



UNDER PRESSURE

THE PAST, PRESENT, AND FUTURE MARKET FOR SPACESUITS



SPACE ANGELS
NETWORK

PREFACE

Space Angels Network continually endeavors to understand new market opportunities for investment. Our position, at the forefront of early-stage space investing, gives us a unique vantage point from which to assess nascent markets. And this knowledge provides our investor members with the insights they need to make informed investment decisions in this dynamic industry.

With the proliferation of new in-space destinations coming online (Bigelow BA330, Axiom, ROS, Tiangong, cis-lunar, lunar surface, Mars surface) and new crewed launch vehicles (SpaceX Dragon, Boeing Starliner, Virgin Galactic SpaceShipTwo, Blue Origin New Shepard), we are at an inflection point for human spaceflight. Therefore, we believe the market for spacesuits is growing and could present an attractive opportunity for investment.

The market dynamics of the spacesuit industry are daunting: few customers, high development risk, and dominant incumbents. The long-term success of a spacesuit business is predicated on the proliferation of human spaceflight, whether commercial or otherwise. If indeed human spaceflight is on the cusp of becoming mainstream, then spacesuit companies will be our proverbial canary in the coalmine.

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Executive Summary

The market for spacesuits is remarkably consolidated. A handful of space agencies, the likes of NASA and ROSCOSMOS, have been the main customers of space and high-altitude pressure suits to-date. The few existing producers of spacesuits have established customer relationships spanning as far back as the Gemini missions in the 60s¹, which presents a daunting challenge for new entrepreneurs wanting to break into this niche industry. For incumbents, on the other hand, it presents the question of how to face nimble and innovative competitors.

Spacesuits and pressure suits have become a mainstay for space flights. These suits preserve atmospheric pressure that maintains normal bodily functions, provides life sustaining air, and serves as an interface to the vehicle. There are three types of suits that reflect their use: Intra-Vehicular Activity (IVA), Extra-Vehicular Activity (EVA), and Environmental Activity (Planetary) suits. Altogether, in 2015 approximately 50 suits were sold, which amounted to a value of circa \$100M. The relatively simple IVA suits are priced at approximately \$180K, while the more complex EVA suits sell for upwards of \$12M.

Traditionally, space agencies designed suits and commercial contractors manufactured them.² The two commercial incumbents that dominate the U.S. market are ILC Dover and David Clark. In Russia, NPP Zvezda has supplied suits to ROSCOSMOS since the beginning of the Soviet Space Program, operating as a non-commercial research organization. Incumbents are characterized by expertise in proven technologies, a reputation for safety, and strong government relationships. With national space agencies as the sole customers, they operate on long design cycles and product lifetimes, exacerbated by “cost plus” contracts where companies are paid all costs plus a profit margin.³ There are resounding similarities between the current spacesuit industry and the legacy launch and satellite industries.

Over the last decade, however, the space industry has experienced a profound economic shift. National space agencies are moving out of the International Space Station (ISS) and Low Earth Orbit (LEO) operations, and setting their sights on planetary exploration.⁴ Commercial companies, funded predominantly by private capital, are filling the vacuum by creating manned launch vehicles and human space habitats. Under the Commercial Crew Space Act Agreement, NASA will begin purchasing LEO launches from commercial launcher providers⁵ like SpaceX and Boeing. Bigelow Aerospace successfully tested their Bigelow Expandable Activity Module (BEAM) habitat in 2016. Sub-orbital and near-space flights are being offered by companies like World View Enterprises. Other space agencies in India, China, UK, and the broader EU are emerging with plans to reach LEO and cis-lunar space. Today, participants in the space industry have a strong focus on cost. Space is now more accessible than ever, and this bodes well for enthusiasts of human spaceflight.

More manned missions will undoubtedly create more demand for space and pressure suits. However, the needs of commercial launch companies will be vastly different to those of NASA and ROSCOSMOS. According to Tom Shelley, President of Space Adventures, “If you build a station with commercial customers and tourism in mind, of course it would be different. Everything would change.”⁶ Firstly, commercial companies will be servicing their own private clients who will demand a different level of

¹ Porters five forces: Bargaining power of customers

² <http://mentalfloss.com/article/55823/15-secrets-space-suit-design>

³ <http://arstechnica.com/science/2015/11/quietly-the-new-space-race-between-spacex-and-boeing-burns-hot/h>

⁴ <http://www.wired.co.uk/article/nasa-iss-2024-return-to-moon>

⁵ <https://www.nasa.gov/content/commercial-crew-program-the-essentials/>

⁶ Tom Shelley, President, Space Adventures, Interview with Space Angels Network, July 2016



amenities, comforts, experiences, and safety that matches the potentially \$40M ticket price.⁷ Secondly, destinations for most commercial launch will be centered around near-space and LEO, while government crew, and a select few commercial companies, will be exploring planetary bodies and conducting maintenance, a highly utilitarian use of spacesuits. Thirdly, commercial launch companies will want to differentiate between themselves, SpaceX for example, has begun positioning on aesthetics.⁸

We anticipate that the first successful company, operating in this new business paradigm, will instigate a discontinuity in design – delivering a step change in suit capability. Our belief is that diversified customers and increased competition amongst suit manufacturers will shorten design cycles and product lifetimes. Innovation will be further spurred by recent advancements in material sciences and computations. Successful companies will also have to navigate the low tolerance to risk, which has historically inhibited any dramatic changes in design. There are several strategies that have worked for existing companies in navigating risk and other barriers to entry. Oceaneering, another incumbent spacesuit company, has taken a piece-meal approach to manufacturing by building single components and supplying them to larger suit manufacturers, thereby spreading development risk. ILC Dover has diversified their product offering by applying spacesuit technologies to generic protective equipment, thereby mitigating financial risk. SpaceX has vertically integrated their launch business and are building their own suits, thereby mitigating operational risk.

The incumbent players have an equal chance of success in this new paradigm. Brandishing a record of safety, they can present a strong offering to commercial and government customers alike. All have the expertise in current technology, and some, like Oceaneering, have the capital to invest into new product development. The greatest challenge for incumbents will be to orient their business processes toward agility and innovation. The space industry has seen many large, incumbent businesses falter when competing against smaller, more agile new entrants.⁹ The companies that have succeeded have found ways to manage the tension between fast decision making and bureaucratic processes designed to manage risk. Some companies have overcome this by creating a separate organizational pillar which operates under their own processes and incentives, while having access to the talent and resources within the core business. Designing an effective organizational model for incumbent players will need thoughtful consideration of the inherent culture and existing processes.

Having considered the intrinsic market dynamics, we believe the spacesuit industry could develop in one of several ways. The spacesuit industry is analogous to the pharmaceutical industry in that development risk is uncommonly high. Well-capitalized incumbents that identify successfully tested technologies may strategically acquire them to avoid development risk. In this scenario the production of suits remains as consolidated as it is today, with the balance of power shifting to the manufacturers. Another scenario is that launch providers deem spacesuits to be of high operational risk, and hence pursue vertical integration. In this scenario the remaining spacesuit companies that lack innovative designs, will not generate sustainable cash flows. Alternatively, it is plausible that a company with superior technology dominates market share, since the market itself is relatively small. To observe any of these scenarios is a signal for ensuing growth of human spaceflight.

⁷ <http://spaceflightnow.com/news/n1009/15boeingtourism/>

⁸ <http://www.ibtimes.co.uk/iron-man-captain-america-costumer-designer-makes-spacesuits-spacex-astronauts-1558406>

⁹ <http://fortune.com/2016/03/17/ula-exec-admits-company-cant-compete/>



Report Findings

Lack of competition has led to decades of incremental design, the suits used today are not substantially different from those developed in the 1960s. Even the most recent shuttle IVA suit, ACES S1035, is a direct decedent of the US Air Force S1034 designed for the U-2.^{10,11} As more entrants begin operating in the commercial space transportation market, that dynamic will change. More demand will introduce more competition by increasing supply in commercial space transportation, which in turn will result in buyers' ability to demand differentiated products at lower price points. This is mirrored by the expected differentiation in product offerings for commercial space and traditional government customers. While the ISS was developed for, and primarily used by, government employees, destinations like Bigelow's BA-330 habitat are designed with commercial customers in mind. With a price tag of \$25 million for 60 days, plus between \$27-58 million for a seat on SpaceX's Dragon or Boeing's Starliner,^{12 13} these commercial customers will expect greater amenities and services.

The difference in catering to government customers and new commercial customers was expressed most clearly by SpaceX when they put out a call for spacesuit proposals that looked "Badass".¹⁴ While the incumbent players in this market have expertise and established resources, new entrants are agile and arguably better-equipped to address the evolving needs of this new, dynamic market.

It's clear that pressure suit manufacturing is a low-volume, high-margin industry, and our research suggests that is unlikely to change in the near-future. Even with new entrants in commercial transportation and space habitation, the market for commercial spacesuits will be growing at a moderate pace over the next 15 years. While it is undeniable that commercial space activity is increasing significantly, and expected to continue, we expect that a number of new entrants will either manufacture their own spacesuits (in the case of SpaceX), or not require spacesuits at all (in the cases of suborbital and near-space tourism).

There are over 10 active companies manufacturing spacesuits, with varying levels of competitiveness. Our analysis concluded that the market is technologically stagnant, and that a new innovation cycle will come about with the maturation the broader space industry. These changes will shift the balance of power, which in turn will change how the market operates.

Spacesuit market expected to be a low-volume, high-margin business for at least the next 15 years; diversification into tangential products is essential

Destinations drive demand for human spaceflight & space suits

Discontinuity of design is required to address the different demands of commercial & government customers

New players can enter the market via component manufacture

Incumbents will need to reinvent & re-organise themselves to compete and stay relevant in a disrupted and dynamic market

¹⁰ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

¹¹ NASA Space Shuttle Advanced Crew Escape Suit Development, Barry, D. & Bassick, J., SAE Technical Paper 951545, 1995

¹² Bigelow Aerospace: Colonizing Space One Module at a Time, Erik Seedhouse, 2014

¹³ <http://www.theverge.com/2016/5/12/11662214/boeing-starliner-iss-delay-2018>

¹⁴ <http://gizmodo.com/spacex-wants-future-astronauts-to-look-badass-in-spac-1735190895>



PRESSURE SUIT COMPETITIVENESS SCORES

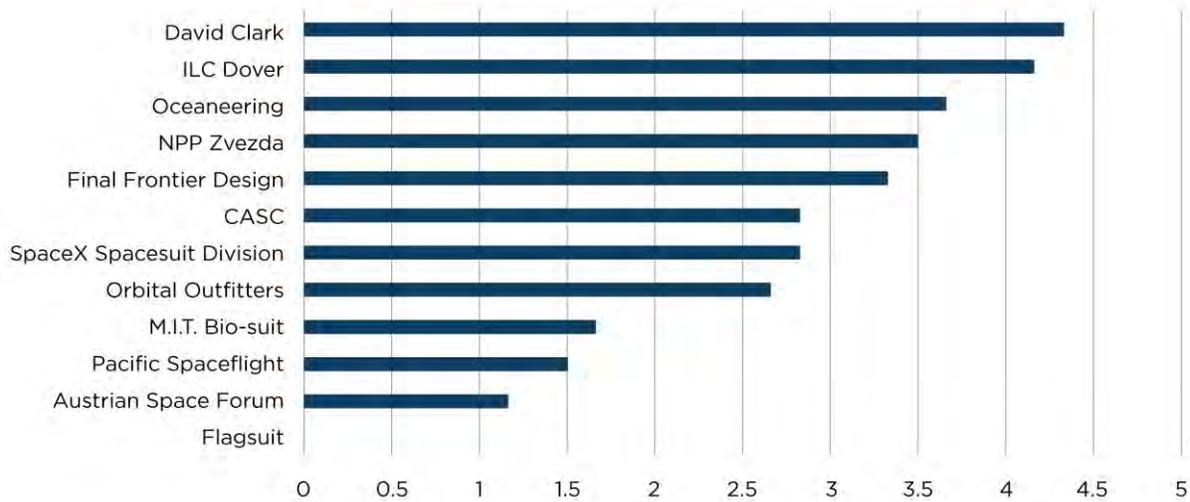


Figure 1 - Competitiveness Scores for the Incumbents and New Entrants of the Space Pressure Suit Market

Keys to Success

As shown in the Overview

Since 2001, there has been a continual human presence in space aboard the ISS, which is currently the primary market driver. There are up to six passengers aboard the ISS at any given moment and seat allocations go to those countries who contributed to its development and ongoing operations. Russia has three seats that is increasing to four, the US typically has two seats, and Japan, Canada and the EU rotate among the last seat. This limited number of seats has created a restricted market, with a low-volume of spacesuits required for operations, and customers with strong buying power. It also means that primary customers have been governments.

Market section, over 90% of the market value is attributable to EVA suits. Ted Southern, President of Final Frontier Design states, "Overall, the IVA suit market represents a very small and limited market. EVA represents a much larger market both short term and especially longer term."¹⁵ For businesses that want to capitalize on the pressure suit market, we have identified four strategies:

1. Market Entrance Through Components

The major problem faced by new entrants is the lengthy technology adoption lifecycle. Pressure suit customers are likely to favor flight-tested equipment that have a proven safety record. This makes it very difficult to enter the market as a lead manufacturer, but it does offer an opportunity to enter the as a component manufacturer, under the umbrella of another proven lead manufacture. This approach has a number of benefits, namely:

- Access to customers who demand proven suppliers
- Opportunity to inherit knowledge from experienced manufacturers
- Opportunity to build a reputation through relationships and a track-record

¹⁵ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016



- Early revenue to support technological development

While this approach is essential for new entrants to establish themselves, it creates benefits for incumbents as well:

- The ability to leverage the advanced research and development undertaken by agile, innovative companies
- The ability to concentrate on core competencies, while using other products to complete the pressure suit as a lead developer

This approach was used by Oceaneering, a company that makes advanced life support systems, tools for all current EVA operations and that operates NASA's Sonny Carter Training Facility Neutral Buoyancy Lab.¹⁶ Oceaneering was the lead manufacturer of the now cancelled Constellation Spacesuit. David Clark and ILC Dover also use this approach for pressure suits on the ISS and Orion.

2. Innovation and Discontinuity in Design

The strategy to outcompete by making competitors' technology obsolete also has potential. Through innovation and new technology, it's possible to introduce discontinuous design in the very mature pressure suit market. A new innovation will provide a substantial competitive advantage for the companies catering to emerging commercial customers.

The technological state of the pressure suit market has been stagnant since the development of a dominant design in the early 1960s. Today's suit design can be traced directly to the Gemini suits of the early US Space program. This offers a great opportunity to use the technological advances of the past five decades to gain a competitive advantage.

While genuine discontinuous design is very difficult to achieve, we have identified a number of horizon technologies that would allow such change. These include:

- Mechanical Counter Pressure (MCP) suits
- Advanced computer integration and connectivity
- Advanced HUD and augmented reality
- Gravity Loading Countermeasure suits
- Aesthetics and visual design

3. Claim, Demarcate and Control the Market

A new entrant or an incumbent seeking to solidify their position in the market can choose a strategy of claiming, demarcating, and controlling.¹⁷ A new entrant will need to 'claim' a position as the market's cognitive referent (knowledge leader) by sending dominance signals. In a similar vein, incumbents will need to re-establish themselves as a knowledge leader to become perceived as technologically relevant. The organization seeking to become a cognitive referent can create and disseminate success stories to raise awareness about the new design, and signal external and internal market actors to create a legitimacy around the new design.

A company can also 'demarcate' the market into a new configuration that benefits their business. This will involve anti-leader positioning, which will be especially effective against a more powerful incumbent. This may take the form of partnerships, joint ventures, or may go as far as equity purchases

¹⁶ <http://www.oceaneering.com/space-systems/human-space-flight/>

¹⁷ Santos & Eisenhardt, 2009



or revenue sharing arrangements. Incumbents are incentivized by opportunities to have a stake in new growth, while new market entrants can leverage the resources and talents of the incumbent.

Finally, companies can position themselves to 'control' the market by eliminating competing models. This can be done in one of several ways: creating technological advantages that competitors cannot match; blocking entry into the market by acquiring new rivals; entering new markets by acquiring rivals with diverse products; or acquire companies in adjacent sectors that have technologies that can help this sector.

These actions will result in increasing resources for companies managing the evolving market, which in turn enables innovation.

4. Diversified Product Offering

As shown later in the Market Overview, the size of the pressure suit market is not yet large enough to accommodate a great number of competitors. Therefore, successful companies are those that develop other sources of revenue from tangential markets. There are a number of similar markets, which could use technology adapted from pressure suit designs. These products are outlined in the Other section and include:

- HAZMAT Suits
- G-Suits
- Gravity Loading Countermeasure Suits
- Airbags
- RADOMES
- Airships
- Flexible Containment Systems and Bulk Packaging
- Aviation Helmets Flight Suits and Oxygen Systems
- Personal Protective Equipment
- Disposable Clean-up Equipment
- Technical Sports Apparel
- Spacesuit fittings



Technology

Dominant design is a technology management concept that identifies key designs in technology or manufacturing that become the industry standard¹⁸. The current IVA and EVA pressure suits reached dominant design decades ago and have been in a stage of incremental innovation ever since. This is in part due to the long lead times of the design process, which inhibited fast deployment. Further, there are a number of technologies on the horizon, which could lead to a discontinuity in suit design, for example, the MIT Bio-Suit or the use of integrated computers for higher levels of connectivity and sensing. This section will review the history of space and pressure suit technology, outline the current changes in suit technology, and explore horizon technologies.

Physiological Effects of Altitude on Humans

As explorers embarked on setting high altitude records, the need to protect their bodies from effects of low pressure became more apparent. The first pressure suits were investigated prior to 1900, patented in 1908¹⁹ and published in the 1920s. By the 1930s balloons were carrying explorers protected by these suits.²⁰ The suits encapsulated the pilots in a flexible, robust pressurized chamber and protected them from the cold and low pressure environment of the upper atmosphere. This became the basis for almost every pressure suit designed thereafter.

Humans function normally below 10,000ft (the physiological-efficient zone), since oxygen levels are high.²¹ The physiological-deficient zone extends from 12,000ft to 50,000ft, which results in an increased risk of hypoxia and decompression sickness, amongst other ailments. Above 50,000ft respiration is not possible as the pressure at which human lungs excrete carbon dioxide, exceeds outside air pressure.²²

Above 63,000ft (the Armstrong Limit) fluids in the lungs and throat boil away. However, the human body does not react to high altitudes and space vacuum in the manner that is often depicted in science fiction movies.²³ Human flesh does not expand in dramatic ways, nor is there a 'snap freeze' effect. Oxygen deprivation occurs after 10 seconds, leading to a loss of consciousness, but death is often slower.²⁴ To mitigate the effects of low pressures, human skin is mechanically compressed by suits to retain its normal shape.



Figure 2 - The First Russian Space Pressure Suit – The Vostok mission SK-1

¹⁸ https://en.wikipedia.org/wiki/Dominant_design

¹⁹ <http://www.wired.com/2011/10/spacesuit-evolution/>

²⁰ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

²¹ Physiological hazards of flight at high altitude, Pilmanis, A., The Lancet, 2003

²² Physiological hazards of flight at high altitude, Pilmanis, A., The Lancet, 2003

²³ Physiological hazards of flight at high altitude, Pilmanis, A., The Lancet, 2003

²⁴ Physiological hazards of flight at high altitude, Pilmanis, A., The Lancet, 2003



SPACESUIT TIMELINE

Pre-Space

1940s-1950s



Manned Spaceflight

1960s



Lunar Spaceflight and Skylab

1969-1980s



Mir and the Shuttle

1980s-1990s



ISS and post-Shuttle

2000-Present



Multiple Space Stations, Cis-Lunar and the Next Generation

2012-2024



Post-ISS and the Mars Generation

2025+



Chinese Taikonaut Suits

Russian Cosmonaut Suits

US Astronaut Suits



First Chinese Spacewalk
Feitian (based on Orlan)
Shenzhou
2008



Sokol-K
Soyuz Flights
1973 - 1981



Orlan-D
Salyut and Mir Flights
1977 - 1984



OrlanMK
ISS Flights
2009 - Present



Russian
Sokol-KV2
Soyuz Flights
1980 - Present



Orlan-MKS
ISS Flights
2016 - Future



US
Sokol-KV2
Soyuz Flights
2011 - Future



Final Frontier
Design Gloves
Future



Modified Advanced
Crew Escape Suit
Prototype 2016



Z-1 Environmental
EVA Prototype
2012

Z-2 Environmental
EVA Prototype
2015



MIT Biosuit
Far Future



Speed of Sound Flights
T-1 Pressure Suit
X-1 Flights
1945 - 1950



Hypersonic Flights
XMC-2 Pressure Suit
X-15 Flights
1950s



First US Space Flight
Navy Mark IV
Mercury Flights
1961 - 1961



First US Spacewalk
G4C Gemini Spacesuit
Gemini Flights
1965 - 1966



AX-3
Hard-Shell Prototype
1970



First Lunar Missions
Apollo/Skylab A7L
Apollo and Skylab
Flights
1968 - 1979



AX-5
Hard Shell Prototype
1985



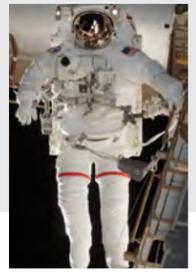
Extravehicular Mobility Unit
EVA Shuttle and ISS Flights
1983 - 2002



Launch Entry Suit
IVA Shuttle Flights
1988 - 1998



SpaceX IVA Suit
FutureAdvanced Crew
Escape Suit
IVA Shuttle Flights
1994 - 2011



Enhanced Extravehicular
Mobility Unit
EVA Shuttle and ISS
Flights
1998 - Present



Final Frontier
Design IVA
Future



SpaceX IVA Suit
Future



Orbital Outfitters
IVA
Future

History of Pressure Suits

Pressure suits were developed in the US toward the latter end of the Second World War, as aircraft began flying higher and pilots had to be protected in the event of cabin decompression. David Clark, a G-suit manufacturer, supplied much of the initial technical services and resources. Prototype suits were developed in 1946 and tested to 90,000ft.²⁵ David Clark also developed the S-1 and T-1 suits for the Bell Aircraft Company X-1 pilots, won the first contract for the Model 4 full pressure suit, and developed pressure suits for the North American Aviation X-15.²⁶ The Russian aerospace industry kept pace with the US and developed their first full pressure suit for spaceflight in 1959.²⁷

At the dawn of the space age, a more durable suit was required to withstand the harsh environment of space. The earliest operational space-pressure suit was the SK-1. It was used by the Soviet Space Agency during the famous Vostok 1 spaceflight by Yuri Gagarin – the first human in space (above the Kármán line).²⁸ The US, through the newly formed National Aeronautics and Space Administration (NASA), used a modified high altitude fighter pilot pressure suit, the Navy Mark IV, for the Mercury project space flight.

Russia continued to use the SK-1 suit for the Voskhod missions and then used a modified suit, the Berkut developed by NPP Zvezda, for the first space walk on Voskhod 2.²⁹ NASA used a modified X-15 high-altitude pressure suit for the Gemini missions. The first US space walk in 1965 used a G4C suit developed by David Clark, which was a modified IVA / EVA suit with seven different layers of fabrics.³⁰

New spacecraft and missions have typically spurred the development of new spacesuits. As NASA began preparing for the Apollo missions, a new suit was required for the Apollo spacecraft, and for the surface of the moon. ILC Dover manufactured the Apollo A7L, which was designed to be an IVA, EVA, and Lunar Environment suit. It was used for Apollo missions 7 through 14 and was described by Neil Armstrong as “tough, reliable and almost cruddy.”³¹ The suit was later adapted as the A7LB for use on Skylab.³²

The Soviet Space Agency stopped using pressure suits during the early Soyuz flights (Soyuz 1 – 11, 1967 – 1971).³³ This decision was later reversed after a re-entry decompression accident on Soyuz



Figure 3 - The first US Space Pressure Suit - the Mercury Project modified Navy Mark IV

²⁵ Bioastronautics Data Book, 2nd edition, Parker JF and West VR (editors), NASA, 1973, <http://www.geoffreylandis.com/vacuum.html>

²⁶ X-15: The World's Fastest Rocket Plane and the Pilots Who Ushered in the Space Age, Anderson J, Passman R, Zenith Press, 2014

²⁷ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

²⁸ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

²⁹ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

³⁰ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

³¹ Science Friday Archives: How to Dress for Space Travel. NPR. March 25, 2011

³² US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

³³ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003



11 that resulted in the deaths of three cosmonauts, the only human deaths to have occurred in space. Since the accident all Russian flights have used pressure suits.³⁴

The development of the second-generation Soyuz spacecraft brought about the Sokol-K space suit, designed by NPP Zvezda and launched in 1973.³⁵ Different versions of the Sokol suit have been used by the Soviet Space Agency and ROSCOSMOS (Russian Federal Space Agency) spacecraft passengers since.³⁶

In the late 1970s the Soviet Space Program and NPP Zvezda developed the Orlan-D, an EVA suit for use with the Salyut and Mir space stations.³⁷ The suit was first used in 1977 on a space walk from Salyut 6. The Orlan suit series has undergone a number of development stages including the DM, DMA, M and MK models, the most recent of which was commissioned in 2009 and is still used for ISS missions today.³⁸



Figure 4 - The assembly of the Apollo A7L

For the testing of the Shuttle orbital vehicle in 1981-92, a modified SR-71 high-altitude pressure suit was used by NASA. However, after certification of the shuttle the crew used a simpler flight suit, with a helmet and oxygen mask. In 1986 the Challenger Shuttle experienced a failure and NASA subsequently reintroduced the use of (partial) pressure suits during the launch and re-entry phases, using the David Clark LES IVA (Launch Entry Suit).³⁹

Introduced in 1981, the EMU (Extra-Vehicular Mobility Unit) was designed and manufactured by ILC Dover for NASA's future EVAs.⁴⁰ It is a modular, semi-rigid suit that can operate independently with a 'Manned Maneuvering Unit'. It was used for all shuttle EVAs until 2011, the enhanced EMU is still used on the ISS today and costs circa \$12 million USD for NASA to purchase.⁴¹ In a recent RFI, NASA estimates the cost of maintenance and operations of their EMUs alone at \$80 million every year for the next 10 years.⁴²



Figure 5 - Sokol IVA Suit Used by US Astronaut Peggy Whitson on ISS Expedition 16, launched October '07

³⁴ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003, US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

³⁵ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

³⁶ <http://www.nasa.gov/audience/forstudents/k-4/stories/history-of-spacesuits-k4.html#.Vnea9hV97IU>

³⁷ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

³⁸ Manned Spaceflight Log II—2006–2012, Shayler D and Shayle M, Springer Publishing, 2013

³⁹ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁴⁰ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁴¹ <http://www.space.com/26978-commercial-spaceflight-requires-safety-of-new-space-suits.html>

⁴² <http://www.space.com/26978-commercial-spaceflight-requires-safety-of-new-space-suits.html>



In 1990 the ACES (Advanced Crew Escape Suit) was introduced as the successor to the LES. It was also developed and manufactured by David Clark and is a direct decedent of Gemini SR-71 and the LES pressure suits. The ACES is a full pressure suit and costs circa \$180,000 USD for NASA to purchase.^{43,44}

The Orlan MKS, the most recent EVA suit developed by NPP Zvezda, has recently been completed and is due to replace the Orlan MK models on the ISS in 2016.⁴⁵

NASA had envisioned using the new Constellation suit for future missions on the Orion spacecraft. However, in 2010 the Constellation program was cancelled along with plans to develop the suit.⁴⁶ Development on the Orion spacecraft continues, but it will use a modified ACES suit being developed by David Clark.^{47 48}

There are a number of spacesuits in development, but the only spacesuits in current operation are two full EMUs, one short EMU, two Orlan suits on the ISS, and four Soyuz crewed launches to the ISS per year with three IVA suited crew. There is also a Chinese crewed mission scheduled for launch in 2016, which uses an IVA suit that is visually similar to the Sokol-K.⁴⁹



Figure 6 - Sokol-K Series Spacesuit

⁴³Dressing for Altitude, Jenkins, D., NASA, 2012

⁴⁴ <http://www.space.com/26978-commercial-spaceflight-requires-safety-of-new-space-suits.html>

⁴⁵ <http://www.zvezda-npp.ru/en/node/103>

⁴⁶ <http://www.bbc.com/news/science-environment-11518049>

⁴⁷ Use MACES IVA Suit for EVA Mobility Evaluations, Watson, R., NASA, 2014

⁴⁸ <http://www.nasaspaceflight.com/2014/12/nasa-evaluating-shuttle-aces-asteroid-eva/>

⁴⁹ <http://www.ft.com/intl/cms/s/0/59a60404-8a66-11dd-a76a-0000779fd18c.html#axzz3y830LZpu>



Defining a Spacesuit

Theories of design

Pressure suits generally endeavor to keep the pressure and volume constant within the suit, regardless of body movement. Since mechanical work is required to change the volume of a constant pressure system, any movement that changes the volume will fatigue the wearer. It is particularly not ideal for wearers interested in making delicate or precise movements.⁵⁰ There are four approaches to suit design that endeavor to minimize volume changes:



Figure 7 - Sokol spacsuit worn by Helen Sharman in 1991



Figure 8 - AX-5 Hard-shell Prototype



Figure 9 - AX3 "hybrid" spacsuit developed NASA Ames in 1974



Figure 10 - MIT biosuit

Soft-shell suits

These suits are typically made of soft, flexible fabrics (for the most part, all suits require some hard bearings or joints and a hard visor and helmet). Most IVA suits use this design approach and many earlier EVA suits used this approach.

Hard-shell suits

Hard-shell suits are commonly made of metal or composites. They use bearings to attach multiple hard-shell segments together to allow the wearer to maintain maneuverability. The suits can also operate at higher pressures, which may reduce or eliminate the need for astronauts to pre-breathe oxygen.⁵¹ The AX-5 was an all hard-shell pressure suit developed by NASA's Ames Research Centre in the 1980s. It takes advantage of the constant volume of hard-shell suits such that wearer does not require any mechanical force to maintain suit position. The gloves still maintain a soft-shell design.

Hybrid suits

Hybrid suits use a combination of hard and soft shell components, to leverage the benefits of both. Many of the current EVA suit designs use a hybrid approach, for example, the NASA EMU EVA suit on the ISS uses a fiberglass, hard-shell upper torso while the lower torso, arms and legs are soft-shelled to increase maneuverability. Many majority soft-shell suits use hard elements for joints and seals.

⁵⁰ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁵¹ http://www.nasa.gov/centers/ames/multimedia/images/2010/iotw/ax_5_astronaut.html



Mechanical Counter Pressure (MCP) suits

These suits are also known as skintight suits or space activity suits. They use a mechanical force exerted on the skin of the wearer to mimic the effects of air pressure on Earth or the pressure in a pressure suit. Although they still require a helmet for breathing, the rest of the body is not under gas pressure. MIT is working on this concept with their Bio-Suit, but no fully functioning prototype has yet been developed. The suits are generally viewed as lighter with lower movement effort and an almost unrestricted range of motion.⁵²

Suit Components

There are a number of different, interconnected components that go into building a full spacesuit. Historically, the different parts of NASA spacesuits have been manufactured by multiple companies and combined by a lead company into the final suit. For example, ILC Dover, Hamilton Standard, AiResearch, and Air Lock Inc. manufactured the Apollo and Skylab A7LB suits, and David Clark and Air Lock Inc. manufactured the ACES suit.⁵³ This was also the case with NASA's recently cancelled Constellation Spacesuit where an Oceaneering lead team worked with companies including United Space Alliance, David Clark, Air-Lock, Harris Corporation, Cimarron Software Services, Paragon Space Development Corporation, Hamilton Sundstrand Corporation, and ILC Dover.⁵⁴

According to Ted Southern, Final Frontier Design has “manufactured a number of EVA components for NASA since 2009” which “represents the largest revenue stream” for the company.⁵⁵

The EMU suit has 18 separate assemblies which are manufactured by multiple companies, and joined by a lead manufacturer. Many of these assemblies are applicable to both EVA and IVA, though for IVA suits some functions like life support are undertaken by the vehicle. Using the EMU as an example, the main assemblies of space suits are outlined below and defined by NASA's ‘Suited for Spacewalking’ activity guide.⁵⁶

Suit Segments

Upper Torso (EVA, combined with Lower Torso for IVA)

Upper torso of the suit, comprised of a hard fiberglass shell. It provides structural support for mounting other assemblies. An IVA suit does not require structural support and historically has been a softshell component, combined with the lower torso in a similar fashion to an air-tight flight suit.⁵⁷

Lower Torso (EVA, combined with Upper Torso for IVA)

Softshell spacesuit trousers, boots, and the lower half of the waist. The suit has a waist bearing for body rotation and safety tether mounts. As noted above IVA Lower Torso is usually combined with a softshell Upper Torso.

Arms (left and right, EVA, combined with Torso for IVA)

Shoulder joints and joint bearings, upper arm bearings, elbow joints and glove attachment closures are required to maintain dexterity of astronauts undertaking work during spacewalks. IVA suit arms are softshell components that are attached to the Upper Torso, similar to a flight suit, and are therefore much more mobile for use inside a vehicle.

⁵² US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁵³ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁵⁴ <http://www.oceaneering.com/471/oceaneering-signs-contract-with-nasa-to-develop-and-produce-the-constellation-space-suit-system/>

⁵⁵ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016

⁵⁶ Suited for Spacewalking, NASA, EG-199803-112-HQ

⁵⁷ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012



Contributing technologies

<i>Gloves (EVA/IVA)</i>	Wrist bearing and disconnect, wrist joint and fingers are required to try to maintain some finger dexterity. The gloves also have loops for tethering tools. Astronauts generally wear thin fabric comfort gloves under the EVA gloves. IVA gloves are softshell but are also connected with a wrist joint bearing in the case of the ACES suit.
<i>Helmet (EVA/IVA)</i>	Plastic pressure bubble, similar to Apollo A7LB helmets, with a disconnecting ring and ventilation distribution pad. Both NASA EVA and IVA suits use detachable helmets but the Russian Sokol suit uses an integrated helmet.
<i>Liquid Cooling Garment (EVA/IVA)</i>	Long underwear-like garment, worn inside the pressure suit. It has liquid cooling tubes, gas ventilation ducting and multiple water and gas connections to life support.
<i>Maximum Absorption Garment (EVA/IVA)</i>	As adult-sized diaper with extra absorption materials added for urine collection
<i>Service and Cooling Umbilical (EVA/IVA)</i>	Connects the airlock to the EMU to support the astronaut before the EVA and to provide in orbit charging to the Primary Life Support System. It contains lines for power, communications, oxygen and water. The IVA umbilical cord provides all life support capabilities from the vehicle during use, not just a recharge capability.
<i>Primary Life Support System (EVA)</i>	A self-contained backpack system containing an oxygen supply, carbon dioxide removal equipment, warning system, electrical power water-cooling, ventilation, machinery and radio. In the case of an IVA suit these tasks are undertaken but the vehicle and connected to the suit by internal umbilical cables.
<i>Displays and Controls Module (EVA)</i>	Chest mounted control panel, containing all controls, a digital display and all machinery, gas and electrical interfaces. In the case of an IVA suit this will likely be combined with the life support controls of the vehicle housing the astronauts.
<i>EMU Electrical Harness (EVA)</i>	A harness worn inside the suit to provide bioinstrumentation and communications connections to the Primary Life Support System. Current IVA suits do not have an equivalent component.
<i>Secondary Oxygen Pack (EVA)</i>	Two oxygen tanks with 30-minute emergency supply combined with valves and regulators. It is usually attached to the bottom of the Primary Life Support System.
<i>Battery (EVA)</i>	The battery supplies power to the EMU during EVA. Power for an IVA suit is supplied by the vehicle.
<i>Contaminant Control Capsule (EVA)</i>	Cleanses suit atmosphere of contaminants, with an integrated system of lithium hydroxide, activated charcoal and a filter. It is replaceable in orbit.
<i>Extra-Vehicular Visor Assembly (EVA)</i>	This assembly contains a metallic gold covered sun-filtering visor a clear thermal impact-protective visor and adjustable blinders that attach over the helmet. It also houses four small head-lamps, a TV camera and transmitter.
<i>In-suit Drink Bag (EVA)</i>	Plastic filled water pouch mounted inside the upper torso.



An Industry in Flux

The pressure suit industry reached a state of dominant design several decades ago, as demonstrated by the similarities between the traditional U-2 and SR-71 pressure suits designed in the 1950s and 60s, and the modern ACES suit used by Shuttle astronauts until 2011. The suits have undergone incremental changes in materials and performance but there have not been any major, discontinuous design changes. Figure 11 illustrates that once a product has achieved dominant design, it often remains in state of stasis until a new entrant introduces a significant improvement in capability or cost reduction.

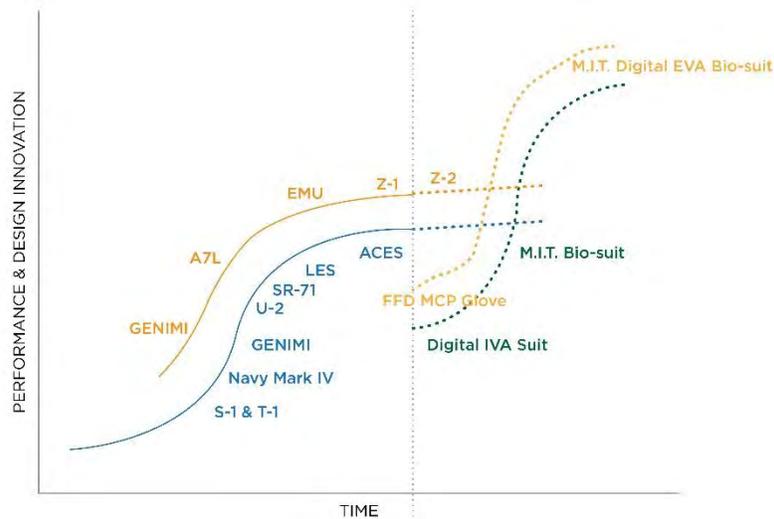


Figure 11 - United States Pressure Suit Technology S-Curve

Component and the Integrated Manufacturing Approaches

There are advantages and drawbacks of the component manufacturing approach. While it allows those companies to focus on design elements in which they have the most expertise, it often increases the cost of each component as each manufacturer adds margin. It does however, spread the risk and development costs across several companies. This approach has been used to build the LES/ACES and the EMU suits, which NASA has used for the last three decades.

In contrast, a vertically integrated manufacturer will design and build the entire suit themselves, maintaining control over the cost, schedule, and quality. This approach can increase the economies of scale of production and is the approach currently taken by SpaceX's vertically integrated Spacesuit Division.⁵⁸

Technological Flux

Two key factors will enable a discontinuous design leap in pressure suits. First, the miniaturization of computing technology, and second, the advancement of materials science.

Computing technology

Since the design of the most recent operational pressure suits, the size, power and battery life of computing technology has increased remarkably.⁵⁹ Like much of the space industry, due to the long

⁵⁸ <http://www.bloomberg.com/news/articles/2015-01-08/spacex-space-suit-will-combine-function-with-design>

⁵⁹ 50 Years of Moore's Law, <http://www.intel.com.au/content/www/au/en/silicon-innovations/moores-law-technology.html>





Figure 12: SpaceX Concept Design Suit. Credit: Annie Leibovitz, Vogue, October 2015

design contracts used by NASA and ROSCOSMOS, the pressure suits in use today have not caught up with recent technological achievements. Although the Orlan MK and MKS were designed recently, they do not utilize the high levels of computing technology available and are incremental design improvements of the Orlan M model.

Advanced Materials

The second technological change that will enable a shift in the S-Curve is the advancement of materials science, some of which is leading to the development of MCP suits. These suits are designed to provide the same benefits as pressurized gas suits but with increased mobility

and decreased fatigue. Advances in ‘memory materials’ (or ‘smart materials’), including piezoelectric, magnetostrictive, and temperature-responsive polymers, which all change properties in reaction to an environmental change, may lead to MCP suits that can adapt to changing conditions or can be dynamically altered through computer control.⁶⁰

The New S-Curve

A new suit design may be one that is skin-tight, with no reliance on pressurized gas, that has mobility and flexibility, that has on-board mission computers, functional displays, and is digitally connected to spacecraft, other astronauts, and mission control. Such a suit would be drastically more effective and safer than conventional designs.^{61,62}

Multipurpose Suits

Many of the early EVA suits were combination EVA/IVA suits used during launch, EVA, and reentry. The suits were later separated and specialized because EVA and IVA suits have distinctive requirements that often conflict.⁶³ EVA suits are more expensive, but not used as often and they required a larger space aboard spacecraft.

The benefits of multi-purpose suits have been demonstrated since the Apollo A7L. As the costs of advanced materials decreased, the costs of producing protective suits also decreased. NASA’s next suit will likely be a combined EVA/IVA suit dubbed the MACES⁶⁴ (or Modified ACES).



Figure 13 - An Example of Advanced Materials in a Spacesuit, NASA’s Z-2 Prototype. Credit: NASA

⁶⁰ <http://news.mit.edu/2014/second-skin-spacesuits-0918>

⁶¹ Mechanical Counter Pressure Space Suits: Advantages, Limitations and Concepts for Martin Exploration, J. Waldie, RMIT Melbourne, 2005

⁶² <http://www.nasa.gov/directorates/spacetech/strg/holschuh.html>

⁶³ Crew Protection, Contingency EVA and the Crew Exploration Vehicle, Harris, G., Department of Space Studies, University of North Dakota, Commissioned by ILC Dover, 2006

⁶⁴ Use MACES IVA Suit for EVA Mobility Evaluations. Watson, Richard D. Tucson, Arizona: 44th International Conference on Environmental Systems, 2014. JSC-CN-29963



Critical Dependencies

The successful commercialization of advanced suits is reliant on three critical dependencies: 1) development of advanced materials; 2) acceptance by governmental and commercial customers; and 3) barriers to adoption for competitors. We have observed progress on all these critical dependencies. MIT's Bio-Suit and Final Frontier Designs' MCP Glove have developed advanced materials.⁶⁵ NASA, the largest customer of pressure suits, is funding research on advanced pressure suit designs and has signaled that it is open to the possibility of new technology.⁶⁶ Well capitalized companies can build barriers by applying for intellectual property rights, by outcompeting on price, leveraging first mover advantage, or by acquiring competitors.

In an interview with Space Angels Network, member and private astronaut, Richard Garriott outlined his priorities when selecting a spacesuit, "Safety is obviously a must, then comfort because I have to wear it, then cost so I can keep it."⁶⁷

Horizon Technologies

A number of emerging technologies have not been fully developed or prototyped. Future businesses may be interested in them as a way to increase capabilities or competitive advantage in product offering. These emerging designs take advantage of recent and future technology advances and may lead to movement to a new pressure suit S-Curve.

Mechanical Counter Pressure

MCP suits have already been mentioned a number of times in this report and they will be mentioned again because "Sci-Fi has told us this would be the future for the last 50 years!"⁶⁸ The promise of lightweight, flexible comfort⁶⁹ cannot be achieved with gas pressure suits. The advanced materials required to manufacture an MCP suit are being developed but once it is operational, they will render the current suits obsolete. MCP suits "have greatly reduced weight as bearings are not needed, increase the range of motion and functionality, greatly increase safety factors, and decrease cooling requirements", according to Ted Southern.⁷⁰

3D Printed Materials

The ability to manufacture complex, customizable components using 3D printing (or Additive Manufacturing) has not yet revolutionized mass production manufacturing yet.⁷¹ However, it has resulted in an S-Curve shift for quick prototyping and the low-scale, highly customized components that are required for pressure suit manufacture. The ability of 3D printing to manufacture designs



Figure 14 - NXD-1 Spacesuit Prototype Developed by the University of North Dakota during Testing with NASA at Kennedy Space Centre. It will be Used to Trial Different Technologies for Surface Exploration on Mars (NASA)

⁶⁵ <http://www.finalfrontierdesign.com/r-and-d/>

⁶⁶ [http://us8.campaign-archive2.com/?u=b41deb1641138c3249b50ff28&id=c3987e8044&e=\[UNIQID\]](http://us8.campaign-archive2.com/?u=b41deb1641138c3249b50ff28&id=c3987e8044&e=[UNIQID])

⁶⁷ Richard Garriott, private astronaut to ISS, Interview with Space Angels, July 2016

⁶⁸ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016

⁶⁹ <http://news.mit.edu/2014/second-skin-spacesuits-0918>

⁷⁰ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016

⁷¹ Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness, Ford, S., United States International Trade Commission, Journal of International Commerce and Economics, Sept. 2014



anywhere (even in orbit), reduces the requirements to carry inventory and allows repairs to be undertaken or new designs to be implemented in space.⁷²

Wearable Tech

Wearable Tech is gaining traction on Earth, but it also has the potential to improve pressure suit design in orbit. An astronaut using a HUD with Augmented Reality⁷³ will benefit from greatly increased safety and efficiency. They will be able to connect with experts on Earth and will be able to see manuals and instructions projected onto a helmet display. The effective use of such technology will also generate a large competitive advantage for space tourism operators. An ability to display flight data and project information about areas of interest on a customer's helmet visor could be a desirable product enhancement for customers.



Figure 15 - Concept Design of a Spacesuit HUD

Advanced Materials

The evolving properties of cutting-edge materials is continuing to reduce weight, increase strength, and allow tailored material solutions for pressure suit design. Innovation in materials used to manufacture pressure suits will allow lighter, safer and more versatile suits. This opens the door for competitive advantage for manufacturers, especially when considering the high cost of launching each kilogram into orbit⁷⁴ and the safety factors of operating in orbit.

Space Dive

Space diving is essentially a skydive undertaken from above the Kármán line (an altitude of 100km), although there are a number of more complex issues than during a skydive. The pressure suit that would be required for such an activity would need to provide life support systems for the wearer, similar to an EVA suit, as well as being robust enough to resist the extreme conditions of the upper atmosphere and re-entry.⁷⁵ The two most common uses envisaged for a space diving suit are space diving tourism and emergency escape from orbital spacecraft.



Figure 16: Red Bull Stratos Dive (2012). Credit: Red Bull Stratos



Figure 17: StratEx Space Dive (2015). Credit: Stratex



Figure 18: Re-entry Suit Concept Art. Credit: dfacto (via Gizmodo)

Interfaces and Integration

Human Interfaces (Human – Suit)

A constant issue with pressure suits is the lack of dexterity that a wearer is able to achieve. As pressure suits and spacecraft become more technologically advanced, past methods of controlling the digital

⁷² Suited for Spacewalking, NASA, EG-199803-112-HQ

⁷³ www.microsoft.com/hololens

⁷⁴ http://www.nasa.gov/centers/marshall/news/background/facts/astp.html_prt.htm

⁷⁵ Tourists in Space: A Practical Guide, Erik Seedhouse, Springer Science & Business Media, 2008



systems on board will not be adequate. Manufacturers who are able to design novel and effective control interfaces for complex human-computer interaction, including voice and gesture control, will have a more effective product.

Wi-Fi and Connectivity (Suit – Ship Software)

As the digital capabilities of pressure suits and spacecraft increase, so will the connective capabilities of the hardware that ensures up-to-date information is passed between Earth, spacecraft, and suit. The increased connectivity of pressure suits will be a greater priority for commercial operators who are looking for a competitive advantage to lure customers in a limited marketplace. Utilizing high speed Wi-Fi and GPS to provide spacecraft and location data to astronauts, as well as instructions to workers or video conferencing to experts, all in an augmented reality format.



Figure 19: Astronaut Scott Kelly wearing Microsoft HoloLens aboard ISS

Physical Integration (Suit – Ship Hardware)

The ability of an IVA suit to integrate with different spacecraft will affect the usability and salability of a pressure suit system. The point of integration between the pressure suit system and a spacecraft may vary a lot depending on design. This problem is amplified when different companies and design teams work independently. It is further exasperated when space tourism is considered because the size of the participants and, therefore the size of the pressure suit and the locations of the connections, may vary widely on every flight. The spacecraft cannot be modified for each flight and the presence of many tubes and pipes may affect the experience of a commercial tourism flight. New methods of integrating the pressure suit with the controls, the systems, the seat and the spacecraft are necessary to meet the new requirements of commercial and tourism space flight.

Airlock Spacesuits (Suit – Vehicle Hardware)

More recent pressure suit designs have incorporated a rear entry hatch that allows the pressure suit to ‘dock’ with another spacecraft.⁷⁶ There are benefits to this type of suit design including no wasted air due to venting an airlock to reduce pressure and ease of donning the pressure suit.⁷⁷ There are also disadvantages in that a hard flange currently needs to be designed into the back of the suit (or life support backpack) for docking.



Figure 20: A NASA diagram of an Airlock Spacesuit docked with a rover

⁷⁶ <http://www.space.com/18998-nasa-z-1-spacesuit-graphic.html>

⁷⁷ <http://www.space.com/25708-how-nasa-z2-spacesuit-works-infographic.html>



Market

Overview

Since 2001, there has been a continual human presence in space aboard the ISS, which is currently the primary market driver. There are up to six passengers aboard the ISS at any given moment and seat allocations go to those countries who contributed to its development and ongoing operations. Russia has three seats that is increasing to four, the US typically has two seats, and Japan, Canada and the EU rotate among the last seat.⁷⁸ This limited number of seats has created a restricted market, with a low-volume of spacesuits required for operations, and customers with strong buying power. It also means that primary customers have been governments.

Market Value

The market value is driven by EVA suits, but there are far more IVA suits sold. EVA suits have historically been over 50 times more expensive. LEO EVA suits drive the market value before 2025 beginning with the Chinese Tiangong 2, 3 and Bigelow's B330, which are all expected to become operational before 2022. Further into the future, the value is driven by Beyond LEO EVA suits operated by NASA's cis-lunar missions, SpaceX's Mars missions, ESA's lunar missions and Lockheed's planned mars mission.

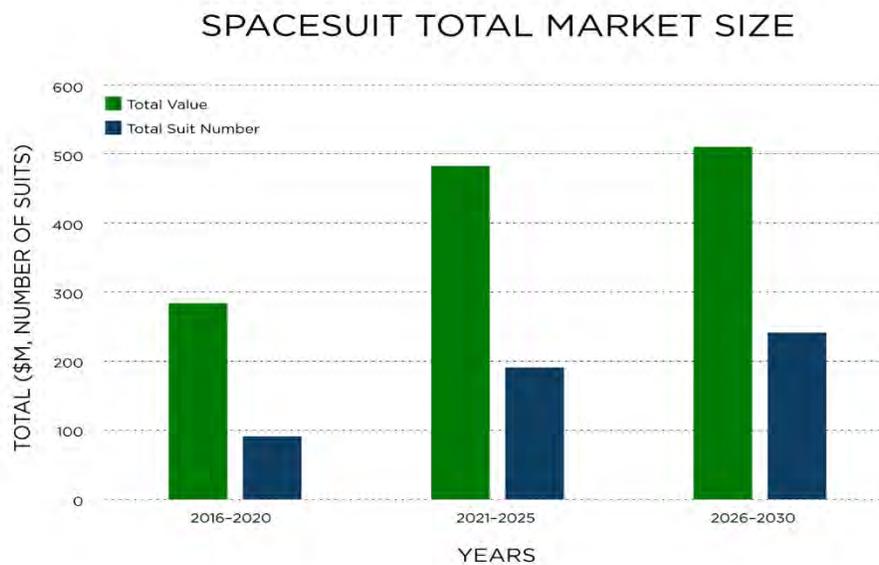


Figure 21 - Size of the Spacesuit Market through 2030 as determined by research of this report

Sub-orbital, near space and space diving add to the market, but they are not market drivers. Even if Virgin Galactic and/or Blue Origin were to utilize IVA suits, the product would still make up only a small fraction of the total due to the low cost relative to EVA suits.

Market Drivers: Location, Location, Location

Since the beginning of the space industry, there have been only two major customers for human spaceflight equipment: NASA and ROSCOSMOS. The European Space Agency (ESA) have used ROSCOSMOS equipment and the China Aerospace and Technology Corporation (CASC), while only a

⁷⁸ Memorandum of Understanding between the National Aeronautics and Space Administration of the USA and the Russian Space Agency Concerning Cooperation on the Civil International Space Station, 1998



recent customer, has also heavily relied on Russian equipment. The small number of traditional customers and small volume of sales has led to significant customer power and a few competitors: ILC Dover, David Clark, and NPP Zvezda.

In addition to few institutional customers, designs have a very long lifetime which leads to only a few companies with successful tenders winning contracts for 20 or more years. Often, pressure suits are designed for use in a particular vehicle, and a design will be unlikely to change during the life of that vehicle. For example, the Extravehicular Mobility Unit (EMU) used for EVA missions on the Shuttle or the ISS was introduced in 1981 and has undergone one incremental design change since then.⁷⁹ The ACES, used during Shuttle missions as an IVA suit, was a direct decedent of pressure suits used during the Gemini missions.

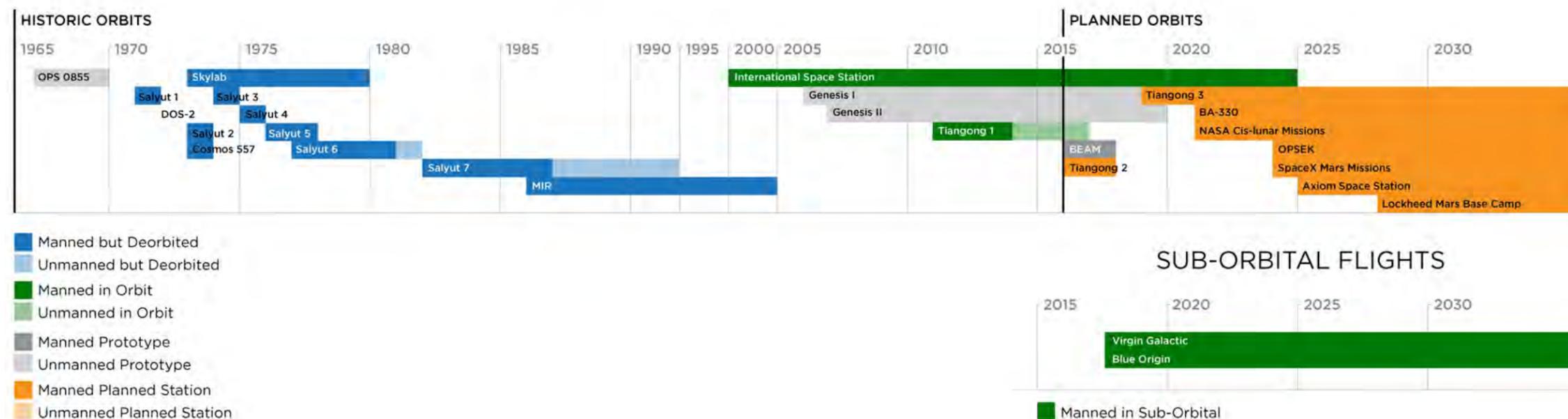
The variable that will most likely result in significant changes to the size of the market is availability, accessibility, and timelines for when new destinations come online. Destinations drive demand for IVA, EVA, and Planetary suits. “There are a whole host of providers who will need EVA capabilities sooner, rather than later, and for this market there is currently one provider in the United States, one in Russia, and one in China”.⁸⁰ Therefore, the timeline when these destinations are operational is the dominant factor in determining the size of the pressure suit market, both in volume and value. There are a number of potential destinations that have been identified as becoming operational before 2030:

The Commercial Crew Space Act Agreement (SAA) has enabled two new vehicles/companies – SpaceX with its Dragon capsule and Boeing with its CST-100 Starliner – to transport astronauts to the ISS. Both companies are expected to begin operations in 2017.⁸¹ SpaceX is developing their own spacesuits, while Boeing plans to purchase suits from David Clark.⁸² This report assumes that commercial transport providers will provide the necessary IVA suits and training as part of their service offering, because the suit constitutes so much of the customer experience and because the IVA suits must interface with the vehicle.⁸³

The United States, Russia, Japan, and ESA agreed to extend their support of the ISS to 2024.⁸⁴ However, the ISS will likely be decommissioned after that date. “We’re going to get out of ISS as quickly as we can,” said William Gerstenmaier, NASA’s chief of human spaceflight. “Whether it gets filled in by the private sector or not, NASA’s vision is we’re trying to move out [beyond LEO].”⁸⁵ With that said, it does appear that the private sector will be prepared to fill that gap in the market by 2024.

ROSCOSMOS has recently suffered a 30% budget cut, over the next decade, which has resulted in delays or cancellation of a number of projects, including human space flight programs.⁸⁶ The planned manned moon flight has been delayed until 2035 and a reusable space rocket has been abandoned

MANNED SPACE STATIONS AND PROTOTYPE STATIONS (LOW EARTH ORBIT & BEYOND EARTH ORBIT)



⁷⁹ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

⁸⁰ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016

⁸¹ <http://spaceflightnow.com/2015/01/27/boeing-spacex-on-track-for-commercial-crew-flights-to-station-in-2017/>

⁸² <http://www.inc.com/oscar-raymundo/elon-musk-to-unveil-spacex-mars-ship-spacesuit-2015.html>, <http://spacenews.com/boeing-to-unveil-crew-spacesuits-for-cst-100-test-flight-this-summer/>

⁸³ <http://spacenews.com/boeing-to-unveil-crew-spacesuits-for-cst-100-test-flight-this-summer/>

⁸⁴ http://global.jaxa.jp/press/2015/12/20151222_iss.html

⁸⁵ <http://arstechnica.com/science/2015/12/nasa-official-warns-private-sector-were-moving-on-from-low-earth-orbit/>

⁸⁶ <http://www.reuters.com/article/us-russia-space-idUSKCN0UY271>



still planned to be used on the ISS from 2016. A major project that may not face delays, and will require pressure suits, is the Russian Orbital station (ROS)⁸⁷, formally OPSEK.⁸⁸ The station is planned to reuse three of the Russian ISS modules and the 2024 decommissioning of the ISS will restrict the timeframe of this project.



Figure 22: Inside Soyuz. Credit NASA



Figure 23: Inside SpaceX v2

Bigelow Aerospace, a commercial space company based in Nevada USA, is developing the BA-330, an inflatable habitat. It is a design evolved from NASA's TransHab habitat concept from the 1960s, which will serve as a commercial replacement for the ISS. We assume that the BA-330 station, similar to the ISS, will require one or two EVA suits on board for construction and maintenance. Bigelow's inflatable habitats are also planned for moon habitation. The company has indicated that the habitat could be launch-ready by 2017.⁸⁹ A precursor to the BA-330, the Bigelow Expandable Activity Module (BEAM) was launched to the ISS inside the unpressurized trunk of a SpaceX Dragon during the 2016 SpaceX CRS-8 cargo mission. It was successfully installed in the ISS and inflated on 28th May 2016.^{90,91}

Another commercial station is in the early planning stages by Axiom Space and Mark Sufferdini (former NASA ISS Manager). The company is in discussions to attach a commercial module to the ISS that will become flight rated in 2021.⁹² It will detach and become the core of a new private commercial space station once the ISS is decommissioned in 2024. The company plans to attach a range of other modules to the core module to create a capable private space station. There have also been other commercial space stations proposed for the next century, and there will likely be more. One station of note is the Orbital Technologies 'Commercial Space Station' that was publicized in 2010.⁹³ The station was envisioned as a space hotel and orbital laboratory that would orbit near the ISS.⁹⁴ Orbital Technologies and the CSS have not been heard from since 2011. Although it appears unlikely that Orbital Technologies will launch the CSS, other commercial space stations will increase demand for pressure suits.

⁸⁷ <http://www.popularmechanics.com/space/a21543/russian-plan-new-space-station-iss/>

⁸⁸ <http://www.themoscowtimes.com/article.php?id=511299>

⁸⁹ <http://www.space.com/32541-private-space-habitat-launching-2020.html>

⁹⁰ <http://www.space.com/32600-beam-experimental-inflatable-room-space-station.html>

⁹¹ <https://blogs.nasa.gov/spacestation/2016/05/28/beam-expanded-to-full-size/>

⁹² <http://spacenews.com/former-nasa-iss-manger-planning-commercial-space-station-venture/>

⁹³ <http://www.space.com/9223-world-commercial-space-station-planned-russia.html>

⁹⁴ <http://www.dailymail.co.uk/sciencetech/article-2026534/Commercial-Space-Station-Russian-firm-Orbital-Technologies-reveals-hotel-plans.html>





Figure 24 - Concept Images of the Orbital Technologies CSS. Credit: Orbital Technologies (L, R), Reuters (middle)

Also regarding Moon habitats, the new ESA Director, Johann-Dietrich Wörner, announced in January 2015 that the agency plans to begin construction of the first Moon habitat by 2030 – which it is calling ‘Lunarville’ – with the goal of supporting up to four astronauts at a time.⁹⁵ The project has also received interest from Russia.⁹⁶ NASA has expressed interest in a supporting role, but agency director Charlie Bolden has publicly announced that they will not take the lead on the mission.⁹⁷

China has steadily increased the budget for its space program at a rate of over 10% a year for the last decade. Tiangong is the space station program of the People's Republic of China, with the goal of creating a third generation space station, comparable to Mir. This program is autonomous and unconnected to any other international space-active countries.⁹⁸ As of January 2013, China is moving forward on a large multiphase construction program that will lead to a large space station around 2020, which will consist of a 20-ton core module, two smaller research modules, and cargo transport craft.⁹⁹ The Chinese have successfully tested the Long March 7 rocket¹⁰⁰ that will be critical in the construction of its space stations; it is the most powerful rocket developed by the Chinese. Tiangong 2 has also recently been transferred to a Jiuquan Satellite Launch Center and is expected to launch in September 2016.¹⁰¹ The ISS required a number of spacewalks during construction¹⁰² and the same is assumed for Tiangong 3, implying they will require a number of Chinese EVA pressure suits. It will support three astronauts for long-term habitation and is scheduled to be completed just as the ISS is



Figure 25: Tiangong-3 Space Station Concept. Credit: Bisbos.net

⁹⁵ <http://www.businessinsider.com/european-space-agency-plans-to-build-lunarville-moon-habitat-in-2024-2015-6>

⁹⁶ <http://www.bbc.com/news/science-environment-34504067>

⁹⁷ <http://www.space.com/29285-moon-base-european-space-agency.html>

⁹⁸ <http://www.theguardian.com/world/2011/apr/26/china-space-station-tiangong>

⁹⁹ http://usa.chinadaily.com.cn/china/2016-04/29/content_24957452.htm

¹⁰⁰ <http://spaceflightnow.com/2016/06/25/chinas-new-long-march-7-rocket-successful-on-first-flight/>

¹⁰¹ http://news.xinhuanet.com/english/2016-07/10/c_135501915.htm

¹⁰² http://www.nasa.gov/mission_pages/station/structure/iss_assembly.html



retired.^{103,104} A Chinese official has also stated a desire to land astronauts on the lunar surface, although it will not be before 2036.¹⁰⁵

NASA is preparing for a manned Mars mission in the 2030s¹⁰⁶, or even earlier assuming Lockheed Martin's 2028 plan¹⁰⁷ is endorsed and executed by NASA. NASA is also planning a one-year manned cis-lunar mission in the early 2020s (at Lagrange Point 1) in preparation to slingshot to Mars.^{108,109} These goals will exclude the option of NASA returning to the lunar surface.¹¹⁰ Speaking in Hong Kong during the last week of January 2016, Elon Musk said that he was planning SpaceX's first missions to Mars in 2025.¹¹¹ Suits to support humans in the Martian environment are already in development. Recently, United Launch Alliance (ULA), a joint venture between Boeing and Lockheed Martin, outlined CS-1000, a vision to have 1,000 humans living and working in space by 2030.¹¹²

Suborbital spaceflight is expected to begin in the very near future, with a choice between rocket and spaceplane. In November 2015, Blue Origin completed a huge milestone when the company successfully landed the crew capsule and propulsion module of its New Shepard vehicle, designed to transport six paying passengers past 100km and into space.¹¹³ The company plans to begin commercial suborbital research flights in Q2 2016.¹¹⁴ However, a date for human suborbital spaceflight aboard Blue Origin's New Shepard vehicle has not yet been announced, the founder announced the company will likely take paying customers in 2018.¹¹⁵ Suborbital spaceplanes are expected to launch in the next 1-2 years as companies such as Virgin Galactic near commercial operations; XCOR Aerospace recently put development of the Lynx sub-orbital space plane on hold.¹¹⁶

Near-space balloon tourism is also expected in the near future. Companies such as World View Enterprises and Zero 2 Infinity are developing pressurized capsules that will lift to 100,000 feet by balloon.¹¹⁷ While IVA suits will most likely be required for testing purposes, it is unclear whether these providers will require IVA suits among passengers during commercial flights.

"Price tag would be the only thing preventing me doing a Gagarin. Drop the cost and count me IN!"¹¹⁸ As public perception of human spaceflight increases, more people will likely want to experience it whether by purchasing a ticket to space, training at a center such as NASTAR in Pennsylvania, visiting museums and spaceflight exhibitions, or paying for the experience of donning a spacesuit. "I would absolutely travel to space again, price dependent, on-board a government or commercial certified operator, both are just fine."¹¹⁹

¹⁰³ <http://www.space.com/11048-china-space-station-plans-details.html>

¹⁰⁴ <http://www.spaceflightinsider.com/missions/human-spaceflight/china-reveals-design-planned-tiangong-3-space-station/>

¹⁰⁵ <http://www.reuters.com/article/us-china-space-moon-idUSKCN0XQ0JT>

¹⁰⁶ <https://www.nasa.gov/content/nasas-journey-to-mars>

¹⁰⁷ <http://www.spaceflightinsider.com/organizations/lockheed-martin-organizations/lockheed-martin-outlines-plan-to-send-humans-to-mars-orbit-by-2028/>

¹⁰⁸ <http://spacenews.com/nasa-developing-plans-for-human-missions-to-cislunar-space-in-2020s/>

¹⁰⁹ <http://www.spaceflightinsider.com/organizations/orbital-sciences-corp/orbital-atk-proposes-lunar-orbit-habitat/>

¹¹⁰ <http://www.space.com/31835-nasa-needs-single-mission-goal-congress.html>

¹¹¹ <http://money.cnn.com/2016/01/30/news/companies/spacex-elon-musk-mars-2025/>

¹¹² <https://www.youtube.com/watch?v=uxftPmpt7aA>

¹¹³ <https://www.blueorigin.com/astronaut-experience>

¹¹⁴ <http://spacenews.com/blue-origin-plans-to-begin-commercial-suborbital-research-flights-in-2016/>

¹¹⁵ <http://www.abc.net.au/news/2016-03-10/paid-trips-to-space-likely-in-2018,-blue-origin-boss-says/7236030>

¹¹⁶ <http://spacenews.com/xcor-lays-off-employees-to-focus-on-engine-development/>

¹¹⁷ <http://worldviewexperience.com/voyage/>

¹¹⁸ Trevor Beattie, Adman, Movie Producer, Future Astronaut; Interview with Space Angels Network, July 2016

¹¹⁹ Richard Garriott, private astronaut to ISS, Interview with Space Angels Network, July 2016



Market Segmentation

There are a number of different customers in the pressure suit market who perceive the industry differently. They have very different operational requirements, cost expectations, and supply chains. In order to understand the market, we have segmented it to account for the requirements of the different customers and to target those customers and determine the market size.

The first segmentation is made between the uses of the suits: operational versus training suits. This is due to the prices of the suit types driving the size of the market. Operational suit sales will be based on the number of flights or the requirement of the relevant destination. Training suits, on the other hand, will be kept in a reusable inventory at training facilities and will only be replaced as they wear out.



Figure 26 - Segmentation of Pressure Suit Market Customers

The second segmentation is the region of space that the mission will travel to beyond LEO, orbital (LEO), sub-orbital, near-space, and space dive. The destination has a disproportionate effect on the number of pressure suits required because the number of flights that will be purchased by the operator and the company that will be providing the flights will differ significantly. Further different regions of space will require varying mission outcomes which will change the requirements of the suits necessary to undertake the missions.

The final segmentation is between IVA, EVA, and Environment suits due to the fundamental cost and function differences them. There are also different assumptions regarding each suit type, which make it a logical distinction.



Figure 27 - Further Segmentation of Pressure Suit Market Customers



Market Size

In general, it is assumed that an operational IVA suit is used once for a flight and not used operationally again, due to the critical nature of the suit. In normal flying conditions, the suit is un-pressurized but will pressurize in an emergency. It will be required to work first time, without fail, and will only be used for a single flight. It is further assumed that private astronauts will purchase their IVA suits as a memento if, according to private astronaut Richard Garriott, “the price remains a small fraction (ie. < 10%) of the total flight cost”.¹²⁰

Beyond LEO

This report believes there are three potential destinations beyond LEO currently in development: cis-lunar space, the lunar surface, and the Mars surface. To-date, only government agencies and SpaceX have announced plans to send humans into deep space before 2030.

NASA’s Cis-Lunar Space Station is planned to be in orbit by 2020 and occupied by 2021¹²¹, ROSCOSMOS and ESA are intending to launch missions to the Moon in the near future¹²² and SpaceX and NASA have expressed their intent to go to Mars.^{123,124} Of these, it is likely that only NASA’s cis-lunar station, the SpaceX Mars missions, and Lockheed’s Mars plan¹²⁵ will launch before 2030¹²⁶. There are three spacecraft that could service these destinations, Soyuz, Dragon, and Orion.

It is assumed that NASA will service the cis-lunar space station bi-annually, after an initial flight in 2021, with the Orion spacecraft. Assuming NASA endorses Lockheed’s Mars plan, the ‘Mars Base Camp’ will also be serviced by the deep space Orion spacecraft with annual flights from 2028. SpaceX will use the Dragon capsule series to reach Mars and this report has assumed the company will meet its 2025 timeline and launch an annual flight thereafter. The report has assumed that a space station will require three EVA suits (similar to the ISS) and that a planetary based location will have at least one Planetary EVA suit per astronaut. Therefore, it is assumed that SpaceX will have five suits for the five occupants of a Dragon capsule.

Orbital (LEO)

NASA recently announced that it will be ceasing operations in LEO after the decommissioning of the ISS. From a US perspective, this leaves the LEO region to commercial space companies from 2024¹²⁷. Both ROSCOSMOS¹²⁸ and the Chinese Space Agency¹²⁹ are planning to operate space stations in LEO, but so are American companies with NASA’s departure.

This report assumes that the ISS continues to operate normally, an average of four crewed flights per year, until decommission in 2024. From 2017, the flights will change from being all Soyuz spacecraft to being a combination of Soyuz, Dragon, and Starliner¹³⁰. The ROS station is assumed to come online

¹²⁰ Richard Garriott, private astronaut to ISS, Interview with Space Angels Network, July 2016

¹²¹ <http://www.spaceflightinsider.com/organizations/orbital-sciences-corp/orbital-atk-proposes-lunar-orbit-habitat/>

¹²² <http://www.bbc.com/news/science-environment-34504067>

¹²³ <http://money.cnn.com/2016/01/30/news/companies/spacex-elon-musk-mars-2025/>

¹²⁴ <https://www.nasa.gov/content/journey-to-mars-overview/>

¹²⁵ <http://www.spaceflightinsider.com/organizations/lockheed-martin-organizations/lockheed-martin-outlines-plan-to-send-humans-to-mars-orbit-by-2028/>

¹²⁶ <http://www.reuters.com/article/us-russia-space-idUSKCN0WJ1YJ>

¹²⁷ <http://www.wired.co.uk/news/archive/2015-12/08/nasa-iss-2024-return-to-moon>

¹²⁸ <http://spaceflights.news/?p=29258>, <http://tass.ru/en/science/866011>

¹²⁹ <http://www.popularmechanics.com/space/a14480/china-space-station-2016-tiangong-2/>

¹³⁰ <http://www.nasa.gov/press/2014/september/nasa-chooses-american-companies-to-transport-us-astronauts-to-international>



after the ISS is decommissioned and will sustain two Soyuz flights in 2024 and four flights thereafter. ROS is assumed to have the same ratio of EVA suits as the ISS, three Orlan EVA suits.

Tiangong 2 is planned to be launched in September 2016. It will then be replaced by China's Tiangong 3 Space Station in LEO beginning in 2018.^{131,132} This larger station, which is due to become operational in 2022, will initially host a single flight in 2022 and then build up to three flights per year. All flights will be undertaken with China's Shenzhou spacecraft. Both Tiangong stations are assumed to house two EVA suits during operations.

The first commercial space station, operated by Bigelow Aerospace, is planned to become operational in 2021¹³³, following the successful deployment of the BEAM prototype module on the ISS in mid-2016 to the ISS's Tranquility module.¹³⁴ Commercial flights will begin with the Dragon and Starliner spacecraft immediately and build up to twelve flights per year by 2030. Bigelow is assumed to house five EVA suits, at least two for operation and maintenance of the station and the remaining for experimental and commercial activities. Alongside commercial customers, a large component of Bigelow customers will be made up of emerging government space agencies who want a presence in orbit but lack the capabilities to launch astronauts.

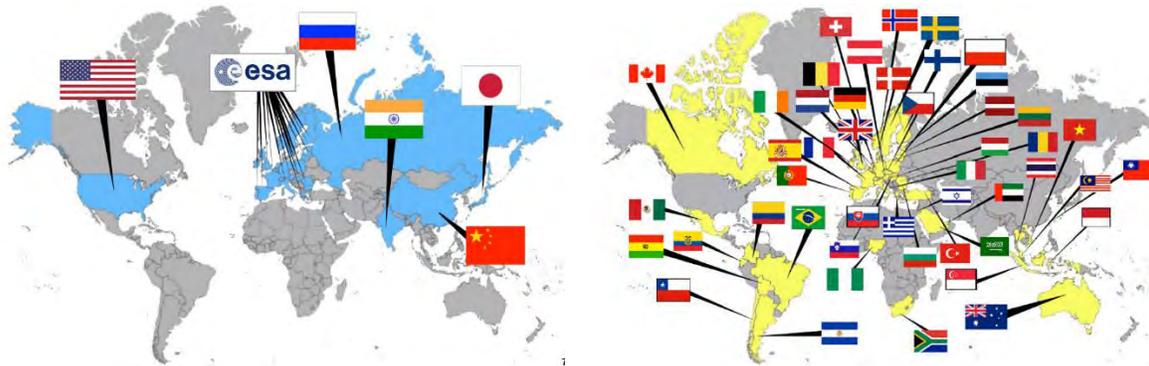


Figure 28 - (Left) Established space agencies (Right) Emerging space agencies. Credit: Astrobotic

The Axiom station is assumed to be a similar size to Bigelow. It will cater to similar customers and will have the same IVA and EVA suit usage and early flight requirements, although beginning later in 2024. The station is not assumed to increase manned flights to the ISS pre-2024.

It is assumed that private astronauts will view government and commercial operators indifferently. All else equal, private astronauts are likely to prefer shorter training and enhanced amenities. Richard Garriott tells us that, “A reduction in training time, from the current six months, would increase consumer interest, more so than any ‘luxury’ amenities offered by commercial operations.”¹³⁵ “I think there's a world (pun intended) of difference between the suborbital and orbital experiences. And the people who'd wish to participate. I'm not sure that many of those signing up for the suborbital "Thrill Ride" would be willing to put up with what it takes to go for The Full Orbital Monty. The lengthy training, I could handle, the food I'd put up with, the learning of Russian I'd struggle with, the view I'd be forever inspired by...the cost would scare me to death.”¹³⁶

¹³¹ <http://spacenews.com/chinas-space-station-planners-put-out-welcome-mat/>

¹³² <http://www.spaceflightinsider.com/missions/human-spaceflight/china-reveals-design-planned-tiangong-3-space-station/>

¹³³ <http://www.space.com/32541-private-space-habitat-launching-2020.html>

¹³⁴ <http://spacenews.com/nasa-urged-to-develop-post-international-space-station-strategy/>

¹³⁵ Richard Garriott, private astronaut to ISS, Interview with Space Angels, July 2016

¹³⁶ Trevor Beattie, Adman, Movie Producer, Future Astronaut; Interview with Space Angels Network, July 2016



Sub-Orbital

Sub-orbital space offerings from commercial companies are nearing operations. We don't expect to see government operations in the future as national space agencies concentrate on LEO space stations and beyond. Commercial sub-orbital flights will have different requirements than orbital and will therefore require a different type of pressure suit, if any at all.

Two operators are likely to be flying commercial suborbital flights in the near future: Blue Origin in 2018¹³⁷ and this report assumes that Virgin Galactic¹³⁸ will launch in a similar timeline. It is assumed that there will be no pressure suits used on these sub-orbital flights. Virgin Galactic has announced the use of flight suits¹³⁹ and Blue Origin's flight experience video shows flight suits instead of pressure suits¹⁴⁰.

It should be noted that both the Soviet Space Program and NASA have also sent astronauts into space without an IVA suit, during the beginning of the Soyuz program (Soyuz 1 – 11) and the beginning of the shuttle program (STS-1 through STS-51L, 25th flight). In both instances, after loss of crew during Soyuz 11¹⁴¹ due to accidental decompression during re-entry, and during STS-51L¹⁴² due to loss of launch vehicle, space agencies chose to reinstate IVA suits for emergency use. Nevertheless, "I wouldn't expect to fly in a pressure suit on a suborbital trip. The craft itself would act as my pressure suit. I'd prefer the freedom of a more down-to-earth 'Overalls Outfit', akin to that worn on Zero-G flights."¹⁴³ At this stage, suborbital pressure suits have not been included in market sizing exercises.

Near-Space

Near-space experiences will be similar to sub-orbital flight in terms of lower altitude, but will be achieved with different vehicles and will also likely demand a unique type of suit. These flights will likely remain exclusively commercial as well. World View Experience¹⁴⁴ and Zero2Infinity¹⁴⁵, for example, will use a balloon instead of a rocket for a longer, slower flight. Currently, near-space flights are likely to reach around 100,000ft altitude, well above the requirement for a pressure suit but all companies are planning to conduct flights in normal clothes and hence they have not been included in these market sizing exercises.

Space Diving

Space diving, entering free fall from above the Kármán line (100km altitude) and finishing by parachuting to Earth, will obviously require its own type of EVA suit. The suit will be designed for falling and surviving the high temperatures of re-entry through the upper atmosphere, at speeds faster than the speed of sound. Space diving from orbit is also a possibility, but will require radical enhancements to the suits used. There are currently no companies, who have raised funding, publicly vying to be the first commercial provider of space dives but it is a gap in the market that could be filled by a near-space provider or extreme sports operator. This report assumes that before 2020 at least one company will begin testing a space dive business and will be offering a single space dive each year after 2020. Suits will need to be very robust and will likely survive multiple space dives.

¹³⁷ <http://www.reuters.com/article/us-space-bezos-idUSKCN0WB00T?feedType=RSS&feedName=scienceNews>

¹³⁸ <http://www.virgingalactic.com/>

¹³⁹ <http://www.virgingalactic.com/virgin-galactic-and-y-3-announce-exclusive-space-apparel-partnership/>

¹⁴⁰ <https://www.blueorigin.com/astronaut-experience>

¹⁴¹ <http://www.spacesafetymagazine.com/space-disasters/soyuz-11/crew-home-misfortunes-soyuz-11/>

¹⁴² US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

¹⁴³ Trevor Beattie, Adman, Movie Producer, Future Astronaut; Interview with Space Angels Network, July 2016

¹⁴⁴ <http://worldview.space/voyage/>

¹⁴⁵ <http://www.inbloon.com/en/near-space-flight.php>



Training Suits

Spacecraft operators are assumed to be the companies operating training facilities until at least 2030. These training facilities are assumed to have enough IVA suits to run a full spacecraft simulation. Each operator will have the same number of training suits, equal to their particular spacecraft. For example, SpaceX's Dragon capsule will have seven crew and therefore the training facility will have an inventory of seven training IVA suits.

Training EVA suits will operate within the same parameters. In order to undertake a full simulation, the training facility will require at least the same number of suits that the destination intends to operate. The EVA training facilities will likely be operated by governments instead of commercial station operators, though the commercial companies are expected to supply the EVA suits.



Figure 29 - An employee of the Russian Space Training Center hangs space suits (AP Photo/Alexander Zemlianchenko)

Analogy Environments

There are a number of experimental facilities around the globe that operate as if they are on the surface of another planet, for example, the Mars Desert Research Station¹⁴⁶ and NASA's Houghton Mars Project.¹⁴⁷ They study the effects of planetary environments on human bodies. Many of the analogue sites incorporate 'EVA simulation' activities with suits that are often very similar to actual EVA suits.



Figure 30 - Mars Desert Research Station



Figure 31 - Flashline Mars Arctic Research Station

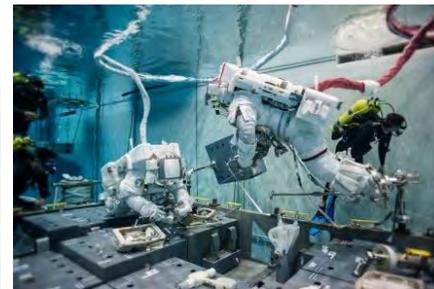


Figure 32 - NEEMO (NASA Extreme Environment Mission Operations)

Market Supply Chain

The supply chain for each government and commercial customers will remain differentiated since each customer type will require a different approach from the manufacturer and the product.

Government Sector

Governments have historically owned and operated the entire value chain, including space-based destinations and the launch vehicles that go there. Although commercial companies are beginning to

¹⁴⁶ <http://mdrs.marssociety.org/>

¹⁴⁷ https://www.nasa.gov/exploration/humanresearch/analogs/research_info_analog-houghton.html



play a larger role in human spaceflight, governments are likely to remain heavily involved in the value chain through 2030, including owning and operating pressure suits. This degree of control along with their size makes them a powerful market force.

Government agencies are unlikely to change their purchasing behaviors and they will continue to order pressure suits through design contracts. Agencies typically grant financial contracts to design a pressure suit to specifications, and then purchase them from the manufacturer. Operations are managed by the agency after purchase. There are benefits to this approach; the government agencies have more control over the design and are able to customize the suit, but results in the long term contracts that characterize the market today. This approach is being used to develop the Modified ACES IVA suit.¹⁴⁸ Much of this approach is a consequence of governments' aversion to risk. Undoubtedly governments prefer designs that are well tested. It is unlikely that they will be early adopters or even participate in the early majority, this presents an innovation barrier.

Regulatory barriers are also present in the industry, manufacturers in the United States are regulated by the International Traffic in Arms Regulations (ITAR) and the Export Administration Regulations (EAR) which restrict the manufacturing, sales, and distribution of technology to non-US citizens. Although pressure suits were recently moved from the ITAR to the EAR¹⁴⁹ (a less restrictive regulation), there may be restrictions on US companies that reduce the global market for spacesuits that is available to them. There is no historical precedent of restrictions on pressure suits, the growing commercial space sector will test these boundaries.

Commercial Sector

The commercial sector for pressure suits is nascent and is likely to take a different approach to the supply chain. Commercial companies will purchase tested pressure suits that are available for purchase 'off-the-shelf', their exposure to the design process will be limited. There are a number of benefits to this approach for the commercial sector: the design risk is borne by the pressure suit manufacturer, not the vehicle operator; the vehicle operator will be able to test the suit before committing; and overall cost will be lower as the market will be open and competitive at the expense of design control.

Commercial customers for suits will likely be the operators of different segments of a mission. They will seek ways to differentiate themselves from competitors. For example, SpaceX passengers will wear SpaceX branded pressure suits¹⁵⁰ and will become as much a part of the differentiation as the spacecraft. SpaceX will therefore would pay attention to pressure suit manufacturers that have differentiated innovations, and may be interested in purchasing the suits or acquiring the company.

Other market opportunities

Successful suit manufacturers have succeeded by offering a diversified suite of products, either closely or tangentially related to pressure suit technology, there are a number secondary industries available to manufacturers. For example, Final Frontier Design has a host of "terrestrial products" that they may sell, derived from "materials and manufacturing researched for NASA."¹⁵¹

¹⁴⁸ <https://www.nasa.gov/content/astronaut-spacesuit-testing-for-orion-spacecraft>

¹⁴⁹ Commerce Control List Supplement No.1 Part 744, U.S Department of Commerce, Bureau of Industry and Security, 2015

¹⁵⁰ <http://gizmodo.com/spacex-wants-future-astronauts-to-look-badass-in-spac-1735190895>

¹⁵¹ Ted Southern, President, Final Frontier Design, Interview with Space Angels Network, July 2016



Relative Market Size (\$ billions)

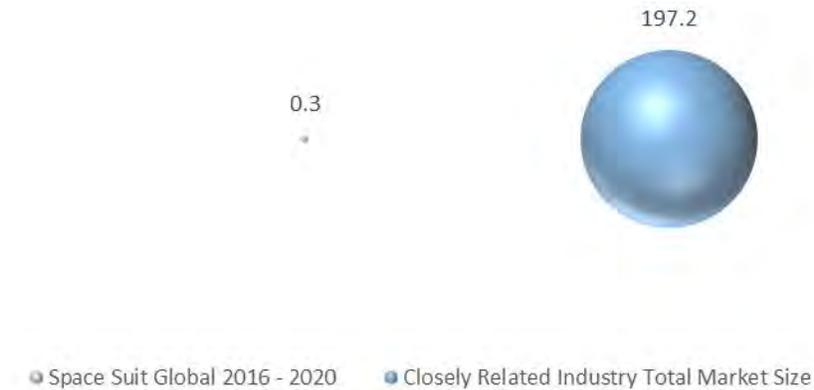


Figure 33 - Relative Market Size of the Pressure Suit Market between 2016 and 2020 compared to Identified Closely Related Industries (single year)

The relative sizes of secondary industries currently dwarf the pressure suit market, and will continue to do so for the foreseeable future. These industries can be segmented into services, closely related technologies, and tangentially related technologies.

Relative Market Size (\$ billions)

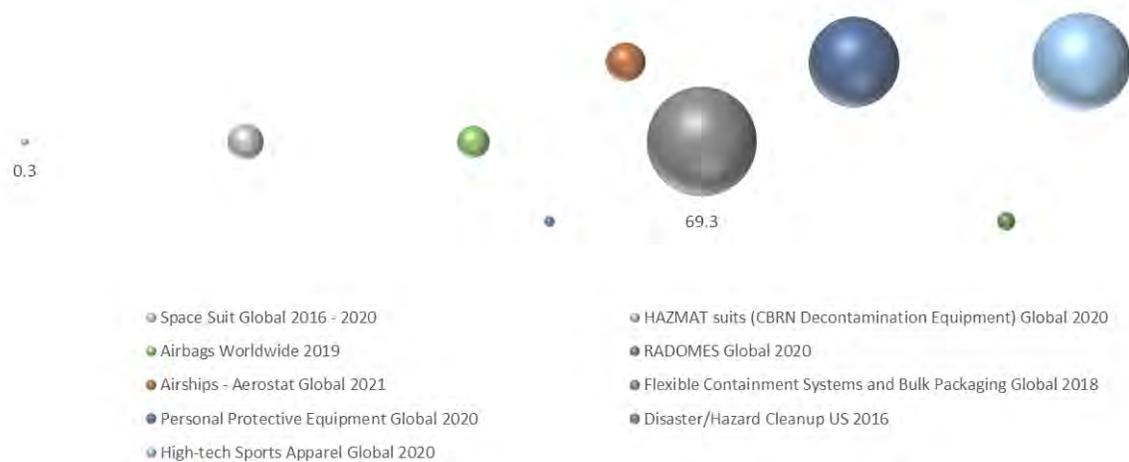


Figure 34 - Relative Market Size of the Pressure Suit Market between 2016 and 2020 compared to individual Identified Closely Related Industries (single year)

Services

There are a number of services that pressure suit manufacturers can offer in addition to the sale of the pressure suit themselves in order to diversify their offering into the service market.

Spacesuit Training

A pressure suit is a complex piece of technology and is unlikely to be operated successfully out of the box. This opens an opportunity for a suit manufacturer to offer continued training services for owners



of pressure suits. This would be a cross selling opportunity for existing customers, and increase customer engagement.

Spacesuit Fitting Experiences

A pressure suit manufacturer is in a position to offer customers who may not want or need to buy a pressure suit, an opportunity to wear a spacesuit. Selling experiences can diversify revenue streams for the manufacturer, whilst also increasing brand awareness.

Spacesuit Collectors

There is also an opportunity to capture the market segment relating to those who haven't flown but want to own a pressure suit. There is already a market for Sokol pressure suits and there is demand for Orange NASA suits (although none have been released to the private market).¹⁵²

Closely Related Technologies

Shown below, Figure 35, is a map of products made by competitors and how they relate to the capabilities required to develop pressure suits by how far they are from center.

HAZMAT Suits

Hazardous Materials, and other respiratory protection, suits offer many of the same features as an IVA or an EVA suit. They create a pressurized, sealed environment that protects the wearer from hostile elements. They need to be flexible and may require life support systems. Much of the technology required for EVA and IVA suits is applicable to HAZMAT suits. The size of the HAZMAT suit market is large as they are required by legislation in a number of industries including nuclear, pharmaceutical, hospital, military, and emergency services. For example, all fire stations in New South Wales, Australia have a HAZMAT capability.¹⁵³ They are generally purchased through government contracts.

G-Suit

During high acceleration maneuvers, humans are adversely effected by the changing acceleration forces. The same forces are felt by astronauts, military pilots and aerobatic pilots, and so G-Suits can be cross functional with minor modifications. The increase pressure on the legs and lower torso during the acceleration maneuver to force blood back into the wearers brain, thus avoiding a loss of consciousness and control. The suits are specialized and generally purchased by militaries for their aviators. Some suits are purchased by the public, and aerobatic enthusiast aviators.

Gravity Loading Countermeasure Skinsuit

The human body undergoes a number of adverse physical changes due to the lack of gravity during spaceflight. Although not a pressure suit, gravity loading suits compress the body from the shoulders down towards the feet thereby simulating the effects of gravity. Reducing the impact of low-gravity is critical to the success of deep space voyages. The suit is currently undergoing testing to determine its long-term effects. A market for this suit currently does not exist.

¹⁵² Tom Shelley, President, Space Adventures, Interview with Space Angels Network, June 2016

¹⁵³ <http://www.fire.nsw.gov.au/page.php?id=143>



Airbags

Airbags have been used alongside parachutes and rockets for planetary landings. Also called Impact Attenuation Systems (IAS),¹⁵⁴ these airbags use many elements of pressure suit technology. The bags need to be light, flexible, and also durable in the hostile environment of space.¹⁵⁵ It has been used before for Mars Rovers, but as the rovers increase in size and weight it may not be possible to use airbags to land.¹⁵⁶ They are purchased through contracts with rover operators, which have historically been NASA or ROSCOSMOS. Though the number of missions requiring a soft-landing is limited, this market may be lucrative in terms of margin. The same applications and technologies may be applied to soft-landings on Earth. This includes car airbags which is a substantially large market that continues to grow.



Figure 35 - Other Technologies and Products Map

RADOMES

Soft RADAR domes also require pressurized, flexible, and durable fabrics. They are constructed with inflated fabrics that protect sensitive equipment from hostile environments. The main customers are governments and militaries that have radar operations. Prospects in this market are narrow since there are many suppliers with low demand.

¹⁵⁴ http://mars.nasa.gov/mer/mission/tl_entry1.html

¹⁵⁵ <http://www.warwickmills.com/Protective-Fabrics-Mars.aspx>

¹⁵⁶ <http://www.space.com/16878-mars-rover-landing-sky-crane-guide.html>



Airships

Airships are constructed using many of the same materials used in pressure suits, such as the flexible fabrics used for the airship's body. There are many varieties of manned and unmanned airships in use today, including military observation¹⁵⁷, transport¹⁵⁸, exploration. It should be noted that many high profile projects do not reach completion. The sector has a large number of companies relative to the demand, and is characterized by low volume, high value contracts.

Flexible Containment Systems and Bulk Packaging

Containment systems used as laboratory equipment, pharmaceutical manufacturing equipment or bulk packaging have commonality with pressure suit technology - they provide protection from a specific environment. This sector has a number of companies but a comparatively larger number of diverse customers, it is characterized by large volume purchases. The market size of this sector is driven by global industries that use these materials to manufacture and transport sensitive goods. One US private equity group is known to have consolidated three companies in this sector.¹⁵⁹

Tangentially Related Technologies

Aviation Helmet, Flight Suit and Oxygen Systems

There are some similar design principles between aviation flight suits, helmets, and pressure suits. Specifically, the life-support and oxygen systems are similar.

Personal Protective Equipment

The design of personal safety equipment, from fireman bunker gear to search and rescue kits, could use elements of pressure suit design.

Disposable Clean-up Equipment (Disaster/Hazard Cleanup)

Durable, flexible materials may have benefits towards the design and manufacture of cleanup equipment such as disposal of asbestos and other hazardous materials from a disaster or construction/demolition site.

Sports Apparel

High performance sporting apparel could leverage pressure suit technology. For example, pressure suits may find use in extreme sports such as high altitude diving, and sports flying.



Figure 36 - Betabrand Space Jacket made with foil used on spacecraft (\$298)



Figure 37 - Spacelife Jacket 3i3s, space-inspired clothing (€1,750)



Figure 38 - 'Couture in Orbit' project: ESA, Science Museum, fashion schools

¹⁵⁷ <http://gizmodo.com/5366082/250-foot-long-hybrid-airship-will-spy-over-afghanistan-battlefields-in-2011>

¹⁵⁸ <http://dynalifter.com/>

¹⁵⁹ <http://www.delawarebusinesstimes.com/space-suit-maker-ilc-dover/>



Organization

Much of the focus of innovation is on the development of technology, but it is just as important to focus on the design of the organization itself and the innovation systems that it supports. An organization that is appropriately designed to achieve its goals will stand a greater chance of success.

Entrepreneurship is a necessary component in the diffusion of new ideas and innovation whether internally or externally of an organization. No one knows for certain which technologies will be adopted by the market, so the process of innovation is inherently risky. Luckily, there are a group of professionals, entrepreneurs and early-stage investors, who have made it their business to manage that risk. Their role is to bring together resources and interested parties so that each participant is within their risk threshold. Organizations need to be structured, to take advantage of these skills, to allow these individuals the greatest chance of success, and to take advantage of the potential competitive advantage.

The Diffusion of Innovation theory recognizes four main factors in the diffusion of new ideas: 1) innovation, 2) communication, 3) time, and 4) social system. Based on this theory, diffusion is largely dependent on distribution and not on the basis of scientifically validated capability. Diffusion occurs through the subjective evaluations of peers who have adopted the innovation. Failure to cross this adoption chasm is the difference between a successful and unsuccessful innovation. Therefore, entrepreneurs are essential to the process of diffusion since they are the ones who market and communicate the innovation.

Incumbents approach this problem with a different perspective since they have existing customers. Their role is to cross and up-sell new innovations by building proof points that compel the customers to adopt the advantages. This requires a different type of organization, one with a team that has authority to operate in a highly dynamic environment, approach new customers, new suppliers, and respond to ever-changing customer demands and price points.

There are a number of factors an innovative company will need to consider when creating enough demand for its product to cross the adoption chasm. These factors are captured in the ACCORD model, but the market characteristics of the pressure suit industry make it challenging to meet many of the factors and achieve a quick adoption rate. *Compatibility* can be a very hard hurdle to surmount as many vehicles are designed for use with a certain pressure suit. This can result in a new, innovative suit being passed over because it would result in an expensive redesign of a spacecraft. Pressure suits are also an inherently *complex* mechanism which reduces the ease with which they adopted. The *Riskiness* of implementing a new pressure suit is high given the cost of development and implementation, and the fact that it is human-rated safety equipment. A pressure suit is also very hard to trial without a flight test, which involves significant cost and lends pressure suits to low *Divisibility*.

Some factors of pressure suits, on the other hand, will generate positive adoption. An innovative suit with a true competitive *Advantage* will outperform the current design, since it does not have clear drawbacks like lack of maneuverability and lack of connectivity. The changes are also likely to be very *Observable*, even if they are harder to quantify.

An organization with the goal of high-volume production will require a different structure to that of a low-volume manufacturer building a complex product. The current pressure suit industry is characterized by long design lives, high levels of incremental development, and very low production



levels. Organizations therefore need to orient themselves around an organizational structure that is designed for high levels of innovation, but may sacrifice production efficiencies, and operational effectiveness.¹⁶⁰

Innovation Systems

The technology of the pressure suit industry is reaching the end of the design S-Curve, shown by decades of incremental design. A new entrant or incumbent will need to be organized for technological development in order to achieve a discontinuous design. This is already happening with the development of mechanical counter pressure suits and connected technology. Companies that are fostering such an organization may find use in the Process, Management, Organization Structure, and Culture framework.¹⁶¹

Process

An organization looking to drive towards a next generation pressure suit will need to have processes in place to achieve a quick prototyping and feedback cycle. The 'Knowledge Brokering Cycle'¹⁶² is an effective method to focus development and innovation within an organization. The cycle involves four steps:

1. *Capturing Good Ideas and Important Lessons* from various fields to solve specific problems
2. *Keeping Ideas Alive* by distributing them widely throughout the organization and with physical repositories accessible by all members of the team
3. *Imagining New Uses for Old Ideas* through interaction and rewards sharing
4. *Put Concepts to the Test* through numerous, cheap experiments, rapid prototyping, and fast feedback

Many of the steps of the Knowledge Brokering Cycle require extensive research into customer needs, and effective brainstorming. Needs-finding involves engaging customers at an early stage in the development process, during pre-design and testing, as well as post-development.¹⁶³ This is particularly critical for low-volume, high-margin models. Effective brainstorming requires a process of structure and goals that are linked to that of the organization. It should further be supported by the culture of the organization, generate group ownership of ideas, and rigorously evaluate ideas without criticizing the idea.¹⁶⁴

Management

An organization that accepts failure and embraces ever changing goals needs to be led, not managed, by individuals who believe in the same methodology. Management must accept that designs will change quickly and they may not be able to follow the details of each iteration. Moreover, they should feel in control of the process of innovation, as opposed to control of innovation itself.

Management needs to accept, and even embrace, the fact that the design process will generate prototypes that will not operate as expected. The non-dominant state of the technology in the industry

¹⁶⁰ What is Strategy? - Porter - Harvard Business Review 1996

¹⁶¹ Oxford University, Said Business School, Professor Marc Ventresca, Strategy & Innovation, Week 4 Lecture: Organizing for Innovation, Hilary Term 2013 / Hilary Term 2015

¹⁶² Building an Innovation Factory, Hargadon, A & Sutton, RI, Harvard Business Review 2000

¹⁶³ Customers as Innovators, Thomke, S & Hippel, E, Harvard Business Review 2002

¹⁶⁴ Oxford University, Said Business School, Professor Marc Ventresca, Strategy & Innovation, Week 4 Lecture: Organizing for Innovation, Hilary Term 2013 / Hilary Term 2015



will require a number of failures before a dominant design is reached. An important aspect of the failure is that the lessons learned must be captured and shared throughout the company so that the knowledge gained by the failure is not lost, but utilized in future designs.

The company management also needs to use and encourage Effectual Reasoning, rather than Causal Reasoning.¹⁶⁵ Effectual reasoning involves using existing resources for flexible and changing goals, while controlling losses.¹⁶⁶ The goals should not be limited to those set at the beginning of the process.

Organization Structure

The structure of an innovative organization is more often than not characterized by a flat hierarchy and small, diverse teams. Teams should be interconnected and formed based on the team's requirements, not the jobs of the team members. A team should not be made up of similar people, but people from many different backgrounds and experiences. For example, fabric specialists, physiologists, and both IVA and EVA specialists could form an EVA glove team. The teams should also take responsibility for prototyping and the ideas and designs that they generate.

During the innovation stage, ideas and solutions will need to flow quickly between teams. Communication should flow through the organization unhindered, which then enables the type of agile, quick prototyping, exploratory innovation that is required in a nascent industry.

Culture

The culture of the research and development team in a nascent industry will also be different from a traditional manufacturer. The design team will need to use Effectual logic to find solutions. They should evaluate their current resources and capabilities, and develop goals based on the current state as the end state is unknown.

The culture of the organization will need to be based around the exploration of new ideas in addition to the exploitation of current ideas and techniques.¹⁶⁷ The culture will need to be accepting of examining and prototyping new ideas, many of which will fail, and accepting that new ideas will not immediately produce a positive cash flow. Pressure suits are designed to protect human lives while astronauts are undertaking work, this inherently means that testing and approval of suits for flights should not be rushed or operationally prototyped. However, the testing and experimentation phase can progress rapidly to prove or disprove the value of the idea, before effort is spent during the approval process. Experimentation with new, non-routine ideas is in stark contrast to the drive towards operational excellence that typical manufacturers traditionally strive for.

Given an organization of many small, diverse teams, a culture of open communication is essential. Partial knowledge of every system should be attained by every team so that full system integration is achievable. An open communication culture is helped by the use of mixed teams. Discussing the results of failed prototypes and lessons learned is useful to further the organizational knowledge of the whole company.

There are a number of goals that a new entrant or incumbent in the pressure suit industry should strive for in order to take advantage of the design stagnation shown in the Technology section. To be successful in the pressure suit industry companies will need to innovate quickly, navigate a fast changing industry structure and keep pace with the advancing technology in the new space industry.

¹⁶⁵ Unpacking entrepreneurship as collective activity, Sarasvathy, S.D, Dew, N & Ventresca, M, 2008

¹⁶⁶ Knowing what to do and doing what you know: Effectuation as a form of entrepreneurial expertise, Sarasvathy, S.D, 2005

¹⁶⁷ Exploration and exploitation in organizational learning – March - 1991



Report Methodology

This report examines the past, present, and future traits of an increasingly dynamic market for spacesuits, or more generically, pressure suits. We examine specifically how the growth of the broader space industry is supporting the commercial pressure suit market. Our analysis relies upon 'Technology-Market-Organization' (TMO) framework developed by Professor Marc Ventresca from the University of Oxford.¹⁶⁸ Use of the TMO framework can provide strategic recommendations for taking advantage of a nascent market opportunity. This report will be of use to new entrants looking to enter the market, incumbents looking to adapt to changing market conditions, or financial investors seeking early investment in high-growth sectors.

The first section of this report delved into the history of the pressure suit market, from its early beginnings to the present day. The remaining sections of the report aligns to the TMO framework: grasping a technological understanding, observing the market dynamics, and developing an effective organizational structure. In the appendix, this report includes a survey of the current competitors in the market, beginning with the large incumbents, the new entrants, and other organizations that are developing horizon technologies, or working in less formal organizational structures. The types of suits covered in this report fall into three main categories: Intra-vehicular (IVA), Extra-vehicular (EVA), and Environment (Planetary).

This report also uses three methodologies to assess technology adoption: The Technology Adoption Lifecycle, the S-Curve model, and the ACCORD model. The Technology Adoption Lifecycle describes five stages of uptake during a technologies growth, as seen in Figure 39:

1. *Innovators* ("tech enthusiasts"): willing to take risks and try untested technology, even with the potential of failure and financial cost.
2. *Early-adopters* ("visionaries"): less willing to take risks but will try a tested technology before it is widely used or accepted.
3. *"The Chasm"*: a difficult gap to cross where a disruptive technology has proven successful with risk tolerant customers but requires the mainstream acceptance to become risk free.
4. *Early majority* ("pragmatists"): willing to adopt technology only when it has been well tested and is entering the mainstream acceptance in society, little risk tolerance.
5. *Late majority* ("conservatives"): will only adopt a technology when it has been accepted totally by mainstream customers, no risk tolerance.

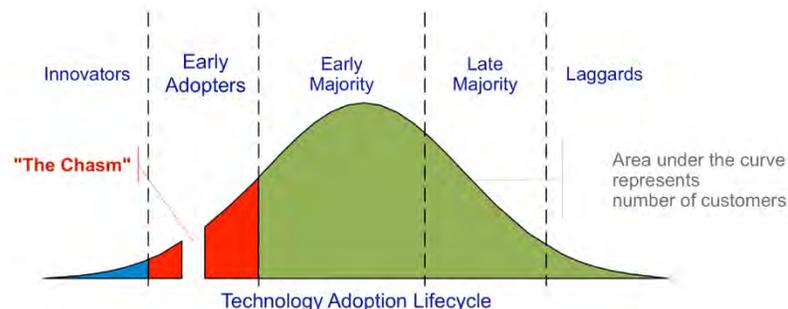


Figure 39 - Rogers Innovation Adoption Curve

¹⁶⁸ University of Oxford, Said Business School, Professor Marc Ventresca, Strategy & Innovation, Week 1 Lecture: Evolution of Markets + tech-market-organization (TMO), Hilary Term 2013 / Hilary Term 2015



6. *Laggards* (“*sceptics*”): are likely to accept a new technology when given no other choice, almost a negative risk tolerance¹⁶⁹.

The second methodology, the S-Curve or Performance Curve¹⁷⁰, maps a technology’s performance against time. This methodology is useful for analyzing the stages of a technological development, its positioning, and its likelihood to continue in the future. The curve itself is characterized by four stages known as the Technology Life-cycle:

1. *Research and Developments Phase*: also called the ‘Era of Ferment’, is characterised by low improvement rates, and high costs. It is relevant for when an innovation is new, there is no dominant design, and competition is fierce.
2. *Take-off*: as the technology is better understood, improvements are made quickly for less cost, and a dominant design is reached.
3. *Maturity* – as the dominant design is accepted by the market, and the technology reaches its physical limits, improvements become harder and costlier to design. Generally, only a few large market participants survive, and products are also typically standardised and less unique.
4. *Discontinuity*: newer technology’s performance begins to surpass the existing mature design. New dominant designs are accepted, the old technology is obsolete, and a new technology curve begins.

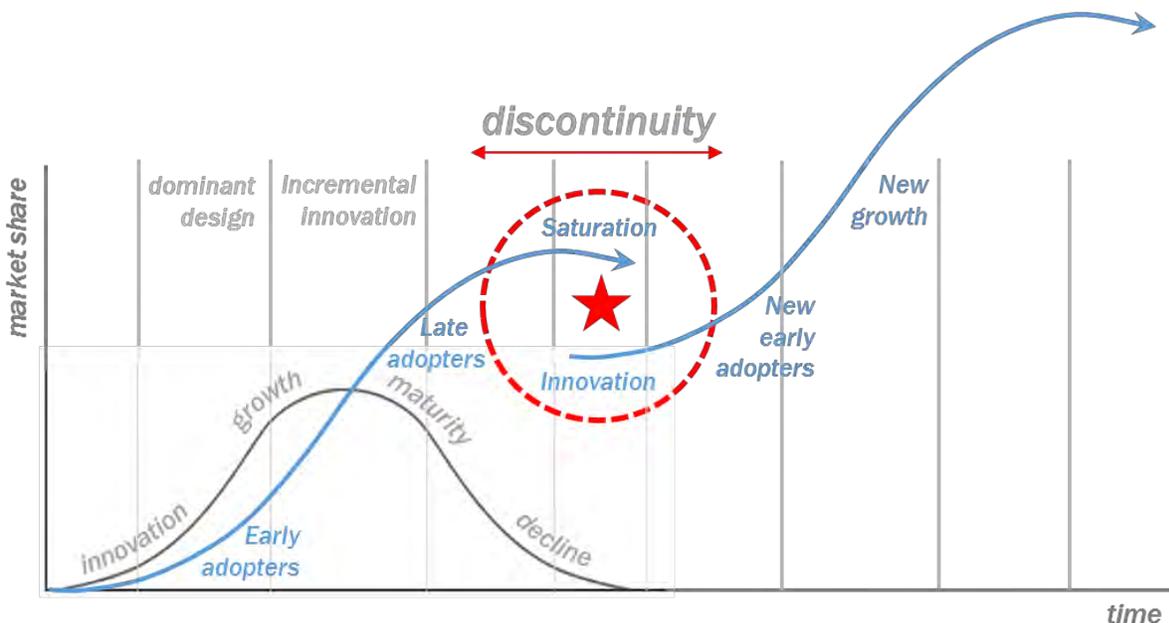


Figure 40 – A Space Angels Network S-Curve Example, combining elements of the Technological Adoption Lifecycle. Credit: Space Angels Network

The ACCORD model frames our third methodology on technology adoption¹⁷¹, it gives insight speed and ease of adoption. The model focuses on six factors for adoption:

¹⁶⁹ Rogers 2003, Moore 1995

¹⁷⁰ Exploring the Limits of the Technology S-Curve, C. Christensen, Harvard University, 1992

¹⁷¹ Rogers 2003



1. *Advantage*: is the new technology relatively more capable? A more capable technology will be faster adopted.
2. *Compatibility*: how well can the new technology integrate with other technologies? An innovation that integrates with current systems will be adopted more easily.
3. *Complexity*: how simple is the technology to understand, integrate, and utilize? An innovation that is intuitive, easily integrated and brought to use quicker will gain users faster.
4. *Observability*: how well can the benefits of the technology be seen and quantified? A technology with obvious and tangible benefits will be adopted rapidly.
5. *Riskiness (perceived or actual)*: how much risk (real or imagined) is required during adoption of the new technology? A less risky innovation will face less barriers to adoption.
6. *Divisibility*: how easily can the innovation be tried on a limited basis? An innovation that can be trialed easily is more likely to gain users.

This report also considers two types of innovation: Incremental (competence enhancing) and Radical (competence destroying, making other products near-obsolete). Often when radical innovation invades a stable industry, the habits, competencies, and processes often prevent dominant firms from radically evolving their product. Instances of this have often been coined discontinuous step. Established firms can successfully renew their competitiveness as one generation of technology succeeds another, however, this would require an accommodating organizational structure and investment.



Acknowledgements

This report estimates the past, present, and future market demand for commercial pressure suits through 2030. The goal of this study is to understand the convergence of technologies and restructuring of systems that are enabling new entrants to compete in this dynamic market.

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APPENDICES

COMPANY PROFILES



Market Incumbents

David Clark

David Clark (DC) has a long and successful history of manufacturing aerospace apparel in the United States for NASA and the USAF (United States Air Force). They do not currently have a spacesuit in use but have recently been active in developing modern suit prototypes for NASA.¹⁷²



Formation History

DC is a privately owned company, incorporated in 1935 and based in Massachusetts. The company initially developed textiles with unique knitted materials for undergarments. DC has been involved in the design and manufacture of aircrew protective equipment since 1941, when it was involved in the development of the first standard anti-G suits and valves¹⁷³. The company has also evolved to specialize in headset communications for high noise environments, including aviation and military.

DC developed the first Anti-G suit, the first USA EVA suit on the Gemini missions, standard full pressure suits for F-15, U-2 and SR-71 crew and the Shuttle Advanced Crew Escape Suits and Launch Entry Suits used until the end of the space shuttle program¹⁷⁴.

It is unknown what fraction of revenue (total revenue \$55m LTM¹⁷⁵) or profits are attributable to the Aerospace Crew Protective Equipment division within DC.

Ownership Structure

DC is currently privately owned by the officers of the company and the exact ownership structure has not been made public¹⁷⁶; it is a profit seeking entity. DC also currently whole owns a subsidiary, Air Lock Inc.¹⁷⁷, which designs and manufactures bearings and connections for 'virtually all high altitude' aircraft and a number of spacefaring pressure suits since the 1940s. The company also designed and



Figure 41 - CHAPS Commercial Suit (David Clark)



Figure 42 - Model S1034 (David Clark)



Figure 43 - Model S1035 ACES (David Clark)

¹⁷² Use MACES IVA Suit for EVA Mobility Evaluations. **Watson, Richard D.** Tucson, Arizona : 44th International Conference on Environmental Systems, 2014. JSC-CN-29963

¹⁷³ <http://www.davidclarkcompany.com/aerospace/history>

¹⁷⁴ <http://www.davidclarkcompany.com/aerospace/history>

¹⁷⁵ **Capital IQ.** *Capital IQ Website.* [Online] 05 August 2015. www.capitaliq.com.

¹⁷⁶ <https://www.google.com/finance?cid=1062267>

¹⁷⁷ <http://www.airlockinc.com/>

polycarbonate “bubble” pressure helmet and visor assemblies for the Apollo, ISS and Shuttle pressure suits.¹⁷⁸

Product Range

DC design, test, and manufacture a number of spacesuits for both EVA and IVA. They have a number of facilities dedicated to each stage of the development process. While they do not publicize current designs, they note multiple types; including Contingency Hypobaric Astronaut Protective Suit (CHAPS), a prototype commercial suit, Model S1034 Pilots Protective Assembly for U-2 Reconnaissance Aircraft, designed for the U-2 aircraft¹⁷⁹ but modern versions no doubt exist, and Model S1035 Advanced Crew Escape Suit (ACES) for NASA Shuttle, used in many shuttle launches until program retirement.¹⁸⁰

An enhanced version of the ACES is currently in development for NASA’s MPCV/Orion program (Modified ACES or MACES) and DC were recently selected as part of NASA’s now cancelled Constellation Spacesuit. DC also developed the space dive pressure suit for the Red Bull Stratos space dive¹⁸¹, the first pressure suit to attain a Mach 1 free fall from over 120,000 feet.

In addition to aerospace protective equipment, DC also designs and manufactures a range of communications equipment for military, emergency, aviation and marine environments.



Figure 44 - Red Bull Stratos Freefall Pressure Suit. Credit: Red Bull(127,000 ft) was the First Supersonic Suit

Business Model

DC operate a standard design, manufacture and sales model, in which the purchaser of the suit operates it. Historically their only customer in pressure suits has been the US Government (NASA in the case of spacesuits) but this part of the business model may change as more competitors enter the market and NASA exits the LEO market.

In the past DC have sold exclusively to NASA and, due to the nature of the NASA contracts, had a monopoly on the US IVA market and sold IVA suits for approximately \$180,000 per suit¹⁸².

Total Estimated Market Share

The latest DC pressure suit to be used was the ACES IVA Suit on the NASA shuttle and there is not a DC suit currently used in space travel. During the NASA Shuttle operation years DC controlled 100% of the US IVA market share and circa 78% of the global IVA market.

DC’s current market share is 0%, although this will grow to 100% of Orion launches if the MACES passes further testing¹⁸³ and is purchased by the Orion operators.

Competitive Landscape

DC is one of the major incumbent companies in this industry, both in the EVA and IVA sectors, and they are producing a number of models available currently. They have had a number of past contracts with

¹⁷⁸ David, James E., et al. Milestones of Space: Eleven Iconic Objects from the Smithsonian National Air and Space Museum. s.l. : MBI Publishing Company, 2014. 1627882030

¹⁷⁹ <http://www.thespacereview.com/article/2695/1>

¹⁸⁰ <http://www.astronautix.com/craft/aces.htm>

¹⁸¹ <http://www.davidclarkcompany.com/two-way/news.php?newsid=18>

¹⁸² <http://www.space.com/26978-commercial-spaceflight-requires-safety-of-new-space-suits.html>

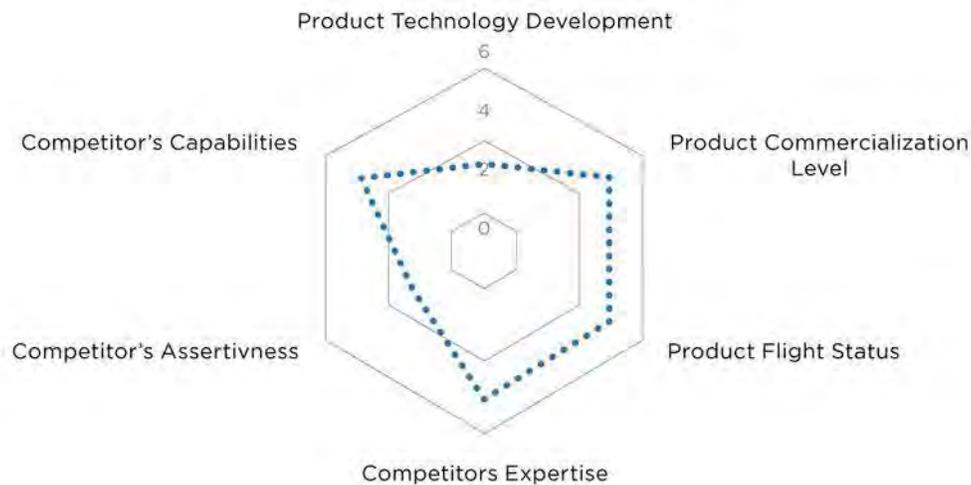
¹⁸³ Use MACES IVA Suit for EVA Mobility Evaluations. Watson, Richard D. Tucson, Arizona: 44th International Conference on Environmental Systems, 2014. JSC-CN-29963

industry leaders and have a long history of operations. Therefore, they will likely move aggressively to protect their market share. However, given the large growth expected in the private sector DC may focus more on growth than competitor competition. *Competitor Assertiveness 3/5; Product Commercialization Level 5/5*

Given the operational design and manufacturing facilities, the past experience and operating history, and the relationships that DC has established it should be considered that the company has a large competitive advantage. *Competitor Expertise 5/5; Competitor Capabilities 5/5*

Although they are considered one of the market leaders DC's designs do not appear to utilize any advanced R&D or computer systems (though it must be noted again that no current suit models are shown) but it is possible that DC is only using incremental design in order to protect its market share. DC's IVA suits are also currently used for NASA operations and are flight ready. *Product Technological Development 3/5; Product Flight Status 5/5*

DAVID CLARK



ILC Dover

ILC Dover (ILC) specializes in the development of high performance, flexible materials, which is how they describe themselves (not a pressure suit developer). ILC has been responsible for the design and manufacture of a number of pressure suits (EVA and IVA) used by NASA since the Apollo missions.



ILC is a private company, wholly owned by private equity firm, Behrman Capital. Behrman Capital, purchased ILC Industries in 2003. ILC Industries had two operating subsidiaries, Data Device Corporation and ILC Dover. After a number of recapitalisations, ILC Dover split from ILC Industries in 2011.¹⁸⁴ Behrman also invests in middle market companies in Defence & Aerospace, Healthcare Services and Specialty Manufacturing. ILC Dover has two subsidiaries: Grayling Industries (2013)¹⁸⁵, advanced industrial packaging and environmental safety product production; and Jet Solutions (2014)¹⁸⁶, custom powder/liquid mixing and processing operations manufacturing systems designer.

Formation History

ILC Dover was initially formed as a branch of the International Latex Corporation (founded 1932) which manufactured latex products during WW2 (e.g. attack boats, life rafts and canteens). In 1947 the parent company was split into four divisions, the Materials division later became ILC Dover.

ILC's earliest work was on high altitude pressure helmets and suits for the US Air Force and US Navy.¹⁸⁷ In 1965, ILC was awarded the prime contact for the Apollo Lunar Spacesuit (the only Environment suit ever used) and in 1977 ILC was awarded the spacesuit section of the Shuttle Extra-Vehicular Mobility Unit (EMU).¹⁸⁸ During this time ILC also expanded in the production of personal protective equipment (CERN hazard suits and military gas masks) and airships. More recently ILC was contracted by NASA JPL to design and manufacture the airbag landing system for the Mars Pathfinder Mission. The system was further used on the Mars Exploration Rover Missions.¹⁸⁹



Figure 45 - Apollo A7LB. Credit: NASA



Figure 46 - The Z-2 Advanced Planetary Suit (latest prototype). Credit: NASA



Figure 47 - The Z-1 Advanced Planetary Suit (first prototype). Credit: NASA

¹⁸⁴<http://www.behrmanicap.com/behрман-capital-completes-330-million-recapitalization-for-data-device-corporation-and-spin-off-of-ilc-dover/>

¹⁸⁵ <http://www.behrmanicap.com/behрман-capital-portfolio-company-ilc-dover-acquires-grayling-industries/>

¹⁸⁶ <http://www.ilcdover.com/ilc-dover-acquires-jetsolutions-sa>

¹⁸⁷ <http://www.wired.com/2015/12/christopher-leaman-ilc-dover/>

¹⁸⁸ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

¹⁸⁹ <http://www.ilcdover.com/space/impact-bags>

Product Range

ILC has designed and manufactured a large number of successful EVA and some IVA suits during its history. It designed and manufactured all suits for the Apollo missions, including the lunar and Skylab EVA suits¹⁹⁰. ILC also designed and manufactured the suit portion of the Extravehicular Mobility Unit (EMU) that has been used extensively for EVA activities during the Shuttle program and is still used onboard the ISS. The EVA Life Support Systems have traditionally been designed and manufactured by Hamilton Standard.¹⁹¹

ILC has also worked on a number of experimental Planetary suits, including Mark III, I-Suit, Z-1 prototype and most currently the Z-2 prototype. ILC recently beat David Clark in the Z-2 development contract. ILC also developed the StratEx space dive suit which successfully undertook a manned jump from over 135,000 feet and holds the record for the highest space jump to date.



Figure 48 - Shuttle and ISS Extra-Vehicular Mobility Unit (NASA)



Figure 49 - StratEx Pressure Suit that holds the Current Record for Free-fall at 135,000 ft (Stratex)

Other Products

ILC has a long history of design and manufacture of Lighter than Air Vehicles, including airship and aerostat large inflatable envelopes. They also manufacture engineered fabrics for RADOMES used at sea and inflatable wings for UAVs.

ILC also develops and has successfully operated 'inflatable impact attenuation systems¹⁹², or airbags, on Mars landings and numerous Earth missions. The systems are used instead of a parachute or rocket assisted landing and were used on the Mars Pathfinder and Mars Exploration Rover missions. ILC Dover also manufactures Inflatable Aerodynamic Decelerators¹⁹³ that act as an inflatable heat shield during orbital re-entry to decelerate spacecraft. The company also develops and manufactures a variety of inflatable targets and decoys for space applications and a number of classified programs.^{194,195} Further the company uses inflatable devices in the bulk packaging and pharmaceutical manufacturing industries.

ILC has also developed containment systems based on the deployment of flexible materials as barriers, for example flood protection for transit systems or subway entrances. The company also

¹⁹⁰ <http://www.astronautix.com/craft/a7l.htm>

¹⁹¹ US Spacesuits, 2nd Edition, Thomas KS & McMann HJ, Springer Publishing, 2012

¹⁹² <http://www.ilcdover.com/space/impact-bags>

¹⁹³ <http://www.ilcdover.com/space/inflatable-decelerators-iads>

¹⁹⁴ <http://www.ilcdover.com/about-space/decoys-and-targets>

¹⁹⁵ <http://www.globalsecurity.org/space/systems/decoys.htm>

produces a range of Personal Protective Equipment used in hazardous materials disposal airlocks and showers, and advanced respiratory protection for the pharmaceutical and healthcare industries.

Business Model

ILC Dover is a profit seeking company. It is unknown what revenue (circa \$35 LTM¹⁹⁶) or profit is attributable to each division. Also, ILC Dover’s owner Behrman Capital is reported to not own assets with revenue below \$100m and a Delaware based investment bank has estimated the revenues to be approaching \$200m.¹⁹⁷

The company designs and manufactures pressure suits for other entities and does not operate the suits itself and it does not appear to design suits unless under contract. The company then produces the pressure suits and supplies them to NASA.

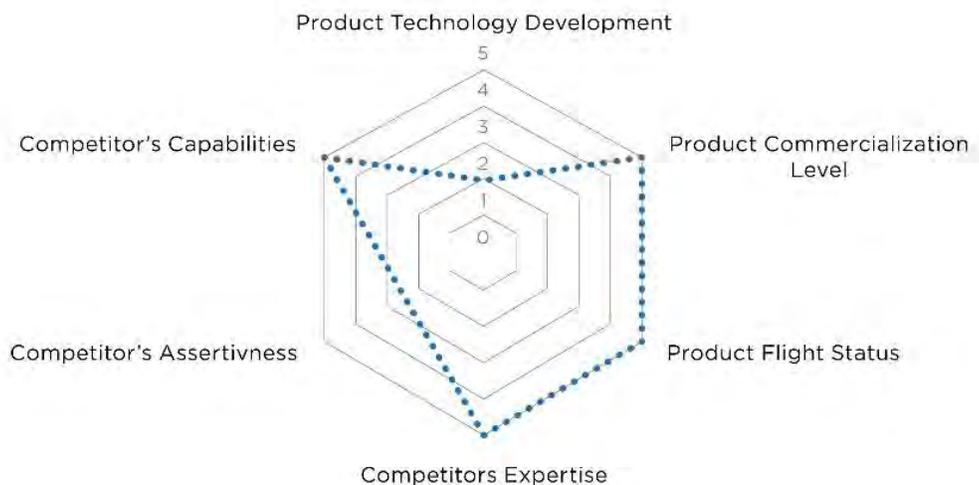
ILC Dover currently controls 47% of the global market and 100% of the US EVA market share per year. Their market share is not expected to grow further in the near future, unless they supply EVA suits to the Bigelow Commercial Space Station.

Competitive Landscape

ILC has not been active in the IVA market recently but they have the knowledge, funding, and network to do so. They have also proven to be aggressive in following contracts for NASA and have demonstrated a desire to move into the commercial space industry. *Competitor’s Assertiveness 5/5; Competitor’s Capabilities 5/5; Competitor’s Expertise 5/5*

They do not demonstrate extensive research and development, except when contracted to do so, and there is no evidence of cutting-edge technology or design in their pressure suits. ILC Dover does manufacture a pressure suit that is used in current NASA operations and has full flight status. *Technological Development 2/5; Commercialization Level 5/5; Product Flight Level 5/5*

ILC DOVER



¹⁹⁶ Capital IQ. *Capital IQ Website*. [Online] 05 August 2015. www.capitaliq.com

¹⁹⁷ <http://www.delawarebusinesstimes.com/space-suit-maker-ilc-dover/>

Oceaneering Space Systems

Oceaneering Space Systems is a subsidiary of Oceaneering International, Inc.¹⁹⁸ They have leveraged their expertise in deep sea to enter the space industry. The company is based in Houston, Texas. Oceaneering is a large publicly traded company, listed on the NYSE and trading under ticker symbol OII. It has an Enterprise Value of over \$3.8 billion and a LTM Revenue of just under \$3.26 billion.¹⁹⁹ It is unknown how large the Space Systems division is as a part of Oceaneering as a whole but they have a stable relationship with NASA in a number of different industries.



Formation History

The company was founded in 1964 to provide engineered services and hardware for marine and other hazardous environments. Its history involves operations in the off-shore oil and gas industry.

Oceaneering has grown into a large company involved in a large number of different industries. Its main focus remains the Oil and Gas industry, especially the subsea sector. However, one division, the Space System Division, has worked in the aerospace industry for a number of years.

Product Range

In early 2009, Oceaneering was selected to led the team developing NASA's next generation spacesuit as part of the Constellation Program. In 2009, President Obama declared the Constellation Program to be "over budget, behind schedule, and lacking in innovation."²⁰⁰ After multiple reviews the program was excluded from the 2011 United States federal budget.²⁰¹ The Constellation Spacesuit was originally designed to be an IVA and an emergency EVA suit in one and with some modifications (configuration two) a Planetary suit. The configuration one suit was originally contracted to be operational by 2015.²⁰²

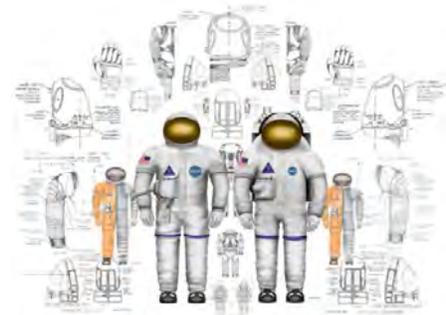


Figure 50 - Oceaneering's Constellation Spacesuit. Credit: Paragon and Oceaneering

Oceaneering have been involved with NASA for a number of years on many products although they have yet to develop a pressure suit. The products they are have been involved with include:

- EVA equipment,
- IVA equipment,
- Astronaut training (both in and out of water) at NASA's Neutral Buoyancy Laboratory,
- Habitation,
- Robotic systems

¹⁹⁸ <http://www.oceaneering.com/about/>

¹⁹⁹ Yahoo Finance, 25/01/16

²⁰⁰ http://articles.orlandosentinel.com/2010-01-27/news/os-no-moon-for-nasa-20100126_1_constellation-program-human-spaceflight-space-agency

²⁰¹ <http://news.bbc.co.uk/2/hi/science/nature/8489097.stm>

²⁰² <http://www.technologyreview.com/news/417216/nasas-next-space-suit/page/2/>

Outside of the space industry the company has a large range of sub-surface products and services, including remotely operated vehicles, built to order subsea hardware, deep-water intervention and manned diving services.

Business Model

Like many of the other companies Oceaneering won a government contract to develop a pressure suit (although the suit was an EVA / IVA hybrid) which would fund the research and development. The company was not planning to operate the suits itself but sell the product to organizations who would operate the suit. Revenue would be generated using a standard manufacturer business model.



Figure 51 - PXS Prototype Planetary Suit. Credit NASA

Total Estimated Market Share

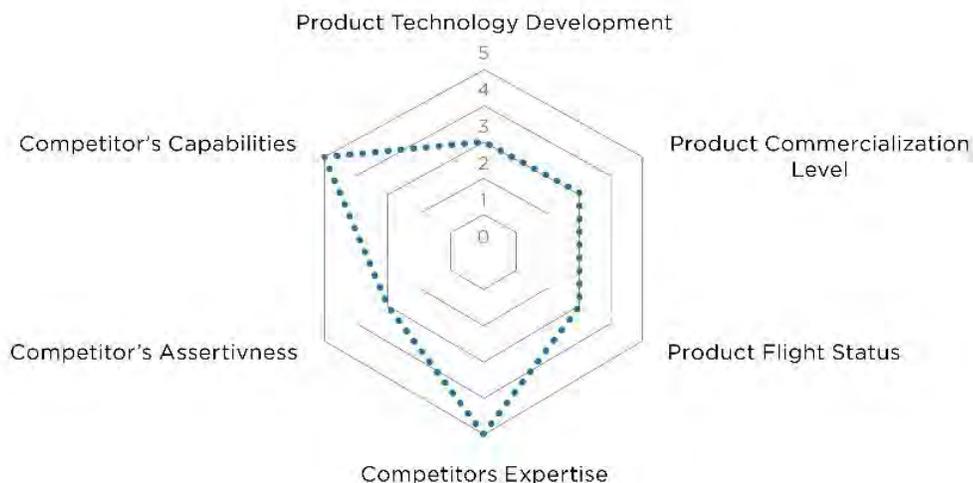
Given that the Constellation suit was cancelled by NASA and that although Oceaneering states they are developing EVA and IVA suits they have not sold any space pressure suit equipment.

Competitive Landscape

Oceaneering is a large, well-funded company with many ties to NASA and the space industry. It has also demonstrated a capability to outperform capable incumbents, although it does not appear to have been active since the Constellation program cancellation. It also has the resources to attain any experience that it requires. *Competitor's Expertise 5/5; Competitors Assertiveness 3/5; Competitor's Capabilities 5/5*

Oceaneering has not demonstrated any suits that have undergone advanced design, manufacturing, testing or commercial pressure suit activity. However, they have the funding and the experience to develop capability and commercialize products in the pressure suit sector and have demonstrated a desire to do so. The level of technology would be advanced to design a lunar EVA and IVA suit but the early designs do not show high levels of technology or technological connectivity. *Product Flight Status 3/5; Product Commercialization Level 3/5; Product Technological Development 3/5*

OCEANEERING



NPP Zvezda

NPP Zvezda has been the manufacturer of pressure suits (IVA and EVA) since the beginning of the Soviet Space Program. They have continued to design and manufacture suits for ROSCOSMOS and currently have operational suits onboard the ISS. The company became a joint-stock company in 1994 and the company is described as a 'non-commercial research organization'. LTM revenue was reported as \$30m USD.²⁰³



Formation History

NPP Zvezda is based in Moscow, Russia. It was set up as an organization in 1952 to develop aviation pressure suits and in-flight refueling systems for the USSR's space program.²⁰⁴ In the 1960s it developed the first Soviet spacesuits (including the suit worn by Yuri Gagarin and the Berkut spacesuit, used during the first human EVA), and has continued to develop modern suits to the present day with a number deployed on Mir, ISS and the Soyuz launch vehicle.²⁰⁵

Product Range

The Sokol-KV2 is the current model of Sokol IVA suit series and it is used by all astronauts on the Soyuz spacecraft, although it was first introduced in 1980, and is the equivalent of the ACES NASA IVA suit.

NPP Zvezda also manufactures an EVA suit for use on the ISS. The Orlan MK (currently on the ISS) and the Orlan MKS (replacing the MK during 2016) are the latest versions of the Orlan EVA suits that have been used since early in the Soviet Space Program.

NPP Zvezda also manufactures a number of non-space aerospace products for the Russian military including aircraft ejection seats used on a number of Russian fighter jets (for example, the MiG-29 and Su-37), air to air refueling equipment, aviation helmets and a range of aircraft oxygen systems.²⁰⁶ The company also makes a range of civilian (and likely military although this is unconfirmed) parachute systems. 'Russian Aviation' also reported that the company has developed an ejection seat for light civilian aircraft as well.²⁰⁷



Figure 52 - Richard Garriott in Cosmonaut Suit (Richard Garriott)



Figure 53 - Sokol IVA Suit KV-2



Figure 54 - A recent version of the Orlan EVA suit, MK

²⁰³ Capital IQ. *Capital IQ Website*. [Online] 05 August 2015. www.capitaliq.com

²⁰⁴ www.zvezda-npp.ru/en/history

²⁰⁵ Russian Spacesuits, Abramov I and Skoog I, Praxis Publishing, 2003

²⁰⁶ <http://www.zvezda-npp.ru/en/taxonomy/term/1>

²⁰⁷ Russian Aviation. Specialists of NPP Zvezda developed a unique ejection system for sport and civil aircraft. *Russian Aviation Website*. [Online] 03 February 2015. [Cited: 29 November 2015.] <http://www.ruaviation.com/news/2015/2/3/2890/>.

Business Model

There is little information on the business model of NPP Zvezda. As it designs and manufactures components for and is associated with the Russian Military and the Russian Government many details about the company are not released. It may or may not compete for contracts within Russia and it has undertaken international business in the past.

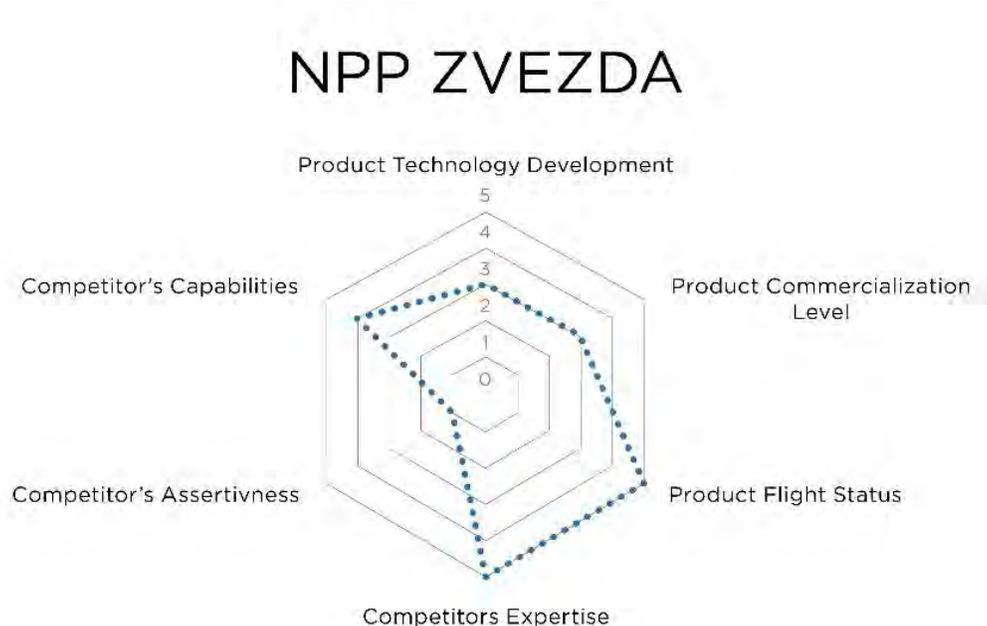
Total Estimated Market Share

Currently Zvezda currently controls 100% of the market share for operational IVA suits and half the market for operational EVA suits. The only vehicle currently transporting humans is the Soyuz spacecraft and all astronauts flying on the Soyuz must use the Sokol KV-2 IVA suit. Zvezda's market dominance will be challenged when new commercial transport providers, SpaceX and Boeing, begin operations.

Competitive Landscape

NPP Zvezda has a huge amount of experience and a long track record developing successful IVA and EVA suits, rivalled only by David Clark and ILC Dover. Although they have shown no desire to produce a commercial version of the Sokol or Orlan pressure suits. It is unlikely that ZPP Zvezda will be a first mover into the commercial space but if the market proves to be lucrative there would be little to stop them entering. They have also shown willingness to cooperate with other national space programs, as the Chinese have a close variant to the Orlan EVA suit. *Competitor's Experience 5/5; Competitor's Capabilities 4/5; Product Flight Status 5/5*

NPP Zvezda has a great deal of experience in the development of aerospace equipment and they could be a competent competitor. However, they do not have commercial experience or any demonstrated assertiveness in the commercial space market at this stage and they have not publicly demonstrated more than incremental innovation in recent suit design. *Product Technological Development 3/5; Product Commercialization Level 3/5; Competitor's Assertiveness 1/5*



China Aerospace Science and Technology Corporation

The China Aerospace Science and Technology Corporation (CASC) is the main contractor of the China National Space Administration who oversee all planning and development of the Chinese space program. Based in Beijing, the company develops a number of systems to enable the space program, including the Feitian spacesuit used during the first Chinese EVA in 2008. As with much of the Chinese government, the corporation is very secretive about its equipment and activities. The organization is owned entirely by the Chinese government.²⁰⁸



Formation History

CASC was incorporated in 1999 as part of a Chinese Government drive to reform the China Space Agency. Various incarnations of the program date back to 1956.²⁰⁹ By the end of 2013, the corporation has registered capital of CN 294.02 billion and employs 170,000 people, according to its own website.²¹⁰

Product Range

The Chinese IVA suits have not been displayed publicly and there is no information readily available about them, it reportedly closely resembles a Sokol-KV2, but it is believed to be Chinese-made rather than an actual Russian suit.²¹¹ Pictures show that the suits on Shenzhou 6 differ from the earlier suit.²¹²



Figure 55 - CASC Feitian Suit. Credit: China Pictorial

The spacesuits used by the Chinese taikonauts during a 2008 spacewalk were manufactured in China by the CASC but they were heavily based on the design of the ZPP Zvezda Orlan EVA suit.²¹³ The suit is visually similar to the Orlan suit and does not show any more advanced design and movements are seriously restricted in the suits, with a mass of more than 110 kilograms each.²¹⁴

CASC provides commercial launch services to the international market and is considered a very advanced organization for the design and operation of orbital launch vehicles.²¹⁵ The organization also manufactures strategic and tactical missile systems for the Chinese military.

In addition to the space sector CASC also develops machinery, chemicals, computers, medical products, and communications, transportation and environmental protection equipment.²¹⁶

²⁰⁸ <http://english.spacechina.com/n16421/n17138/n17229/c127066/content.html>

²⁰⁹ <http://english.spacechina.com/n16421/n17138/n382513/c386575/content.html>

²¹⁰ <http://english.spacechina.com/n16421/n17138/n17229/c127066/content.html>

²¹¹ Testimony of James Oberger: Senate Science, Technology, and Space Hearing: International Space Exploration Program, SpaceRef, April 27, 2004

²¹² China Ramps Up Human Spaceflight Efforts, Malik, Tariq, Space.com, November 8, 2004

²¹³ U.S. Spacesuit Knowledge Capture (KC) Series Synopsis, Croog, L., www.jsc.nasa.gov

²¹⁴ Chinese astronauts begin training for spacewalk, People's Daily Online, Xinhua News Agency, July 18, 2007

²¹⁵ A Profile of China's Public Gem: CASC, The Jamestown Foundation, China Brief Volume :9 Issue: 19, 2009

²¹⁶ A Profile of China's Public Gem: CASC, The Jamestown Foundation, China Brief Volume :9 Issue: 19, 2009

Business Model

CASC is a state sponsored organization which does design and manufacture for other government organizations, but also sells advanced products and services on the international market.²¹⁷

It is unlikely that CASC would sell their products on an open market or for commercial use but they have been increasing military exports in recent years²¹⁸ and are open to exporting sensitive equipment; so it is conceivable that their stance on space-related exports may change. They have also launched payloads for other international customers and have shown interest in the commercial space sector.²¹⁹

Competitive Landscape

The suit is based heavily on the Russian Orlan suit. The suit has been successfully used in orbit and has active flight status but the CASC has shown no intentions to sell the product. *Product Commercialization 3/5; Product Technological Development 2/5; Competitor's Assertiveness 0/5; Product Flight Status 5/5*

CASC has the expertise to modify and manufacture the suit for its own purposes and the resources of the Chinese government. However, if the Chinese did want to sell the suit, it is in a much more advanced stage of design than many competitors. *Competitor's Expertise 3/5; Competitor's Capabilities 4/5.*

The lack of details on pressure suits and the secrecy of the space program results in CASC not being considered a risk in the commercial pressure suit market but they should be observed as the situation could change quickly.



²¹⁷ <http://www.businessinsider.com.au/china-is-manufacturing-drones-to-sell-to-developing-countires-2012-11>

²¹⁸ Chinese arms sales surge 143% in 5 years, Clover, Charles, Financial Times Website

²¹⁹ A Profile of China's Public Gem: CASC, The Jamestown Foundation, China Brief Volume :9 Issue: 19, 2009

New Market Entrants

Final Frontier Design

Final Frontier Design (FFD) is an early-stage pressure suit development company based in the Brooklyn Navy Yard in New York City. The company combines the skills of an experienced pressure suit designer (20 years with NPP Zvezda on all current spacesuit designs) and a designer who has worked on Victoria's Secret wings and Cirque du Soleil costumes. The company achieved 2nd place in a NASA EVA glove prize in 2009 and a fourth NASA 'Small Business Innovation Research' Phase 1 grant and fixed-price contract in 2015 for development of EVA gloves.²²⁰ The company is also in development of an IVA suit, which has been selected for NASA's Flight Opportunities Program in early 2016.²²¹



Product Range

The third generation IVA suit is a single layer pressure suit designed for the commercial sector. The suit has not undergone an altitude or vehicle test but is designed for +5 PSID.²²² The IVA suit was recently selected by NASA to be part of the Flight Opportunities Program to undergo parabolic flights to simulate operation of the suit in a weightless environment.²²³



Figure 56 - FFD IVA 3rd Generation IVA Suit. Credit: Final Frontier Design

The Mechanical Counter Pressure (MCP) glove that has been developed by FFD is an example of discontinuous innovation that has the potential to add a new level of maneuverability to EVA and IVA suits. NASA has contacted FFD to develop the glove further (a fixed-price contract for the delivery of a functioning mechanical counter pressure glove system worth over \$350,000.²²⁴) and the knowledge gained during the development may aid in the development of other MCP suit parts.

The company has also designed and developed a number of other products including: a lightweight communications caps for use inside a spacesuit; a range of compression pants for use as anti-G pants that fit under a spacesuit; reproductions of spacesuits and gear for use in museums or display; emergency garments (firefighting, etc.) using space-tech; a line of sports apparel using space-tech; and they offer a Spacesuit Experience, where customers pay to don the suit.

²²⁰ NASA 2015 SBIR Phase I Solicitation, 15-1 A1.01-9678

²²¹ <http://www.nasa.gov/ames/press-release/nasa-selects-new-technologies-for-parabolic-flights-and-suborbital-launches>

²²² <http://www.finalfrontierdesign.com/space-suits-for-iva/>

²²³ <http://www.nasa.gov/ames/press-release/nasa-selects-new-technologies-for-parabolic-flights-and-suborbital-launches>

²²⁴ <http://www.parabolicarc.com/2015/08/25/final-frontier-design-wins-nasa-spacesuit-glove-contract/>



Figure 57 - Compression Pants
Designed at FFD (FFD)



Figure 58 - Emergency Jacket
Prototype (FFD)



Figure 59 - Mechanical Counter Pressure Gloves
in Testing (FFD)

Business Model

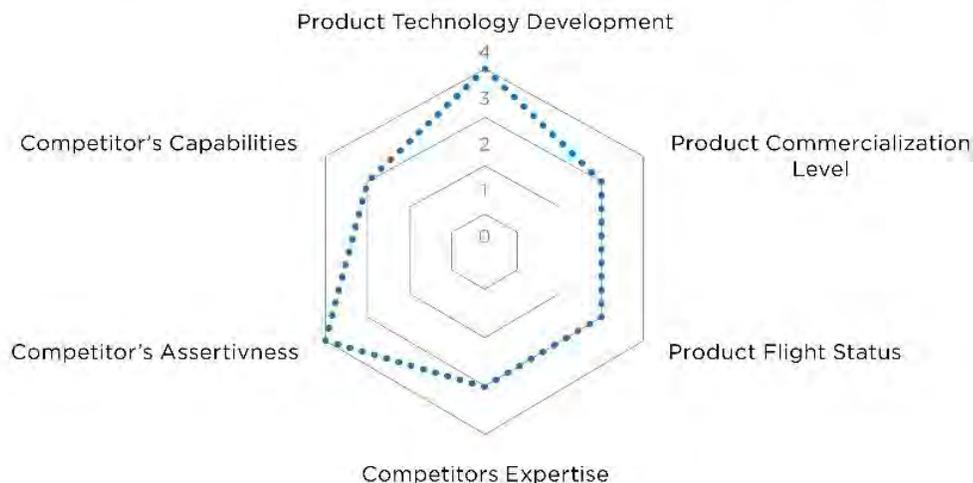
FFD both develops its own pressure suits and develops garments under contract for future use in the commercial and governmental space sectors. The company does not anticipate operating its suits (outside of research and development) and anticipates selling the suits to another party to operate. The company is revenue-generating and has sold units of its IVA product.

Competitive Landscape

FFD is a small company, four employees, that is funded primarily by grants from NASA for EVA glove design. The lead designer has extensive experience with pressure suit design. The company is actively developing a commercial IVA suit but is yet to fully test or manufacture a pressure suit. *Competitor's Expertise 3/5; Product Flight Status 3/5; Commercialization Level 3/5.*

The company has won a number of NASA contacts, but the scalability of their operation yet to be seen. Their technology is more advanced than current NASA technology and their contracts have enabled development of advanced technology, such as MCP gloves, which is a big step toward non-traditional spacesuit technology. The company does not appear to have utilized digital or connectivity technology at this stage. *Product Technology Development 4/5; Competitor's Assertiveness 4/5; Competitor's Capabilities 3/5*

FINAL FRONTIER DESIGN



SpaceX

Elon Musk went on record stating that SpaceX was developing its own spacesuit for use on future missions. He declined to comment on design specifics, whether it was an IVA or an EVA suit. It is due to be unveiled in late 2015.²²⁵ The company is owned by a number of private investors.



Formation History

SpaceX is a privately owned company, based in Hawthorne, California, that operates self-developed spacecraft and launch vehicles. It was founded in 2002 and has moved quickly to establish itself in the aerospace industry. SpaceX became the first company to successfully launch and recover a commercially built and operated spacecraft in 2010.

The SpaceX Dragon spacecraft successfully docked with the ISS in 2012 (the first commercial spacecraft to do so) and has completed 6 successful missions.²²⁶ The seventh mission failed when the Falcon 9 rocket disintegrated shortly after take-off. SpaceX recently won a contract to service the ISS in manned missions on the Dragon V2 Crew Capsule which is currently undergoing testing. This will break NPP Zvezda monopoly on the market for IVA suits.

In 2012 SpaceX entered a contract with Orbital Outfitters to develop a mock IVA suit for design of the Dragon 2 Capsule but has not furthered the contract further than mock suit development.²²⁷

Product Range

SpaceX is designing a suit to be used on its human-rated Dragon v2 capsule. No details of the suit have been released publicly, other than to state SpaceX's intent to use a proprietary IVA suit.²²⁸ SpaceX develops and operates a number of launch vehicles. They currently operate the Falcon 9 rocket system and the Dragon cargo capsule. In the near future they will also operate the Dragon 2 manned capsule and the Falcon Heavy rocket system.



Figure 60 - Falcon 9 Rocket
(SpaceX)



Figure 61 - SpaceX Dragon V2 Crew Capsule
(SpaceX)



Figure 62 - SpaceX concept suit
(NASASpaceflight.com)

²²⁵ Bachman, Justin. Bloomberg Business Week: Elon Musk Won't Send You Into Orbit Looking Frumpy. Bloomberg Website. [Online] 08 January 2015. [Cited: 07 August 2015.] <http://www.bloomberg.com/news/articles/2015-01-08/spacex-space-suit-will-combine-function-with-design>.

²²⁶ <http://www.spacex.com/missions>

²²⁷ <http://orbitaloutfitters.com/suit-mock-ups-for-spacex-nasa-crew-trials/>

²²⁸ <http://www.bloomberg.com/news/articles/2015-01-08/spacex-space-suit-will-combine-function-with-design>

Business Model

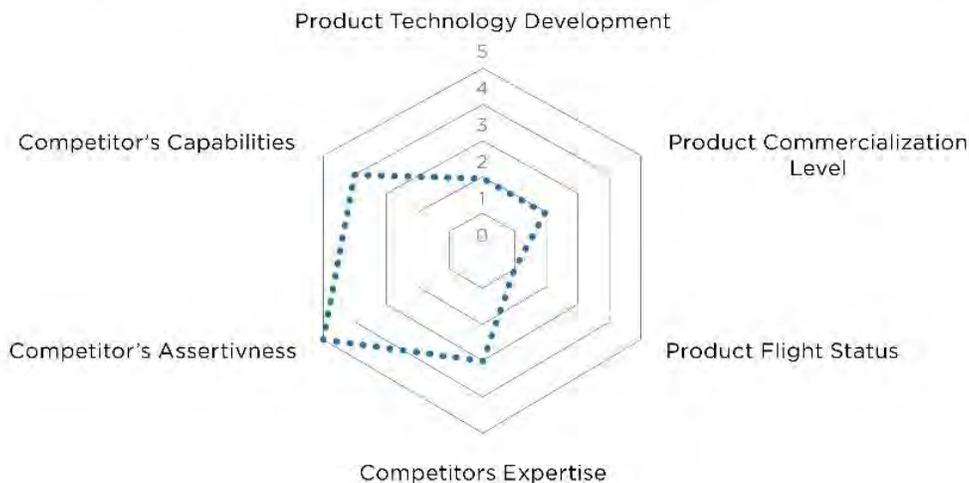
SpaceX generates revenue by launching satellites to orbit and transporting cargo (and soon astronauts) to the ISS through Commercial Cargo and Commercial Crew contracts with NASA. In December 2015, the company reported revenue of over \$380m LTM²²⁹, with an order backlog of \$8 billion.²³⁰ The company's spacesuit division is not likely a profit center, but rather another example of vertical integration by the company. Additionally, the company's stated mission is to colonize Mars.²³¹ Therefore, it is likely that they are developing an IVA suit for their immediate business, while working on an environmental suit for Mars.

Competitive Landscape

SpaceX is a well-funded and high profile company. The company also has a large number of industry contacts and contracts in place. SpaceX has shown to be aggressive in pursuing NASA cargo and passenger contracts and has successfully won a number of them. *Competitor's Assertiveness 5/5; Competitor's Capabilities 4/5*

Whether it will end up designing spacesuits only for its own use or for other commercial applications as well is unknown but it will likely have recruited experienced team that is able to develop a capable design. There is no public information on the stage and level of development, incremental or discontinuous, or commercialization intent of the suits. *Product Technology Development 2/5, Product Commercialization Level 2/5; Product Flight Status 1/5; Competitor's Expertise 3/5*

SPACEX SPACESUIT DIVISION



²²⁹ CapitalIQ, www.capitaliq.com

²³⁰ <http://nypost.com/2015/12/10/spacex-has-8-billion-mission-backlog-after-launch-accident/>

²³¹ <http://www.space.com/28215-elon-musk-spacex-mars-colony-idea.html>

Orbital Outfitters

Orbital Outfitters (OO) is a start-up pressure suit design company, founded in 2006, developing a range of IVA suits for use in the commercial space industry. OO also designs and build vehicle mock-ups for the aerospace industry. The company has established a number of partnerships including XCOR (although the Lynx is now on hold) and SpaceX, and has received seed funding from a handful of angel investors. The company has a west coast office in North Hollywood, California and an east coast office in Washington DC.



Formation History

OO was launched in 2006 to develop pressure suits for the new space industry. The IS³ was already under development and a partnership with XCOR was also well under way. The IS³ was unveiled in 2007 at the X Prize cup and was designed for use with the XCOR Lynx. OO noted that the suit was a first generation, working prototype but more design was required.

In 2008 OO was selected by NASA to develop a 'soft shoulder' concept for the now cancelled Constellation Suit. This was followed in 2012 by the unveiling of a Lynx mock-up for XCOR and the announcement of suit mock-up for the SpaceX crew trials. Finally, in 2014 OO announced the movement to a new test facility in Midland that was due to be completed in the early stages of 2016, and includes testing facilities and a pressure chambers.

Product Range

The two series of suits that have been publicly developed by OO are the IS³ Series, envisioned for use on the XCOR Lynx sub-orbital vehicle and unveiled during the X-Prize Cup in 2007. At least publicly, the IS³ has not been tested to sub-orbital levels or used on a test mission.

The company did design other suit, as a mock up for SpaceX during their crew trails of the Dragon Version 2 manned spacecraft. All details of the suit and all photos remain classified. The suit appears to be obsolete however as SpaceX has shown a desire to product its own pressure suit in house.



Figure 63 - Orbital Outfitter XCOR Lynx Mock-Up and IS³ Pressure Suit. Credit: Orbital Outfitters

Other Products

OO has also developed full size vehicle mock ups for the commercial space industry. OO recently built a full mock-up of the XCOR Lynx sub-orbital vehicle, Figure 63.

OO is also working towards developing pressure suits for Space Diving and developing the capabilities to undertake the dives on a regular basis. Further OO was selected as part of the team to develop concepts for a 'soft shoulder' for NASA's now cancelled Constellation suit in 2008.

Business Model

OO is a profit seeking company. OO operates its own design and development in order to develop suits to market to commercial space companies (as opposed to only designing for a contract). OO does not

currently appear to have ambitions of offering services involving directly operating its own suits and its revenue stream appear to come from the direct sale of pressure suits only (excluding the mock up revenue stream).

Orbital Outfitters was given a \$6.9 million incentive to build a facility at the Midland Air & Space Port²³² that will include a number of design and testing facilities and will locate OO near potential space industry contacts.

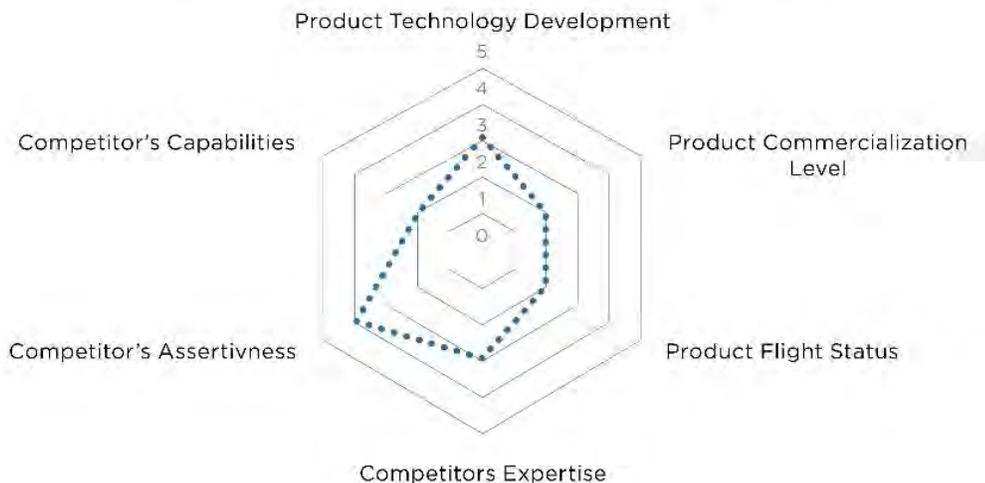
Competitive Landscape

OO is a new company in the development of IVA pressure suits but they have quickly developed a number of key partnerships (including SpaceX, XCOR and NASA). This gives them a big competitive advantage, especially against another early stage company. They operate exclusively in the IVA pressure suit market, although this may change. *Competitor's Assertiveness 4/5; Competitor's Expertise 3/5*

The amount of testing undertaken on the pressure suits is unknown but the company does not have a mission tested suit or an operational track record. The IS³ also does not appear to have a high tech element to it, e.g. HUD and on-board computer and it was originally developed almost a decade ago. *Technology Development 3/5; Commercialization Level 2/5*

Orbital Outfitters is one of the more significant competitors in the 'new space' IVA pressure suit industry at this point in time. Their suits have not public undergone advanced testing or flight testing. They have moved to create partnerships and demarcate the market and are the most flexible and capable 'new' company in the sector. *Competitor's Capabilities 2/5; Product Flight Status 2/5*

ORBITAL OUTFITTERS



²³² <http://spacenews.com/42477orbital-outfitters-breaks-ground-on-texas-facility/>

Pacific Spaceflight

Pacific Spaceflight (PSF) is a pressure suit design and testing organization, based in Portland, Oregon, which has developed and tested a series of IVA pressure suits, including successful high altitude balloon tests. The organization does not seem to generate revenue and has used donations for funding in the past. The organization is set up as a not-for-profit entity and does not have a formal ownership structure. It is unknown who owns the organization.

Formation History

PSF was the US arm of Copenhagen Sub-orbitals (CS), a Danish not-for-profit launch vehicle and guidance system developer (which is entirely crowdfunded), developing pressure suits for use in CS launch vehicles from the organization inception in 2013 until 2014 when CS changed the capsule design. Since then it has continued to develop and test a number of pressure suits for IVA using the same DIY mentality at CS. The next test, FL650: scheduled for 2015, will be a pressure suit test at +60,000 ft.

Product Range

PSF have developed four suits in the last few years. The Mark I through Mark III suits were developed and tested using altitude chambers. The latest design Zaphod I (Mark 4) will undergo testing during the 2015 FL650 high altitude test over the Baltic Sea to an altitude of 65,000ft (above the Armstrong Line). All of the prototypes have been developed for IVA use only.

The suits appear to be incremental design in nature and do not appear to utilize any high tech elements or discontinuous design. The pressure suits do not appear to house advanced technologies, for example computer systems, HUD or advanced connectivity.



Figure 64 - Pacific Spaceflight Suit Under Testing (PS)



Figure 65 - The Zaphod (Mark IV) Glove (PS)



Figure 66 - Mark III Suit in Quarter 3 2015 (PS)

Business Model

PSF operates on a not-for-profit design and development model. It does not seem to generate revenue and no evidence of sales are available. In the past, the organization has relied on donation funding of money and even equipment for its activities.

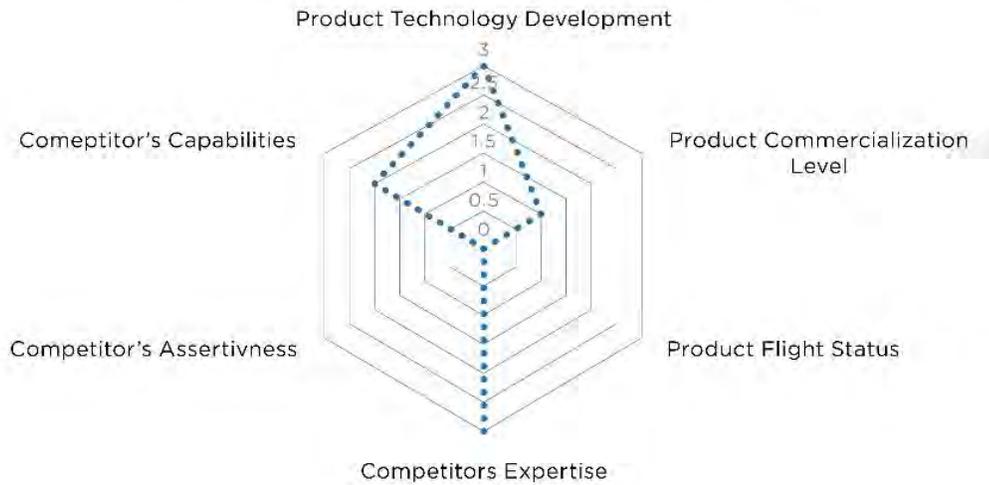
Competitive Landscape

PSF do not appear to have commercial intentions at this stage but they are testing an advanced IVA prototype and there would be little to stop them moving into a commercial space (other than the challenges of moving from a non-profit to a profit structure). The design does not seem to incorporate anything more than incremental design and no advanced technology. The pressure suit prototypes are

undergoing testing and are at a developed test stage but are not intended to fly at this stage. *Product Technology Development 3/5; Product Commercialization Level 1/5; Product Flight Status 0/5*

The organization has developed suits that have passed high levels of testing successfully and they seem capable of development of an IVA suit that may be operational in the future. However, there are no indications of a commercial intent and the organization has made no moves to position itself as a competitor in the industry. The organization do not seem to have any manufacturing capability in order to generate more than prototype numbers of suits. *Competitor's Expertise 3/5; Competitor's Assertiveness 0/5; Competitor's Capabilities 2/5*

PACIFIC SPACEFLIGHT



Flagsuit

Flagsuit developed a new type of EVA glove that would be more dexterous during an EVA. The company was the commercialization of a winning entry in NASA's Astronaut Glove Challenge in 2007. However, the company's website has not been copyrighted since 2012 and there have been no updates to the news section since 2011. There is also no record of activity from this company since 2011.

History, Products, Customers: http://www.flagsuit.com/Flagsuit_Datasheet.pdf



Figure 67 - Flagsuit Gloves Designed in 2008 (Flagsuit)

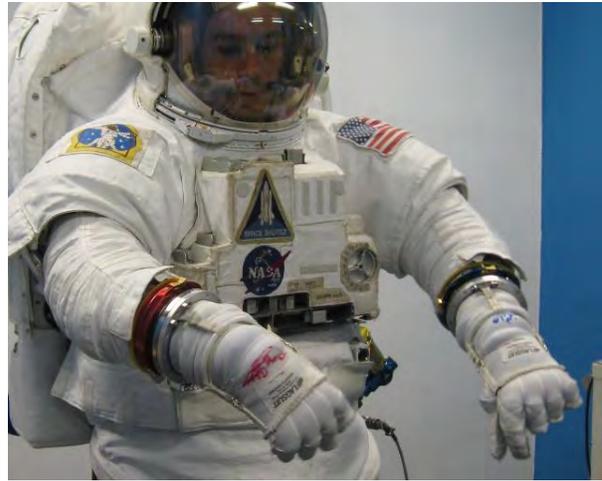
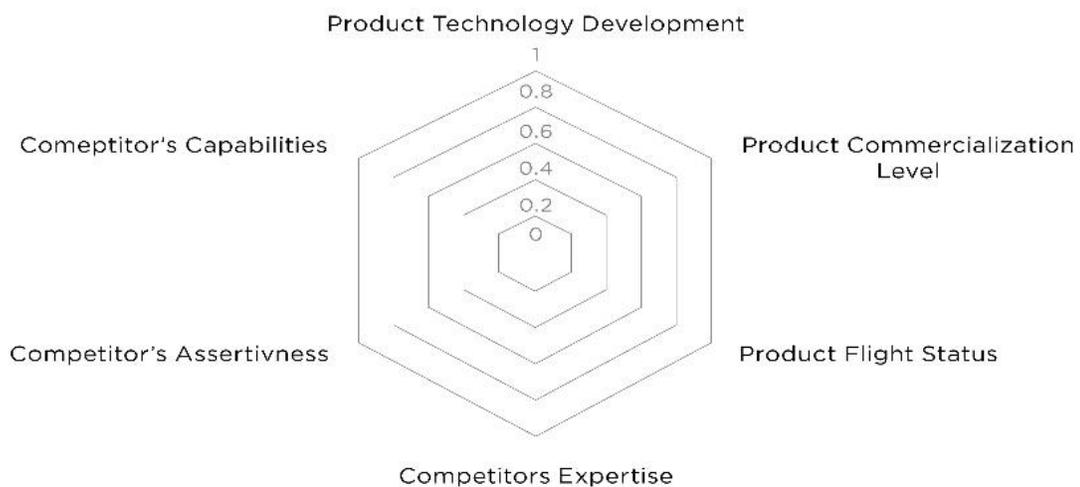


Figure 68 - FLagsuit Gloves Attached to a NASA Spacesuit (Flagsuit)

FLAGSUIT



Other Organizations

MIT Bio-suit

This technology is not associated with any company, but is under development by the Department of Aeronautics and Astronautics and the Man Vehicle Laboratory at MIT. It has been funded by NASA and MIT.



The professor leading the research has been involved with 'bio suit' type mechanical counter pressure spacesuit research since the early 2000s²³³, although it is unknown how long this particular suit has been in development.

Product Range

The MIT Bio-suit²³⁴ is a new type of material developed at MIT that may lead to a new type of pressure suit. The suit will function as a Mechanical Counter Pressure (MCP) suit. A spacesuit that uses mechanical compression would be an evolutionary step in design as it would likely allow much smaller, more maneuverable and much lighter spacesuits.

The MIT material avoids the major issue with current mechanical compression suits, the difficulty entering a tight suit. The MIT material is built with coils of memory material that is activated by heat. This allows a suit to be entered easily and then tightened around the occupant.

Further it is unknown how the suit will function in relation to heat retention or reflection and radiation absorption or reflection. How the suit will work in an environment where it may be damaged also remains to be seen. It is unlikely that the material will lead to a single layer spacesuit but if successful it will greatly reduce the bulk, weight and immobility of current spacesuits.



Figure 69 - The MIT Bio-Suit (Joshua Dalsimer)



Figure 70 - MIT Bio Suit Vision promises to be very flexible (Dava Newman/MIT/Douglas Sanders)



Figure 71 - The MIT Bio Suit Vision (Jose-Luis Olivares/MIT)

²³³ David, Leonard. Bio-spacesuits eyed for 'extreme exploration'. *CNN News Website*. [Online] 26 January 2005. [Cited: 29 November 2015.] <http://edition.cnn.com/2005/TECH/space/01/26/bio.spacesuits/index.html?iref=newssearch>.

²³⁴ Newman, Dava. Building the Future Spacesuit. *Ask Magazine*. Winter, 2012, 45.

Competitive Landscape

The current MIT testing was only undertaken on a small circular band²³⁵, tightening around a single axis. In order to be developed into a functioning compression suit will take much more time. The ability to compress in three axes and the design required to deliver the compression to a human body will take much more experimentation. The design will be a leap in technology but a tested and functioning suit is not likely in the near future. *Product Technological Development 5/5, Product Commercialization 0/5; Product Flight Status 5/5*

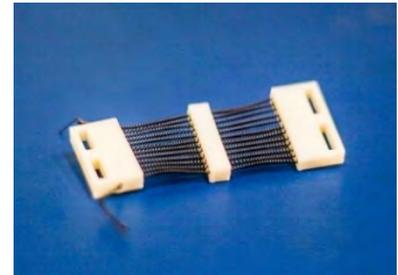
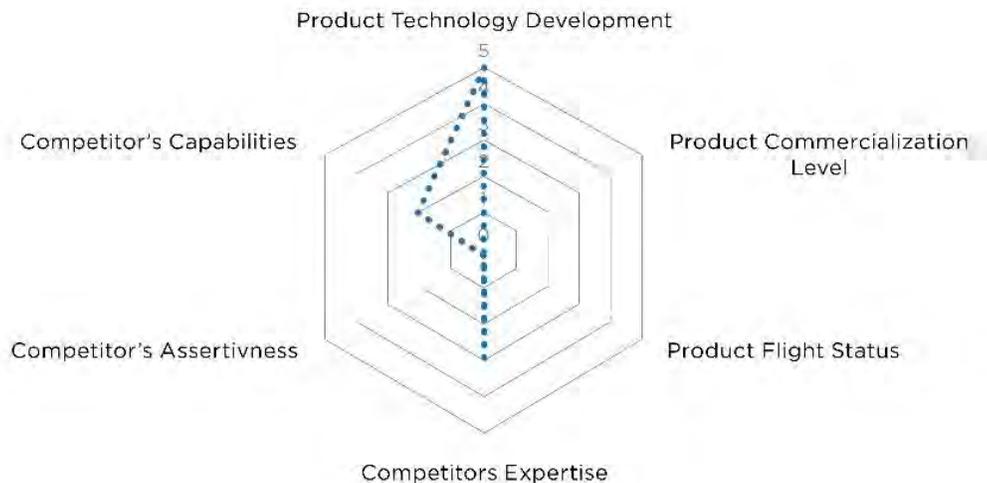


Figure 72 - A close-up view of a 3-D-printed shape memory alloy (SMA) cartridge that packs 24 SMA actuators into a 1-inch-wide structure designed specifically for active compression garments. Credit: Jose-Luis

As the company that will commercialize the suit has not been setup it has no manufacturing capabilities and has no potential of capturing market share in the near future. The company will likely have the leading designers of MCP suits. *Competitor's Capabilities 2/5; Company's Assertiveness 0/5; Company's Expertise 3/5*

M.I.T. BIO-SUIT



²³⁵ **Chu, Jennifer.** Shrink-wrapping spacesuits. *MIT News Office Website*. [Online] 18 September 2014. [Cited: 09 August 2015.] <http://newsoffice.mit.edu/2014/second-skin-spacesuits-0918>.

Austrian Space Forum (Österreichisches Weltraum Forum)

The idea to use a Forum as a communication tool for space enthusiasts, experts, and the next generation of specialists was born in 1997 during the International Astronautical Federation Conference in Turin, Italy. During 1998 and 1999 the Forum organized a number of events and expanded in 2001 to involve projects and workshops.



The Austrian Space Forum (ASF) has developed a number of pressure suits and 'simulations' in order to advance knowledge and develop strategies that can be used during space exploration. They do not appear to be commercially motivated.

Formation History

The ASF is a 'citizen science organization for space professionals and people with a passion for space'. It collaborates with both Austrian and international research institutions and acts as an interface for the Austrian space sector. The company does not appear to be a profit seeking venture and it seems to be based around the search for knowledge than designing and manufacturing a commercial spacesuit.



Figure 73 USA (Utah) / AustroMars Simulated Mars Mission 2006.
Credit: Austrian Space Forum

The organization has run a number of 'Mars simulations' involving human test subjects and a number of different devices. The simulations are run almost every year, the most recent of which was August 2015. They have designed and tested a number of pressure suits including the Aouda X and Aouda S and a number of robotic vehicles and 'mars habitats'. The organization has also run a transatlantic voyage to further study human effects of isolated travel.



Figure 74 - Morocco Mars Simulation 2013 and the Aouda X Spacesuit (Austrian Space Forum)



Figure 75 - Aouda X and ESA's Eurobot on the Rio Tinto 2011 Mars Simulation (Austrian Space Forum)

Product Range

The Aouda X and Aouda S are two units that have been developed to act as a Mars Spacesuit Simulator on Earth. The simulations relate only to EVA on a planet surface. The suit is not designed for use in space (or any kind of extreme environment) or any apparent commercial use but the training of

potential astronauts and development lesson that may be utilized on later projects. ASF has developed and tested a number of rover and habitation systems.

Business Model

ASF appears to be a not-for-profit research and development organization. They do not appear to have a profit motive and have not maneuvered to commercialize their technology, suit, robotics or habitat.

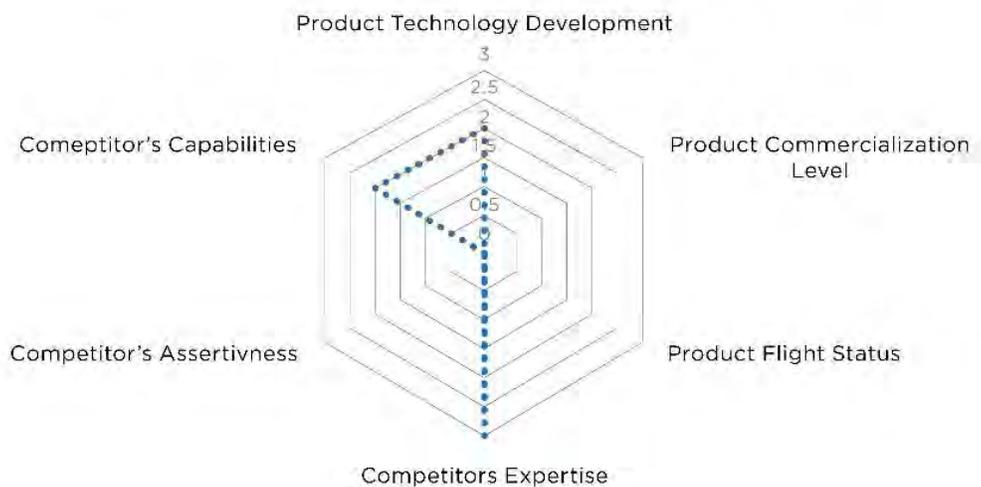
Competitive Landscape

The organization has successfully designed and tested a number of suits, rovers and habitats. However, the suits were not designed to operate in orbit but do show elements of high technologies and more than incremental design. ASF does not have any manufacturing capabilities and would need many additional resources to add more than a prototyping capability. *Competitor's Expertise 3/5; Product Technology Development 2/5; Competitor's Capabilities 2/5*

ASF has never pursued commercial contracts or attempted to influence the market. It has been unaggressive commercially and as the environmental pressure suits are not designed commercially they are not similar to the commercial IVA market. *Product Commercialization Level 0/5; Product Similarity 0/5; Competitor's Assertiveness 0/5*

This company does not pose a great or immediate market threat as their suit is not designed for use in space, use for IVA or use commercially and the company does not appear to be a profit making enterprise.

AUSTRIAN SPACE FORUM





SPACE ANGELS
NETWORK