	1		**1**

Cost	Spherical	Elongated	**Score**
Spherical		1	**1**
Elongated	0		**0**

Tourist Experience	Spherical	Elongated	**Score**
Spherical		0	**0**
Elongated	1		**1**

Criteria	**Weight**	**Spherical**	**Elongated**
Technical Feasibility	47.5	47.5	0.0
Operational Performance	26.5	0.0	26.5
Cost	18.5	18.5	0.0
Tourist Experience	7.5	0.0	7.5
Totals	**100**	**66.0**	**34.0**

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