Space Suit and Protective Equipment Technology for Commercial Launch and Entry Applications

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Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Conops</td>
<td>Concept of Operations</td>
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<tr>
<td>COTS</td>
<td>Commercial Off the Shelf</td>
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<td>CO2</td>
<td>Carbon Dioxide</td>
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<td>EMU</td>
<td>Extravehicular Mobility Unit</td>
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<td>EVA</td>
<td>Extravehicular Activity</td>
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<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>LEA</td>
<td>Launch Entry Abort</td>
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<td>OSHA</td>
<td>Occupational Safety and Health Administration</td>
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<td>PPE</td>
<td>Personal Protective Equipment</td>
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<td>PPS</td>
<td>Personal Protective System</td>
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<td>TRL</td>
<td>Test Readiness Level</td>
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I. Abstract

Commercial spaceflight is growing rapidly and advancing towards human-rated vehicles to support flights to the International Space Station, and commercial endpoints. Provisions for human safety and performance in nominal and emergency situations will be critical to the creation of a reliable space transportation system. Commercial space companies are considering various approaches to Personal Protective Equipment (PPE) ranging from emergency breathing systems to space suits. Several hood/mask and space suits have been developed recently for application in commercial spaceflight. These suits and masks were designed to leverage commercial PPE technologies, such as chemical protective suits and Portable Air Purification Respirators, to minimize production cost and performance risk, and increase safety. By blending components and technologies from existing space suits, commercial PPE, and emerging technologies, an optimal approach to crew protection can be achieved for each vehicle type. This paper will discuss considerations for developing a commercial PPE system for use in space flight applications including system requirements, aesthetics, design and performance details of recently developed equipment, and what is required to transition this equipment into use on commercial vehicles.

II. Introduction

Commercial spaceflight offers the opportunity for unprecedented access to the space environment. Lower cost flights will allow more science, research, and the emerging market of space tourism to flourish. In 1984, Ronald Reagan then President of the United States signed the commercial space act into law. This law encourages the private sector in commercial space endeavors and addresses the need to have ready access to space.¹ Since that time, commercial companies have been competing to become a provider to both government and private customers. Since 2006, the FAA has reported that there have been 24 significant permitted launches by 4 different corporations.² This is the dawning of a new and exciting industry, but in the race to be the first commercial space flight provider care must be taken not to forget the lessons that have ruled new endeavors in the past. These lessons learned must be on the forefront of the minds of those that are paving the way for our future. A few are discussed later in this paper but perhaps the most important lesson learned from the past is that safety is crucial and the loss of life must be treated with the utmost concern. One of the fundamental canons in the engineering code of ethics is that engineers shall

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hold paramount the safety, health and welfare of the public in the performance of their professional duties.\textsuperscript{3} Up to this point, the commercial space industry’s focus has been on launching cargo into space. While this is an important and necessary first step, close behind is the desire to start sending crew and passengers as well. Crew and passenger safety is critical to the success of commercial spaceflight. Any loss of life has the potential to impede the commercial space industry for years. There have been 18 in-flight fatalities and 18 active duty fatalities relating to astronauts dating back to 1964.\textsuperscript{4} Each of these losses was significant and reverberated through the community and in some way affected the progress of our exploration of the cosmos. But as noted by author David Shayler, “without passing the limits of both humans and machines, and testing ourselves against the unknown, no progress would ever be made. As with most affairs, preparation is paramount. For spaceflight, such preparation means endless hours in trainings, simulations and practice, and the evaluation of every possible contingency.”\textsuperscript{5} Unfortunately, the development of personal protective equipment (PPE) to ensure the safety of these first pioneers has already lagged behind. NASA is aware of this lack of development and has been actively trying to fund programs that will help with the development of a low cost PPE solution for the commercial industry. In 2006, Citizens in Space, a project of the United State Rocket Academy, persuaded NASA to request money for funding a low cost space suit centennial challenge in the FY07 budget, however this was later denied due to budget cuts.\textsuperscript{6} In 2007 and 2009, NASA funded the Astronaut Glove Challenge through its Centennial Challenges program in which NASA sought “innovative glove design concepts to reduce the effort needed to perform tasks during spacewalks.”\textsuperscript{7} Additionally, in 2013 NASA funded the development of a single layer, high performance pressure garment shoulder joint for use in commercial space suits as part of its Small Business Innovative Research (SBIR) awards.\textsuperscript{8} There is a common phrase often applied by the commercial industry and even adopted by NASA which is “faster, better, cheaper”. Although a noble cause, this approach can be used as an excuse to downsize or take unwarranted shortcuts with safety, testing, or quality. However, treating it as a disciplined, deep practice provides excellent results.\textsuperscript{9} For the best results, crew safety needs to be developed concurrently with the vehicle design to ensure proper compatibility and maximum safety.

As stated in the Lessons Learned Study Final Report authored by Langley Research Center, “When a prime

![Figure 1. Blending technologies & processes from commercial PPE and NASA/military full & partial pressure suits will aid in creating low-cost commercial space suits.](image-url)
contractor is expected to be the user for a technology development program, that contractor should be involved throughout the development to assure the product has maximum utility with minimum rework." \(^9\)

Understanding, analyzing, and mitigating hazards that affect the crew early on eliminates the need of retro fit and redesign which will impact program cost and schedule. To mitigate the risks, it is essential to have experienced personnel on the spacecraft development team who have experience in designing PPE for human spaceflight. Having an experienced team reduces the learning curve that is required to come up to speed designing and manufacturing a complex system. NASA utilizes the Wright and Crawford learning curve effect in helping to estimate the cost of large systems and therefore understand the importance of experience. \(^11\) While NASA continues to look to other non-traditional sources for innovation in key technology areas, they tend to rely on experienced teams to deliver actual flight hardware. Developmental and system life-cycle costs can be reduced through assembling an experienced team that can effectively draw from experience and apply lessons learned in similar developments. In addition to experience in designing space ready systems, it is also necessary to understand the commercial market and the drive to make products for the consumer appealing, comfortable and low cost. This is the new business of space suit design: to satisfy the needs of commercial customers, whether that means redesigning survivability into a more compact more aesthetically pleasing package, or coming up with novel, cost-saving innovations in structure and materials selection. \(^12\) Drawing from experience and lessons learned designing spacesuits and other military or industrial PPE and being able to determine how to combine and test those technologies while minimizing cost but maximizing safety will reduce potential impacts to cost, schedule and risk in the development of this next generation of personal protective system (PPS) (Figure 1). Examples of lessons learned include the strength required in the garment to overcome “manloads”, reductions of strength in textiles & membranes from flex-cycling, and the impact of combined environmental effects on materials and mechanisms. These are experiences that have taken decades to fully understand are often not in the open literature. A good development team will understand that “you don’t know what you don’t know” and seek experience to fill the gaps to reduce risk. Conversely, examples of components that can be brought forward from commercial protective equipment include neck-dams & valves from commercial respirators, footwear, and materials, to name a few. Drawing solutions from existing products has the potential to reduce development cycles and cost. However, direct application of existing components into new systems can also present unforeseen problems and must be well understood before implementation.

Just as commercial flights into space are an emerging technology, so are the PPS systems that will protect the pilots and passengers of these vehicles. Performance needs may differ for the type of work required by the PPS wearer. Pilots, who are trained to perform emergency procedures, may require systems with greater mobility and performance than passengers who simply require protection. New research is being performed in the development of appropriate protective equipment for commercial spaceflight use by several companies and universities, however much of this information is not readily available yet. This paper will discuss considerations for developing a commercial PPE system for use in space flight applications including system requirements, aesthetics, design and performance details of recently developed equipment, and what is required to transition this equipment into use on commercial vehicles.

### III. Systems Approach to Design

A systems approach used by both vehicle providers and PPS manufacturers will ensure that the PPS design is optimized and that it is the best blend of technologies, comfort and safety while not being cost restrictive. The systems approach as summarized in Figure 2 starts at the top with the customer requirements and will divide those into crew and passenger performance metrics as well as necessary protection components (defined by the customer or government regulations). This is currently a moving target as customer requirements and regulatory requirements are not yet solidified and will require the PPS provider to

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**Figure 2.** A systems engineering approach to PPS development assures design optimization to balance all needs including cost.
work closely with the customer and governing bodies to anticipate future needs and adjust accordingly. The PPS should be developed concurrently with the vehicle design and as new regulations are formed to ensure that all requirements are met with iterations. Governing bodies, as in this case the FAA Office of Space Transportation, are working to define research roadmaps to regulate the commercial space industry. In 2010, the Center of Excellence (COE) for Commercial Space Transportation was formed within the FAA with the goal of identifying solutions for existing and anticipated commercial space transportation problems. Their approach is to gather leaders from industry and collaborate on the best areas of research to further the commercial space market. As milestones are reached, new problems will arise and new areas of research will be needed. The COE is cultivating a living document that they will maintain as a standard that other organizations may utilize.\(^\text{13}\)

It is desirable to define the vehicle architecture and concept of operations (Conops) for the PPS concurrently. This will aid in further requirement definition for the PPS such as needed mobility, potential hazards that maybe encountered both in nominal and in off-nominal conditions. Some commercial drivers are at odds with traditional space suit specifications. An example of this is cost. While cost is always a factor in any government funded program, this requirement more strongly drives a PPS developed for a commercial environment into a range that is considerably less than that of traditional systems. PPS designers need to look to approaches from the commercial world for how to reduce cost while maintaining a high level of safety. An example of this is material development. Typically, traditional space suit designs have allowed for investigation into new and world for how to reduce cost while maintaining a high level of safety. An example of this is material development. Typically, traditional space suit designs have allowed for investigation into new and sometimes even custom made materials for the suits which requires extensive certification testing for use. Commercial systems most likely will not be able to afford any custom and therefore costly material selections and will cause commercial designers to be experienced in material selection and turn to COTS materials that are readily available.

Once the requirements and ConOps are defined, trade studies will be performed to identify one solution that will be best for the transport system being studied. It should be noted that commonality between space suit platforms will reduce life-cycle costs for each commercial customer, and is therefore a goal for space suit developers. Testing is then performed to verify/certify technologies and systems required to human rate the PPS for flight and also verify PPS vehicle interfaces. Ultimately, the type of testing required will be principally customer and vehicle specific but the PPS manufacturer will most likely be required to test to certain criteria.

Testing will include but is not limited to:

- Isometric Manloads – the suit’s ability to withstand loading from the occupant “stretching” in a properly fitted suit
- Cycle Performance – the suit’s ability to not degrade from repeated flexing in the unpressurized and pressurized states
- Materials Properties – the ability of the materials to withstand environmental exposure, combined effects, and human interface
- Ergonomics – the operational characteristics of the human machine interface – donn/doff, helmet operation, comms, vehicle interfaces, etc.
- Egress Performance – the mobility and human physiology characteristics during emergency events (speed, smoke, low light, water, etc.)
- Extraction – interface and performance of an extraction harness for use in emergency operations
- Acceleration Loads & Vibration – the component and systems ability to withstand loads imparted during launch/landing & emergency events
- Hazardous Environment Performance – The ability to protect the occupant from smoke, flame, and exposure to toxic substances
- Comfort – physiological factors during all aspects of suit use – thermal, pressure points, acoustic, breathing, etc.
- Mobility – reach envelopes, kinesthetic motion performance under all flight and emergency situations, pressurized and unpressurized

Figure 3. Testing of the PPS will require an understanding of multiple overlapping requirements

American Institute of Aeronautics and Astronautics
Again, it should be noted that many of these test practices reflect a depth of understanding of pressure suit design that comes from experience, and can be easily overlooked by a less-experienced design team. Maturation of the system through informed testing practices will ensure a high level of confidence that the PPS is ready for commercial use.

IV. Driving Requirements

Identifying and reacting to the driving requirements of the commercial PPS will ensure the development of a low cost, safe, and comfortable solution that will facilitate human rating of the vehicle and encourage the use of the system. Vehicle providers are not only looking for a way to provide “safe” travel into space but they also want to create their own brand image that attracts customers to their services. Virgin Galactic’s website is replete with images showing tourists riding in their space plane with sleek, futuristic looking white suits on with gold and white sun visor helmets. It’s obvious that they are going for a specific aesthetic and emotional response. In general, the “look” of the space suit will be one of the most important factors in getting both the vehicle provider and crew or passenger to want to use the PPS early on. There must be a balance of being aesthetically pleasing to match the customer’s theme and providing a safe and comfortable end user experience for the commercial space suit to be effective. Ultimately, there will be many requirements that will affect the design of the PPS. Some will be customer driven, others driven by the design of the vehicle, and still others will be determined by governing bodies such as the FAA that regulate private companies offering trips to space. The best method for meeting these requirements is to design the PPS using a systems engineering approach. The following requirements outlined in this paper offer some insight into a few of the main drivers affecting the design but is not intended to be an all-encompassing list or reflect order of importance.

A. Cost

In addition to aesthetic appeal, cost is one of the major drivers that will impact the design of the commercial PPS. Going to space is a costly enterprise. Competitors will want to win over potential customers by offering affordable solutions for reaching low earth orbit. The cost of “interface” transportation between the surface of the Earth and low orbit is the determining factor in the feasibility of many schemes for space industrialisation. According to SpaceX’s current launch model, launches that are below 6.4 tons cost $83 million and launches that are above 6.4 tons cost $128 million. Other companies launch cost will be similar which will ultimately be passed on to the customer in the cost of the trip. Companies will be looking for ways to reduce overhead and offer more affordable solutions to open up their market.

Vehicle safety systems may eclipse personal safety systems and some vehicle providers may even feel that a robust vehicle safety approach can eliminate the need for personal safety equipment. Vehicle providers will utilize a cost-benefit analysis that examines the cost of the PPS verses the risks and costs of the loss of mission and the loss of life. Therefore, the commercial PPS must be optimized and offer an attractive price tag to keep vehicle providers interested. In this case protective equipment can be related to a “wellness program” in that paying for it and adhering to it seems like a drain on the bottom line…until it saves your life. There are many factors that influence the cost of a multipart system, especially when it is responsible for protecting life. While safety of critical importance and cuts should never be made to the quality of potential life-saving equipment, there are some approaches that can be applied to keep cost low.

The method of manufacture of the PPS will also influence system cost. Some configuration options require machined components or tooling to support the manufacturing process. The approach to sizing/fit magnifies configuration decisions and therefore cost because multiple sizes of items, or customization approaches that may be required to fulfill specific market approaches, impact stock & tooling quantities. Because of these variables, a careful look at the life-cycle cost of the system must be conducted early in the process.

Vehicle operators will need to decide if they want to take a one or multiple time use approach with the PPS design. Passengers may want the option to purchase their suit and take it home as a souvenir from their ride into space which could provide a means of revenue generation for the vehicle operator. Or, they may want to make the components that come in contact with the body easily replaceable and disposable to eliminate odor and biohazard issues, and reuse everything else. The vehicle provider could setup a leasing system with the PPS manufacturer that would allow the suits to be used for a certain length of time and then returned for refurbishment. The type of approach for PPS use will further drive some cost requirements and will need to be factored into the configuration decisions. Reusable systems do incur some extra costs that a one-time use system would not such as maintenance, storage, wear, maintenance & acceptance testing, and the cost of resizing to properly fit the wearer. However, a
reusable system would allow certain hardware and softgoods to be reused multiple times and the cost savings would then be realized by the vehicle operator.

Finally, trades will need to be made to determine whether components in the PPS system are designed and manufactured from scratch, modified from an existing product, or simply added to the system as a commercial off-the-shelf (COTS) item which requires little to no modification to use. One approach is for the PPS to be comprised mostly of COTS items which have already been proven effective in hazardous environments. These items, such as a respirator for smoke and chemical inhalation, will have already been certified to meet government standards and therefore not require development testing, except at the system level. However, this may not always be possible. Where there is not a COTS item available that can be easily integrated into the PPS, a compromise could be made where a COTS item is modified to work and would only require a minimal amount of certification testing to prove that it works. Finally, it may be found that there is not a COTS item that currently exists to meet a requirement and therefore may require an item to be designed from scratch. The optimal design of a low cost PPS will likely utilize components from all three of these approaches.

The PPS provider will need to draw on a vast array of experience in design and manufacture when considering all of these cost factors and will need to conduct appropriate trades and testing, to prove out that their design will meet all the requirements and minimize life-cycle costs.

B. Safety

Safety is paramount in driving the design of the PPS system. It will be necessary to identify all hazards that are present both in a nominal mission profile as well as in the event of an off-nominal emergency situation to create a unified system, and not a conglomerate of solutions. While modern commercial passenger flights have progressed to that point, going to space is much more risky. Previous accidents in space reinforce the idea that sending humans to space is an inherently risky endeavor, and will continue to be risky for quite some time. Many factors conspire to make this so, including the extreme energies needed to reach Earth orbit and the inhospitable environment of space. “We have to keep admitting that this is dangerous stuff, and we’ve got to treat it that way,” Bryan O’Connor, head of NASA’s Safety and Mission Assurance Office, told SPACE.com. “It’s worth doing, if we have a good mission. But we can’t underplay the risk of it.”

There are many hazards present even in nominal conditions in space flight that a PPS can provide protection for such as acoustic management, vibration isolation, thermal regulation, communication, and orthostatic intolerance protection. These hazards will be present in any vehicle going to space and can all be mitigated by the use of a PPS. In addition to nominal hazards, off-nominal conditions can also occur in an emergency. There is a need for impact protection, smoke and fire protection & visibility, cut and puncture protection, immersion protection, and in a worst case scenario a cabin depressurization. If the vehicle were to make an emergency landing, there may be a need for the crew and passengers to egress the vehicle or be extracted by a hoist and lifted to safety. The PPS provider will need to assess all of these potential hazards and build into the PPS solutions that will mitigate them to a safe level.

C. Aesthetics

As mentioned previously, the “look” of the commercial space suits will be of paramount importance for the commercial market. Vehicle providers will expect the suits to match their brand image and will use the look of the suit as a way to market to customers (Figure 4). The consumer wants to wear something that fits well and looks cool even at the cost of sacrificing performance and sometimes even safety.

Figure 4. PPS Providers must provide a look that will match vehicle primes branding

This phenomenon was noted in Atul Gawande’s book “Better: A Surgeon’s Notes on Performance”. In the book, Gawande notes that during the first Gulf war, soldiers suffered a high incidence of eye injuries. During the second gulf war the incidence of eye injury dropped to nearly zero. He attributed this effect to the difference in style of the dust, wind & sand goggles worn during the 1st Gulf war and the Oakley sunglasses worn during the 2nd Gulf war. The sunglasses were very well styled and made the wearer look “cool” as opposed to the dust, wind and sand goggles. The style drove usage over safety. This phenomenon will apply to commercial space as well. Customers
will want to use a space suit if they think it looks cool. This will require the PPS provider to pay special attention to the types and colors of materials that are selected for the suit and cleverly balance them with safety needs (low light visibility, reflectance, flame retardancy, etc.). Suits will be expected to be conformal and form fitting unlike traditional space suits of the past. This will require some innovation in material handling so that the suit unpressurized looks well managed and not bulky. Clever uses of contour lines, styling, and materials can give the garment the illusion that it is more conformal than what it needs to be for protection in the pressurized state. Other components of the PPS will need to be styled as well. The entire system must promote itself as being desirable to wear.

D. Comfort

Comfort will become important once the consumer begins using the suit and determines whether they have a favorable impression of how it feels. Once the PPS is donned, the wearer will immediately begin to take note of the fit including constriction, contact points, bulk, skin contact feel, thermal build-up, and motion inhibitors. In the commercial world, consumers are accustomed to assessing how a new article or clothing feels and will make purchasing decisions based on this feedback. In a similar way, a passenger buying a ride into space will want to be comfortable on their journey, not hot and irritable because they are encumbered by an poorly fitting suit that draws their attention away from the flight experience, or worse poisons it. Consideration will need to be given to preventing compression “hot spots” from forming on a person’s skin where equipment comes in contact. Most likely, the crew member or passenger will be sitting in a seat for prolonged durations wearing the garment so it will need to be free of any hard contact points that would cause irritation after prolonged use. Finally, the PPS will be the interface between the person and the rest of the cabin in the vehicle, so the ergonomics of the suit will have a large impact on the perception of comfort of the wearer.

E. Performance

Performance speaks to how well the PPS accomplishes given scenarios measured against predefined standards. This can include factors such as range of motion, visual field of view, tactility, etc. The PPS’s performance will be evaluated both at the component and at the system level. Heritage flight programs will be used as a baseline against which to measure performance. Derived requirements from the vehicle architecture and conops will be used to determine what the performance characteristics of the PPS should be. For example, if the vehicle has a hatch on the top of the cabin that is accessible via a ladder, then in an emergency scenario it could be feasible that a person would need to be able to egress out of the hatch while wearing the PPS. The performance indicators will show things like the mobility and range or motion performance for all possible scenarios, and how easy it is for a person to don emergency equipment in a hazardous situation (Figure 5). Part of the challenge of delivering an optimized PPS will be determining all operational scenarios and design equipment that can function adequately in every scenario, while balancing all other requirements. Laboratory testing of components as well as human performance testing of the system will be performed to derive certain performance requirements. Other important performance factors include items such as mass of the system, and stowed volume.

Figure 5. Performance of the PPS will need to be evaluated at both the component level and the system level to derived vehicle requirements
V. Historical Perspectives

Commercial space suit providers will enhance their chances of development success if they are able to draw from lessons learned from previous space suit and commercial PPE (respirators, chemical protective suits, etc.) development and operational performance. Some of these lessons were given in “Lessons Learned Final Study Report” led by Langley Research Center in 2004 and are applicable to this paper. They include:

- **Human space flight experience is critical**: The experience of human space flight developers, managers, and operators is different from that of other engineering endeavors. In order to avoid repeating costly mistakes, key leaders in these areas must have personal experience in the unique opportunities and traps of human space flight.

- **Early identification of appropriate, validated requirements is key**: The complexity of human space systems makes their success totally dependent on effective systems engineering. Requirements identification and management is the life-blood of systems engineering, so the success of the program depends critically on the quality of the requirements provided at program implementation.

- **COTS systems have potential to reduce system costs**, but only if all of their characteristics are considered before hand and included in the planned application.

- **COTS systems that look good on paper may not scale well** to NASA needs for legitimate reasons. These include sustaining engineering/update cycle/recertification costs, scaling effects, dependence on third party services and products. Need to assure that a life-cycle cost has been considered correctly.

- **The risk to the crew is a major driver for technical issues**, often leading to late band-aid fixes to critical problems, with associated cost and schedule growth. Early claims of high reliability in hardware and software are frequently not substantiated by detailed analyses such as FMEA, hazard analyses, and probabilistic risk analyses. Realistic or conservative expectations of system reliability, reflected in appropriately robust system design and crew escape capabilities, are net cost savers.

- **Do not underestimate the impact of human rating and crew survival requirements** through all aspects of its human space flight program.\(^\text{10}\)

It is most beneficial if designers have a broad spectrum of experience in many forms of protective equipment including full pressure suits, partial pressure suits, anti-g suits, air crew respiratory protective equipment, rescue devices, and commercial/industrial respiratory protective equipment such as Portable Air Protective Respirators and Escape Masks. Lessons learned from previous experience and the ability to harvest appropriate components and technologies from prior products will facilitate building the optimal commercial spacesuit. Examples of lessons learned include the strength required in the garment to overcome “manloads”, reductions of strength in textiles & membranes from flex-cycling, and the impact of combined environmental effects on materials and mechanisms. Examples of components that can be brought forward from commercial protective equipment include neck-dams & valves from commercial respirators, footwear, and materials.

Space suits developed for NASA use have relied almost solely on astronaut subject critique & guidance\(^\text{19}\) which presents both positives and negatives when designing a suit for commercial use. Astronauts are able to provide invaluable insight due to the experiences they have had using suits in the respective environments both for launch / entry and for Extra-Vehicular Activity (EVA). However, using only astronauts to guide emergine commercials suits may not yield the full-picture of what commercial passengers will desire and expect. Astronauts often come from military backgrounds where they are very used to performing work in protective equipment, or are highly educated mission specialists who spend considerable time training in protective equipment for their missions and embrace its importance. Commercial passengers will likely have a different mindset, level of understanding of safety, and education, so the equipment will need to reflect these needs. Developers of commercial space suits and respiratory protective equipment must be able to test new concepts on a wide spread of test subjects that will represent the user population. Techniques borrowed from the commercial world (testing subjects with the

![Figure 6. Test procedures used in commercial PPE development such as Protection Factor testing shown here, are](image-url)
anticipated experience level) will need to be employed to provide appropriate data for design guidance (Figure 6).

It is also important that commercial space suit designers have experience working with human factors. Important physiological factors include hypoxia and hyperoxia, hypercapnia, temperature regulation, g-tolerance, and decompression sickness. Also designers need to be well versed in anthropometrics to create proper sizing schemes to fit the population. Understanding sizing and fit requirements will have an impact on decisions that greatly impact the life-cycle cost model as the developer will determine if the suits will be custom sized, reusable standard sizes, or have replacable components (for hygiene purposes). Space suits have been custom sized as with the Apollo suits, and produced in reconfigurable standard sized components Shuttle Extra-Vehicular Mobility Unit (EMU) program. PPE products such as military or commercial respirators are designed to fit the anticipated population through as small a number of standard sizes possible. Care must be taken by the commercial suit designers to pick a scheme that will bring the best of both worlds together while keeping costs down but also providing a unique user experience. Experience in designing customized and standard sized suits and other PPE will factor into the aesthetic and desirability of the PPS. Employing techniques learned from previous programs such as effect ways to utilize draw strings, elastic bands, zippers, and lacing to manage excess material help to keep costs down while still making the garment fit and be aesthetically pleasing.

VI. Transitioning Concepts to Flight Hardware

The ability to properly validate and certify a commercial space suit or other PPE is also important. This is possibly one of the most under valued and least understood parts of what it takes to protect lives in space. The key to being able to move concepts from concept to reality lies in being able to mature a system and raise its Technology Readiness Level (TRL) from a low to high value in a controlled and well understood manner.

Figure 7. The system developers testing and qualification facilities/experience can dramatically reduce development and life-cycle cost and risk

The PPS system will most likely be composed of a combination of COTS parts, modified COTS parts, and parts designed from scratch, so varying component TRL’s will be observed. However, the PPS system will collectively be at a level that reflects the TRL of its lower TRL components and will therefore require staging through a rigorous test and certification program. This will begin at the analysis level and will combine experience from legacy hardware already certified and component bench top testing. Finite Element Analysis (FEA), or other tools, will be used to numerically test components prior to fabrication when practical. Next, components and subassemblies will
be subjected to a series of tests including impact, vibration, and hardness if it is hardware and tensile, abrasion, wear, and seam construction testing.

At a system level, many tests that are typically unique to space suit or PPE development will be performed to raise the overall TRL of the system (See Figure 7). Some examples include impact testing for helmet design, CO₂ washout testing for face masks or helmet bubbles, protection factor testing of filters, and human performance testing of the entire PPS. Human testing will include range of motion, joint torque assessments, timing events such as vehicle ingress/egress, thermal comfort, and field of view.

Validation of the design is then followed by the certification process. Certification is a rigorous process by which the system is tested to reflect its useful life. This can include flex cycle testing, pressure cycle testing, vehicle interface testing, and numerous other tests that reflect what the system will be exposed to in its useful life. Detailed inspections are conducted throughout the process to document and understand the effects of use of the system in respective environments. Flight certification is verification that the [PPS] meets requirements, and validation that the design and manufacturing process can be reproduced for flight. It is the final gate and one of the most expensive parts of a [PPS] development program due to the cost of flight hardware, manned testing, and rigorous documentation.²⁰ It will be paramount in keeping the cost of this testing down by drawing upon experience certifying hardware for flight use.

Each PPS system will be subjected to pre-delivery acceptance testing as a quality control measure. This will ensue that each unit meets the required specifications aiding in quality and reliability assurance.

### VII. Recent Technology Advancements

Several companies have been working on developing new technologies for use in commercial space flight. A few examples include FlagSuit LLC which is working on developing low cost, space suit gloves and David Clark which recently had a successful test of their commercial space suit at altitude which was used for the Red Bull Stratos jump.²⁰ Over the past few years ILC Dover has been developing prototype commercial space suits for demonstration and testing (Figure 8). This paper will focus on technologies being developed by ILC.

![Figure 8](image8.png)

**Figure 8.** ILC launch/entry space suits. From left to right: ESR3D Suit, ZEI Suit, Pathfinder Suit.

The ILC suits were built under several different contracts to demonstrate new technologies that can be incorporated into commercial suits. These concept demonstrator suits were developed using the principles discussed previously and have been used in a variety of tests including comfort evaluations, pressurized mobility, seat interface, extraction, egress, range of motion, torque, CO₂ washout, PPE component integration, and thermal control to collect data on suit design. The opportunity to develop new suits has facilitated the incorporation of new technologies that will help to increase the comfort and functionality of future suits. Numerous advancements were made in developing low-cost, high-performance suits, but only a few of them will be discussed here.

Safety requirements may determine that it is necessary for crew and passengers to wear a helmet for impact and respiratory protection during launch and re-entry. Traditional rigid helmets do not pack well

![Figure 9](image9.png)

**Figure 9.** A soft helmet and impact protection system offers convenience, comfort, and safety for passengers, while minimizing cost through hardware elimination.
so they require considerable stowage volume which will be limited on a commercial vehicle. ILC has developed a soft helmet approach to answer this requirement (see Figure 9). A soft helmet has benefits over rigid shell helmets in this case because it can be worn for launch and re-entry and then easily stowed out of the way behind the passengers head during zero-g activities. A conformal rigid visor provides a wide field of view and protection for the eyes. A pressure sealing zipper at the neck line provides an easy method for opening and closing the helmet and sealing it to the suit. Impact protection is provided via impact foam that is attached to a skull cap which is worn underneath the soft helmet. The foam is similar to the foam used for crash impact protection in NASCARs. ILC has developed this two piece system because it will meet the impact protection requirements but allows for the convenience of easy removal and stowage.

Adding a protective coverlayer over the suit offers several benefits that make it an attractive option. Beyond providing cut, abrasion and fire protection, adding a cover layer is an inexpensive method of customizing the look of the suit for different customers. It will also cut down on overhead cost of maintaining the suit by protecting it from wear and exposure to potential damage threats. In order to remain unobtrusive and keep the suit from being bulky, ILC has developed several innovative attachments methods to secure a coverlayer to the underlying restraint layer. The goal when designing these interfaces was to make the cover layer easily removable and replaceable while minimizing bulk and maintaining mobility. Concepts have been designed and fabricated that improve cover layer mobility and were evaluated in manned tests on both unpressurized and pressurized spacesuits. The effects of coverlayer segmentation on donning and doffing were also assessed to add in creation of a simple sizing system. Several different closure mechanisms for the cover layer were also designed and fabricated (see Figure 10). Further testing will be conducted to assess which segmentation options and closure mechanism will be best suited to fit a particular set of vehicle requirements.

![Figure 10. Innovative techniques are being developed for PPS cover integration and closure for commercial suits.](image)

Customers and vehicle providers will be looking for a spacesuit system that compliments their brand image. ILC has been studying brand imaging in an effort to meet this need. We have partnered with Philadelphia University’s Kanbar College School of design to understand how a spacesuit cover can be tailored to meet a each customer’s desired appearance reflecting their brand image. Philadelphia University is uniquely positioned for the task because of the close working collaboration between their fashion design and engineering programs. This allows them to create technical apparel that is aesthetically pleasing and at the same time meets performance needs. The process began with Philadelphia University students learning about space suit design and commercial suit requirements from ILC Dover Space Suit Engineers. The fashion design students formed small teams and performed background research to better understand the end customer’s history, desires (colors, themes, etc.), and related inspirational technology areas such as biometrics. Once the functional foundation and inspiration for company identities were established, the teams got creative and developed design concepts for the outer layer of a space suit. The mechanical engineering students reviewed and guided the design process to ensure functional performance goals could be met. Seven student teams participated and the top three were awarded prizes by ILC. ILC will draw from the creative concepts generated in this partnership in future commercial space programs as the commercial space industry matures (see Figure 11).
Technology innovations have also been made towards improving the comfort through an improved human interface. Several of ILC’s prototype commercial suits have incorporated a bladder made out of a breathable material which facilitates thermal regulation and moisture management. The breathable material is not air permeable but instead utilizes moisture vapor transfer (MVT) technology to pass water vapor through its structure. The materials used are hydrophobic meaning they have a microporous coating which contains pores that are small enough to allow water vapor through but not air molecules. Breathable material will help the suit to maintain a low humidity level thus making the wearer more comfortable.

PPS designers will need to utilize technology advancements to enhance the user experience so that both wearers and vehicle providers will see the PPS as an exciting part of the spaceflight experience. Improving comfort, ease of use, and style over traditional space suits will increase the desire to include the PPS as part of the overall package.

VIII. Conclusion

As the commercial space industry grows and establishes human-rated flights, they will develop protective equipment that meets their requirements. This will extend beyond the normal fit, form & function of NASA space suits, and be motivated by added needs such as cost and aesthetics that match economic models and marketing pressures. As with any commercial product development, it is advantageous to draw from existing or historical solutions, while blending in new technologies when developing a new commercial space suit or emergency respirator. Developmental and system life-cycle costs can be reduced through assembling an experienced team that can effectively draw from experience and apply lessons learned in similar developments.

From an outsiders perspective space suits, respirators and other protective equipment can appear to be simple in design and construction. However, experience dictates that this is not true and without proper precautions in system development, users can be seriously or fatally injured. A deep knowledge of the behavior of flexible inflatable structures made from textiles and membranes is critical to achieving the required system safety levels, while avoiding unforeseen risks that can dramatically escalate life-cycle costs with system failures, or worse yet, injure someone which can damage the credibility of the commercial endeavor and cripple its economic viability.

Many examples of components, processes or lessons learned that can be drawn from previous NASA programs and commercial Personal Protective Equipment to reduce cost and risk of future commercial equipment can be identified. Examples of lessons learned include the strength required in the garment to overcome “manloads”, reductions of strength in textiles & membranes from flex-cycling, and the impact of combined environmental effects on materials and mechanisms. Examples of components that can be brought forward from commercial protective equipment include neck-dams & valves from commercial respirators, footwear, and materials.

As a community, the commercial space industry must strive to create low-cost space suits and other equipment that emulates the look of the next generation of astronauts to draw customers and grow the market. However, safety
and performance throughout the systems life-cycle and in all emergency situations must also be considered to ensure success. Companies that understand this and can identify a balanced approach will likely become the industry leaders in a way similar to that of the commercial airline industry.

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