The Design and Development of an Extravehicular, Stratospheric Exploration (StratEx) Pressure Suit

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In October of 2014 a Stratospheric Exploration (StratEx) technical team comprised of ILC Dover, Paragon Space Development Corporation (SDC), and United Parachute Technologies (UPT) demonstrated an extravehicular pressure suit capable of prolonged exposure to stratospheric conditions by successfully launching, loitering, and recovering a manned StratEx suit to stratospheric, or near stratospheric altitudes, on three separate occasions. This paper will discuss the design and development of the pressure suit portion of the flight system including the challenges associated with loads management, environmental control, pilot accessibility of control systems, and design for rapid system turnaround. Component and system level testing is reviewed and lessons learned, along with suggestions for future flight systems, are presented.

Nomenclature

˚F	=	degrees Fahrenheit
ft	=	feet
g	=	one unit of Earth gravity
lbs	=	pounds
m	=	meters
min	=	minutes
mph	=	miles per hour
psi	=	pounds per square inch
psia	=	pounds per square inch, absolute
psid	=	pounds per square inch, differential
psig	=	pounds per square inch, gauge
s	=	seconds

I. Introduction

IN December of 2011 a StratEx team consisting of ILC Dover, Paragon SDC, and United Parachute Technologies was formed with the goal of designing and developing a pressure suit, launch, flight and recovery system that would enable a person to directly and safely interact with high altitude, stratospheric environmental conditions for an extended period of time. A small, lightweight, highly mobile single user system that operated in the same context as a SCUBA system for underwater survival and exploration was envisioned. Like a SCUBA system, one basic premise of this type of stratospheric exploration system was that minimal training would be required for its successful and safe operation thus opening access to the stratosphere for both leisure and scientific endeavors to those without an expert level of skydiving and ballooning experience. Such a system could then be applied toward more mission centric goals, such as applied science and exploration, than just merely successful occupant survival and recovery.

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A. History of Stratospheric Balloon Flights

The very first efforts to venture into the stratosphere using balloons began in the 1930s with altitudes of over 70,000 ft being attained; however they were limited by the heavy rubber materials used in the construction of the balloons at that time. While lighter materials were being investigated, the breakout of the Second World War interrupted high altitude ballooning for several decades. After the war, the introduction of these lighter materials, together with interest demonstrated by the United States military, reinvigorated research into manned access to the stratosphere. The following are the major United States historical military and civilian programs that have sought to provide this type of access.

1. Strato-Lab I-V[1]

High altitude exploration began in earnest in the 1950s and early 1960s with the Navy's Strato-Lab project which was initiated to look at biomedical requirements for America's manned rocket program and a myriad of other scientific objectives including gathering data in the fields of astronomy, atmospheric physics, and human physiology. Five numbered flights were undertaken and included both open and pressurized gondolas. Progressively they included flights that ranged from 76,000 to 113,740 ft in altitude. The longest of these flights, Strato-Lab III, reached 82,000 ft and remained aloft for nearly 35 hours in a pressurized gondola. Strato-Lab V, the last and highest flight in the series used an open gondola together with the B.F. Goodrich Mark IV full pressure suit, the precursor to the Project Mercury suits. This would mark the first use of a full pressure suit for exposed stratospheric ballooning.

Figure 1. Strato-Lab Capsule[3].

For all of these flights the aeronauts stayed with their respective capsule or gondola for the entire duration of the flight. A common theme amongst these flights was difficulty controlling the descent rate of the balloon. On more than one occasion unintentionally fast and potentially fatal descent rates had to be overcome by discarding all ballast as well as all other equipment that could be expended. The program's only fatality came after the successful completion of the Strato-Lab V flight when one of the pilots slipped into the ocean after a water landing and drowned when his suit filled with water and rescue personnel could not retrieve him in time.

2. Manhigh I-III[1]

As the Navy was progressing with their Strato-Lab program the Air Force was concurrently conducting a similar manned high altitude program of their own. Dubbed Project Manhigh, it began in 1955 with the objective of studying the effect of cosmic rays on human anatomy. For this project three flights were conducted using pressurized capsules each containing a single occupant. These three capsules achieved altitudes that ranged from just under 97,000 ft to just over 101,500 ft with Manhigh II setting the original endurance record of 32 hours before it was broken the following year by the Navy with their Strato-Lab III flight. As with the Strato-Lab flights, personal 'bail-out' parachutes were available for extreme emergencies, however the nominal concept of operations dictated that capsule pilots remain in the capsule from launch through to touchdown.

Both Manhigh II and III experienced difficulty with descent rate control which was made worse in the case of Manhigh III where the pilot also experienced a loss of cooling. This placed the core body temperature of the pilot in the range of 107˚ F for an extended period of time. If not for the unusual ability of the pilot to endure the elevated temperature, many associated with the program believe that conditions within the capsule would not have been survivable.

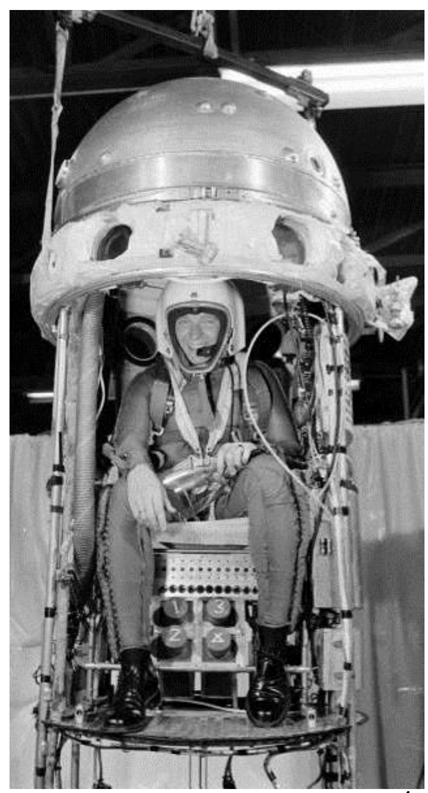

Figure 2. Manhigh Flight Capsule[4].

3. Excelsior I-III[1]

With the dawn of manned rocket flight in the 60s, and the increased ability of military pilots to fly higher and faster, there were increasing concerns regarding the ability of an astronaut or pilot to survive a high altitude ejection or bailout from an aircraft or spacecraft. Open questions about how a pilot should freefall after ejection, what altitude a parachute should be opened, and how a pilot would survive environmental conditions remained unanswered. And unfortunately low altitude testing could not provide either the right environmental conditions or freefall speeds necessary to provide these answers. Thus in 1959 Project Excelsior was authorized to perform a series of full-scale stratospheric skydives.

Despite careful planning and preparation, the flight of Excelsior I was a near tragedy. This initial flight was only slated for 60,000 ft, however helmet fogging and the glare from the unfiltered sunlight made it difficult for the pilot to read his instruments and arrest his balloon ascent. Additional problems in removing himself from his seated position prevented him from actually jumping until he was at almost 76,000 ft. During the descent the main parachute deployed early and in the thin air wrapped around the pilot's body before it could properly fill. The pilot also entered an uncontrolled flat spin which caused him to lose consciousness until after he had landed. Only a well-designed set of safety features built into the reserve parachute system saved his life.

Despite the near fatal outcome of Excelsior I project managers were able to secure the go-ahead for a second jump attempt. The difficulties encountered in the first jump, caused mostly by the unexpected effects of the extreme cold on the equipment, were taken care of in short order and less than one month later an Excelsior II flight was completed with a successful jump from 74,700 ft. The rousing success of Excelsior II paved the way for the ultimate goal of the Excelsior program, a jump from over 100,000 ft.

Almost one year later, Joe Kittinger, also the pilot for the first two Excelsior flights, made the historic journey to 102,800 ft where he would successfully survive a four minute and thirty seven second freefall of nearly 85,000 ft. The only major equipment malfunction of the Excelsior III flight was the failure of the right glove of Kittinger's partial pressure suit to pressurize properly. Post flight examination and testing of the suit concluded that the suit and pressurization system would have to be rethought and probably overhauled before any further altitude jumping could be conducted. Because the program had demonstrated such great success in its Excelsior III mission however, the decision was made to cancel the program rather than procure the budget required to upgrade the suit.

Figure 3. Joe Kittinger's Excelsior III stratospheric skydive[5].

4. Strato-Jump II-III[1]

Later in the 1960s amateur parachutist Nicholas Piantanida became obsessed with the idea of breaking both the official world record for the highest parachute jump set at 83,523 ft by the Soviet Air Force pilot Yevgeni Andreyev in 1962 and the unofficial record set by Joe Kittinger in the Excelsior Program several years earlier. He personally sought money from commercial sponsors, aid for training from the United States Air Force, and a pressure suit which he received on loan from the David Clark Company to enable his own 'Strato-Jump' program. Strato-Jump I ended at only 16,000 ft with a balloon failure, however Strato-Jump II soared to more than 123,500 ft becoming the highest manned balloon flight in history at that time. Unfortunately he was unable to disconnect his oxygen line and was forced to return to Earth under parachute inside the gondola. A third attempt was made several months later however, Piantanida's helmet depressurized at 57,000 ft which left him brain damaged and in a coma from which he would never recover.

5. Red Bull Stratos I-III[2]

With the move of world governments into the space age and away from manned, high altitude ballooning both Kittinger's and Piantanida's unofficial records stood from when they were set in the 60s until they were once again challenged in 2012. Red Bull GmbH, a sports drink company famous for advertising its product with the use of sponsored athletes who perform extreme stunts, funded the Red Bull Stratos program in an effort to publicly best these fifty year old records. With a goal of minimizing risk, program engineers chose to use a pressurized capsule that would only be depressurized just prior to the jump attempt at altitude. Use of a pressurized capsule would limit direct exposure of the suited pilot to the harsh stratospheric environment to only just the few minutes required for descent, and provide the required consumables for the two and a half hour ascent. Renowned Austrian skydiver and BASE jumper Felix Baumgartner was chosen to pilot the Stratos missions and successfully completed two test jumps of 71,581 ft and 96,640 ft respectively before breaking both the manned balloon and skydiving records later that same year. The skydive records attained for that final mission were the highest skydive altitude (127,852 ft), maximum vertical speed without a drogue (843 mph), and vertical distance of freefall (119,431 ft). Baumgartner also became the first person to break the sound barrier without any type of mechanical assist.

To note, Baumgartner had the ability to deploy a stabilizing drogue parachute at any time but opted not to use it in the pursuit of a faster freefall record. This lack of a deployed drogue parachute increased the risk of entering a flat spin due to small center of gravity perturbations at high air speeds, which is what ultimately happened to Baumgartner during his freefall. Were it not for his extensive skydiving experience this flat spin may not have been recoverable, although an increase in spin rate to dangerous levels would have automatically deployed the drogue stabilization parachute. Additionally, active heaters in the suit helmet visor were unable to prevent helmet fogging for portions of the mission. Several modified S1034 full pressure suits, similar to those worn by high altitude Air Force pilots, were used for the Red Bull Stratos program[7].

B. StratEx Program Overview

In the midst of the very public preparations of the Red Bull Stratos team Dr. Alan Eustace, Senior Vice President of Knowledge for Google, amateur skydiver, and aerospace enthusiast, noted that one common element to all of the high altitude programs to date was the use of either a pressurized capsule or an unpressurized gondola to house the pilot and related equipment for at least the ascent portion of the mission. In an era where people are regularly and safely conducting six and seven hour long spacewalks using spacesuits with attached life support systems he surmised that it would be possible to fabricate a complete flight and recovery system that utilized a self-contained suit/life support system capable of continuous, direct and safe exposure to the environment without the use of a capsule or gondola. Doing so, he saw, would provide several distinct advantages:

1) A Significant Reduction in Payload Mass

At altitudes above 100,000 ft atmospheric pressure is already near zero and it changes by smaller and smaller amounts as altitude increases. In other words as the desired flight altitude increases more significant increases in the buoyancy of a balloon system are required. The Red Bull Stratos balloon, for example, was nearly ten times the volume of the balloon used by Joe Kittinger for the Excelsior III jump. Increasing buoyancy means either increasing the size of the balloon, as was done by the Red Bull Stratos team, or somehow reducing the total system mass. And at nearly 30 million cubic feet in capacity (more than 400 ft in diameter) the ability to manufacture the largest modern lifting balloons is already nearing its limit. Reducing the effective ‘capsule’ mass to just the mass of a small, body mounted life support system stood to save thousands of pounds when compared to prior programs. This kind of mass savings translates into increased altitude thus maximizing access to a fuller range of Earth’s stratosphere.

2) No Requirement for Disconnect Operation

By using a self-contained, continuously attached life support system the pilot is then free from having to disconnect from capsule mounted pilot operated systems in order to descend, a lesson learned from the loss of the Strato-Jump II mission.

3) Simplified Balloon ‘Exit’

With a self-contained, hanging suit system a nominal balloon ‘exit’ does not require an actual exit at all. Simply releasing the suited pilot, versus requiring an equipment laden pilot to stand and maneuver, would be all that was required. A hanging pilot also has the advantage of being able to assume a stable position prior to release, thus reducing the chance of rotational inputs upon vehicle separation. With increased altitude also comes an increase in both freefall time and speed prior to attaining a thick enough atmosphere to inflate a stabilization parachute. Maintaining an initial stable attitude in this region is desirable because there is no way to arrest unwanted rotation in the extremely thin air.

4) Immediate Abort Capability

With safety being the paramount concern, Dr. Eustace also noted that a hanging pilot could be released immediately upon detection of any flight system anomaly at any time. Without having to depressurize a capsule, disconnect any lines or hoses, or even to just stand and maneuver to the edge of a gondola, it would be possible to immediately separate the pilot from the balloon and enact recovery protocols. As with a nominal release, no action on the part of the pilot would be required for emergency recovery operations to proceed.

With these thoughts in mind Dr. Eustace assembled the StratEx team to design, develop, manufacture, and test such a system. As flown the final flight system weighed in at just under 600 lbs, including the bodyweight of the pilot, and was comprised of the pressure suit assembly (PSA), the life support Equipment Module (EM), the parachute/drogue recovery system, the balloon, and the Balloon Equipment Module (BEM) including the pilot attachment rigging. Additionally, ground support equipment was required to enable pilot suit-up, launch, and recovery operations. Dr. Eustace acted as the pilot for all manned flight testing.

1. Pressure Suit Assembly (PSA)

The full Pressure Suit Assembly (PSA) used by the StratEx team was designed and developed for the specific purpose of long duration exposure to high altitude and interim environments. As the pressure suit itself is the subject of this paper a more extensive description of this subsystem is forthcoming. See Section II for suit requirements development and a discussion of the resulting suit design architecture.

2. Equipment Module (EM)

The EM is a front mounted life support pack. This pack has three main responsibilities which include providing temperature controlled thermal fluid to the pilot, providing temperature and pressure regulated oxygen to the suit and housing all flight avionics. The equipment module also serves as a mounting location for several of the pilot interfaces like parachute pull handles. The fluid system consists of a fluid heater and controller to bring heated fluid to the pilot's Liquid Thermal Garment (LTG) in flight, ports to provide cooled fluid to the LTG on the ground, and a heat exchanger / conductive contact system to heat both the oxygen stream and the flight computer box using the heated fluid loop. The oxygen system provides regulated oxygen at ~90 psi to the suit where the demand regulators are mounted. The oxygen stream is heated via a heat exchanger that exposes the oxygen to the heat from the heated fluid. Finally the avionics system, with the capability to both transmit and receive, monitors many aspects of the life support system and interacts with mission control and ground vehicles. Independent voice radios in the equipment module transmit pilot voice signals, and a pilot display panel shows the pilot key life support values.

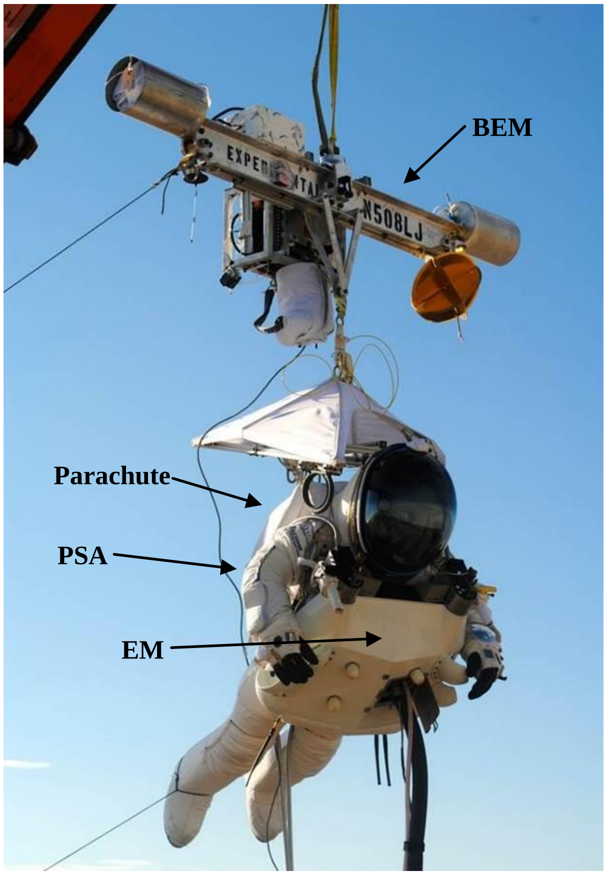

Figure 4. StratEx PSA, EM, and BEM in flight configuration during ground testing[6].

The equipment module integrates to the suit via two structural mounting brackets that connect to the helmet and body seal closures of the suit. The EM passes fluid, oxygen and electrical signals in and out of the suit via the main suit pass-through.

3. Parachute/Drogue Recovery System

The parachute system used in the StratEx program was a modified United Parachute Technologies Sigma tandem parachuting rig. The jump performed was not a tandem parachute jump but the Sigma Tandem rig was well suited for the weight of the system, and its general architecture (which used a stabilizing drogue parachute) fit the StratEx system requirements with little alteration. The final parachute system resembled a standard Sigma rig but with a few key differences. First the main and reserve parachute containers were switched so that the main container was above the reserve (which is opposite of a standard container); second, the connection point of the drogue parachute was higher on the pack than normal; and finally, the drogue itself was physically larger than a standard tandem skydiving system.

Figure 5. Parachute recovery system[6].

The integration of the parachute pack to the relatively complex suit system also drove substantial alterations to the attachment rigging. The parachute pull handles were moved from the main lift webs to the EM where the suited pilot could easily reach them.

The parachute pack was held to the system via fixed-length leg loops around the upper thighs of the suit and main lift webs going over the suit shoulders. High-strength clips held the chest straps to the EM central frame.

And while a discussion of the development and testing of the drogue system is beyond the scope of this paper it is worth noting that months of very extensive high altitude testing with a mass and volume equivalent pilot simulator did occur with the intent of preventing pilot spin during any portion of the freefall descent. For actual flight the drogue parachute was released at the same moment the pilot was released from the balloon, and no significant amount of spin was noted during freefall.

4. Balloon/Balloon Equipment Module (BEM)

Three different sized polyethylene balloons were used to complete the manned portion of the high-altitude flight test campaign. For the three altitudes achieved (56,800 ft, 105,771 ft, and 135,890 ft) the maximum volume of each of these balloons was 3,000 m^3, 48,000 m^3, and 328,000 m^3 respectively. Each balloon was crowned with a valve that opened to initiate descent and equipped with a destruct fuse that would be commanded to ignite and produce a large hole in the balloon once the pilot was dropped clear. Balloon avionics were mounted to the BEM which hung just beneath the balloon (see Figure 4). The BEM also served as the mounting point for the balloon ballast, cameras for monitoring flight operations, and a recovery parachute for the avionics box which was ejected prior to commanding the balloon destruct sequence. The pilot attachment and release rigging hung just below the BEM. Although not the primary topic of this paper it is worth noting that successful pilot release was considered critical to pilot survival and was the only system with tertiary redundancy; pyrotechnic cutters that could be commanded from the BEM avionics, pyrotechnic cutters that could be commanded from the suit EM avionics, and a manual pull release that could be performed by the pilot.

5. Ground Support Personnel/Equipment

To enable suit donning, balloon launch, mission monitoring and commanding, and post-flight recovery operations a host of ground support equipment and personnel was required. Pre-launch operations included a four hour, pure oxygen pre-breathe as a conservative means of mitigating the risk of decompression sickness at altitude and required a mobile ground cart to provide power, oxygen, and cooling without using flight consumables for pre-flight operations. A large forklift was used to move the suited pilot and mobile ground cart to the launch site where the pilot was then set on a small, wheeled ‘launch sedan’ that allowed him to be positioned appropriately beneath the balloon and attached securely. This wheeled sedan also served as a launch platform to prevent the pilot from being dragged in the event that side loads on the balloon caused some horizontal loading on the suit prior to lifting the pilot clear after balloon was released. Another vehicle with a custom built front end attachment was also used to gently raise the balloon as it was filled with helium and lifted to its standing height from its rolled out length. The balloon was anchored to a large steel plate until it was released. In-flight operations were monitored and commanded by a mission control center with consoles for directing the flight; monitoring the weather; monitoring the health of the balloon, suit, and pilot; and directing recovery operations.

Two trucks, two helicopters, and a fixed wing aircraft were used for post-flight pilot and balloon recovery operations. These vehicles operated under the direction of mission control recovery personnel. For the sake of redundancy one of the recovery trucks and one of the recovery helicopters were set up with small, mobile versions of the mission control infrastructure and were capable of independent communication with and commanding of both the balloon and pilot EM avionics.

II. Pressure Suit Subsystem Requirements and Resulting Design

Although several full documents were produced to describe the many requirements to which the pressure suit was designed, for the purpose of this paper only the major human factors and environmental requirements will be discussed. It should be noted that all program requirements were very carefully considered based on lessons learned from the historical flight experience record as noted in the introduction section of this paper. Ultimately the pressure suit was meant to be as simple in its operation as possible, thus leaving the pilot free to fulfill mission objectives versus having to manage flight systems.

A. Incorporation of a Demand Breathing System

Early programmatic decision making led to the requirement to incorporate a demand regulated breathing system in order to both provide oxygen to the pilot and to minimize flight tank sizing. Oxygen 'on demand' meant that, like a common SCUBA system, oxygen would only be provided to the pilot during the inhalation cycle of the breathing pattern. Re-breathing systems were also evaluated to further reduce the required amount of flight oxygen; however these systems were considered too complex to attempt to fully develop within the scope of the StratEx program.

Accordingly, an external first stage regulator reduced high pressure oxygen from two tanks mounted in the EM to ~90 psi which was then introduced through a suit pass-through bulkhead and into the suit to a second stage dual helmet regulator. The entire helmet region was separated from the body of the suit by a neck dam so that when the pilot inspired oxygen the resulting pressure reduction in the helmet opened the helmet regulator valve and allowed fresh oxygen to be released into the helmet cavity. The helmet region of the suit was maintained at a slight positive pressure compared to the body of the suit. A modified Gentex MBU-20 flight mask was used to capture all exhaled gasses and direct them to the body of the suit beneath the neck dam. Suit pressure was maintained through the use of a modified Dual Suit Controller (DSC); essentially an adjustable back pressure regulator located in the body of the suit. This controller was used to pressurize the suit relative to the external environment prior to launch, and to maintain the required suit pressure difference throughout the duration of the flight.

Figure 6. Demand breathing mask[6].

Use of an oronasal mask for control of expired gasses also offered several other distinct advantages to the suit system from a life support standpoint. The first of these was a simple way of managing expired carbon dioxide. CO_2 management is always a concern in the design of pressure suit breathing systems and it can often lead to complex computational flow dynamics studies and lengthy cycles of helmet inlet vent design iteration and testing. In this case using a mask with a valved exhalation tube minimized the amount of CO_2 remaining in the oronasal region during oxygen inspiration. As an added measure against the potential buildup of CO_2 a pilot accessible purge valve was plumbed to the exhalation tube that, when opened, would allow clean oxygen to free flow into the helmet and through the mask. To note, however, the purge valve was not required during flight operations.

A second advantage to using an oronasal mask was the prevention of expired moisture from entering the helmet region of the suit. The full and partial pressure helmets that have been commonly used throughout historical flight programs (see Section I) tend to use a face seal that surrounds the mouth, nose, and eyes of the pilot to separate that region of the body from the rest of the suit. The result of this design is that the helmet visor is right in front of the mouth and nose of the suit occupant. When exposed to the extreme cold of the stratospheric environment the chilled visor is subject to fogging from the condensation of the moisture in the pilot's warm expired breath. Actively heating the visor in an effort to prevent fogging has been the historical approach to this problem and has had some level of success, but active systems are subject to failure and history has demonstrated that high enough metabolic rates produce enough condensation to overcome the ability of the heating system to remove it fast enough to prevent fogging. Because metabolic rates tend to be highest during the descent portion of the flight where the ability to see the flight altimeter and pick the most appropriate landing site is critical, keeping moisture completely away from the helmet bubble appeared to be the best method of fog prevention for the StratEx paradigm. Routing all exhaled breath from the mask and into the body cavity of the suit proved to be an effective method of fog mitigation. Although other fog countermeasures were provided none of them were required during flight. At no time was condensation noted during any portion of the manned flights.

A third advantage of the mask was that it provided a convenient placement location for the voice communications microphone. Speaker and microphone placement have historically been problematic in extravehicular style suit designs with non-conformal helmets. The choice of a mask with an integrated, off-the-shelf microphone eliminated the need to otherwise devise a method of communications integration. An internal helmet, required for both head protection in the event of flail during descent and landing, and for mounting the oronasal mask to the pilot's face, provided a convenient placement location for the communications system speakers.

B. Helmet Fogging Mitigation

Although the life support design sought to prevent fogging by preventing exhaled moisture from entering the helmet cavity, facial and head perspiration was still recognized as a viable means of producing enough moisture to cause condensation on the inside of the helmet bubble. Passive means of moisture collection, including moisture absorbent head coverings were considered and even tested, however these proved to be too difficult to integrate into the internal flight helmet and were too uncomfortable for practical use. Instead, the requirement for a purge valve that would allow the free flow of dry oxygen into the helmet and through the oronasal mask for off nominal CO_2 washout was also integrated as a fogging countermeasure. Accordingly, a custom spray bar was designed and mounted into the front of the helmet such that oxygen introduced to the helmet cavity would come through this diffuser and blow against the helmet bubble in front of the face of the pilot. Thus when the purge valve was opened a free flow of dry oxygen would spray the bubble to eliminate moisture buildup and prevent fogging. The purge orifice and oxygen tank volumes were sized to account for thirty minutes of purge flow which would have allowed enough time for an abort and recovery if it would have been required.

Another fogging countermeasure was the use of an ultra-bright parachute 'pull-light' LED mounted to the exterior of the helmet bubble. This light worked in conjunction with an altimeter and was programmed to start blinking in the event that the pilot passed through a pre-determined altitude at a pre-determined velocity. If fogging were to occur when passing through the coldest parts of the atmosphere during descent thus preventing the pilot from being able to see his altimeter, this pull-light would serve as an indicator for when to release the main parachute.

Neither of these two countermeasures was required as there was no fogging noted during flight operations.

C. Loads Management

Designing for loads management in the pressure suit was somewhat problematic as it was originally not well understood exactly how and where external loads would be introduced to the suit. Pressure and man induced loads are well understood, and designing for these loads is common. However, external loads going into the suit would mostly be coming from the two most dynamic portions of the flight, parachute opening and landing, and the transfer of these loads into and through the suit were not well understood. The driving system load requirements were for a 5g reserve parachute opening 'jerk' load and a 5g forward ground impact load; the impact load being assumed for an unconscious pilot landing scenario.

To stabilize the system while in flight, a decision was made early in the program to fully pressurize the suit prior to launch, and to maintain full suit pressurization until at least after parachute opening. Because the parachute was soft mounted to the suit using leg, arm, and torso straps, maintaining suit pressure against these straps prevented shifting of the suit and suit components within the straps. Originally the life support EM was also going to be strap mounted to the suit; however it was noted that doing so would have placed massive compressive loads directly into the suit during parachute opening, with the opening event loading the suit in one direction from the parachute and the EM loading the suit in the opposite direction. To mitigate this loading condition the suit was hard mounted to the EM at the helmet and body closure rings, and load sharing straps were used to bypass the suit and transfer a portion of the EM loading directly to the parachute. Doing so meant that the suit did not have to carry the full load of the EM while under parachute. From a dynamic loading standpoint this meant that the suit design could focus on the internal loading induced from the suit pressure and its occupant rather than loads induced from the rest of the flight system equipment.

It's worth noting that the program operated under the premise that pilot survival was paramount under all circumstances which meant that an 'unconscious pilot' scenario had to be accounted for at every stage of flight, including landing. The original concept of operations for landing was that the pilot would execute a pirouette style landing commonly used by tandem parachute instructors in the event of an unresponsive student. For this style landing one foot is planted firmly into the ground and the instructor rotates 180 degrees to execute a back landing. If done properly the decreasing lift of the parachute helps to lower the pilot gently to the ground. In practice, however, the EM placement made the suit too front heavy to allow such a landing. Consequently a 'chest-down' approach became the normal landing method, with the pilot often pitching over his head and onto his back. However, because the system was designed with conservative, unconscious pilot landing loads in mind, these "normal" landings were well within the design envelope of the equipment. Even after the most dynamic landings both the suit and life support system were ready to be used again within a five to six hour cleaning and refurbishment period. Only one suit assembly, including the EM, was fabricated and used throughout the course of the StratEx testing and flight program. This included more than 100 hours of manned pressurized time, eight flight tests (including five airplane jump tests), two vacuum chamber tests, five thermal tests, and countless hours of human factors and communications testing.

Pilot protection was accounted for in these off-nominal (that later became nominal) landings in several ways. Originally it was envisioned that only an unconscious pilot may have to endure a high-g landing in which case ground impact would occur in a fully pressurized suit. A fully pressurized suit would maintain its rigidity, serving as sort of a full body 'air cast' to protect both the spine and limbs of the pilot throughout the landing process. Additionally, an internal helmet was worn by the pilot to protect his head and neck from any type of head flail injury that could occur. Once it became apparent that even nominal landings would be dynamic, impact events it was noted that spinal protection was accounted for in the effective 'roll cage' structure that resulted from hard mounting the EM to the body seal closure at the hip location and the helmet seal closure just below the helmet bubble, even with the suit in an unpressurized state. This, together with the internal impact helmet already in place served to fully protect the pilot from injury during all landings experienced by the pilot during the flight test campaign.

An accelerometer was mounted at the chest of the pilot which recorded the actual pilot loading for parachute opening and landing for the five airplane jumps completed as part of the 'ground' test campaign, and two of the three jumps that were completed as part of the balloon flight test campaign. Unfortunately the accelerometer failed to record flight data on the third and final high altitude jump. See Table 1 for a summary of this load data.

	Airplane Jumps					Balloon Jumps	
Date	5/8/13	8/19/14	8/21/14	9/2/14	9/3/14	10/4/14	10/15/14
Parachute Opening (g)	3.6	3.4	3.9	3.2	2.7	3.7	4.0
Landing (g)	4.8	5.9	5.3	3.9	4.9	3.3	4.7

Table 1: Flight Parachute Opening and Landing Load Data

D. Vomit and Biological Waste Management

Another item of concern brought to the attention of the program was the risk of vomiting in the suit. The use of an oronasal mask also brought with it the risk of vomit being trapped in the mask which would make it difficult, if not impossible, for the pilot to breathe should a vomit incident occur. To account for vomit potential the diameter of the purge line and orifice was maximized, while still accounting for a minimum of 30 minutes of purge time, to allow for vomit purge flow if required. The pilot was then put on a restricted diet for 24 hours prior to flight so that if a vomit incident occurred it would be liquid in nature and could be ejected from the mask through the purge line. This same diet was meant to limit biological waste to urine only, which was absorbed into a commercially available moisture absorption garment worn underneath the internal suit base layers.

E. Decompression Sickness Mitigation

When the partial pressure of constituent atmospheric gasses are decreased rapidly enough relative to the partial pressure of those same gasses absorbed into the blood and tissues of a human body, the decrease in external pressure can cause those gasses to form bubbles while still in the bloodstream and body tissues prior to being expelled through normal respiration. This is a condition called decompression sickness (DCS), the symptoms of which range from light body pains to severe physical impairment and even death depending on the amount of gas formed in body tissues. The major constituent of atmospheric air is nitrogen; therefore it is generally nitrogen bubble formation that is of concern. Because pressure suits tend to become more stiff and difficult to move at higher differential operating pressures it is generally seen as desirable to minimize suit pressure; however with lower operational suit pressures comes an increased risk of DCS symptoms. One method commonly used by high altitude military pilots prior to flight, and astronauts prior to spacewalks, is to breathe pure oxygen for a specified length of time in order to decrease the partial pressure of nitrogen absorbed into body tissues. This decreases the pressure differential between external and internal tissue nitrogen and reduces the risk of bubble formation. For the StratEx program a four hour oxygen pre-breathe protocol, as determined by the StratEx flight surgeon team, was enacted as part of the standard pre-flight preparations, however program flight surgeons remained concerned about DCS risk. To further reduce risk an operational differential suit pressure of 5.4 psi was adopted, as opposed to a much lower 3.5 psid as was the original design requirement. Increasing suit pressure would have been a minor technical enhancement as ILC Dover has been operating prototype pressure suits at differential pressures as high as 8.3 psid in a laboratory environment for nearly a decade. But because suit manufacturing was already underway at the time of the suit pressure increase decision and some of the suit components had not been designed for high operational pressures, an increase of only 1.9 psi over the original design value was implemented. Increased suit pressure beyond 5.4 psid would also have required an increase in the amount of flight oxygen required which would also likely have required an increase in oxygen tank sizing.

F. Pilot Accessibility to Controls

As previously mentioned, minimizing pilot interaction with the flight system was one of the goals of the StratEx program given that the desire was to demonstrate a system that could be used by people with a wide variety of backgrounds and skill sets, as opposed to just military flight personnel and career skydivers. With this in mind the in-flight controls were limited to just two switches (a push to talk communication switch and a temperature control switch) and two valves (a suit depressurization valve and the purge valve). For descent operations four parachute pull handles were also attached to the front of the EM; two that were capable of releasing the main parachute, one that could cut away the main parachute if required and one that could release the reserve parachute as necessary. Through the course of human factors testing every one of these pilot interfaces changed in size, shape, and location in order to accommodate the pilot's ability to see and operate these interfaces. The largest of these changes were to the depressurization and purge valves which were originally located on either side of the suit, just above the body seal closure. While the suit's arm and shoulder mobility enabled access to these areas, the pilot was unable to physically see either of these valves and the minimal tactile feedback available through the glove thermal layers was insufficient enough to allow the pilot to know that his hand was on the valve and that it was operating appropriately. To enable the pilot to both see and know that these valves were actuated properly they were re-located to either side of the top of the equipment module, which also required lengthening the flow lines external to the pressure suit.

Figure 7. Testing pilot access to the purge valve[6].

While under canopy the pilot also had to be capable of reaching and operating the parachute control toggles. In early airplane jump testing it was noted that the toggles were more difficult to reach and operate with a pressurized suit which eventually led to the nominal concept of operations where the pilot would depressurize the suit just after canopy opening but before reaching for the toggles.

In addition to the flight and parachute controls there was also a requirement that the pilot have the capability to operate the helmet bubble latch and remove the helmet bubble in the event that recovery personnel took too long to get to the landing site. Initially the latch was designed to be as small and smooth as possible in order to prevent shroud line snagging as the parachute was opened. Unfortunately the size of the latch made it difficult for the pilot to find and actuate as was the case with the original valve placement. Because this difficulty was not discovered until later into the program where a complete re-design would have been costly and time consuming the solution became one of pilot training. Accordingly the pilot underwent several sessions of training and testing to verify that he was capable of removing the helmet from any physical orientation. This type of human factors training was used throughout the program in order to evaluate the placement and operation of all pilot interface items.

G. Environmental Requirements

In addition to the human factors and load requirements the suit was also required to withstand the environmental conditions at all levels of the stratosphere, from launch to the maximum altitude, for the duration of the flight. Aside from the lack of pressure, the biggest environmental concern was the temperature. Standard atmospheric temperature tables predicted temperatures decreasing consistently to as cold as -90˚ F before beginning to increase again at around 65,000 ft. At an ascension rate of around 1000 ft/min this meant that nearly the entire duration of the flight (the design reference mission was four hours in length) would take place in conditions far below freezing.

To combat the extreme cold several measures were taken to ensure pilot thermal comfort for the duration of the flight. The first of these was the inclusion of a Liquid Thermal Garment (LTG) worn by the pilot internal to the suit. This garment was laced with tubing through which heated water was circulated throughout the course of the flight. The water temperature could be varied either nominally by commanding from the ground or off-nominally by the pilot switch if so required. Over this garment was worn an additional elastic thermal layer that both helped to press the heated tubes against the body of the pilot and to insulate the heat against his body as much as possible. Internal to the suit two pairs of socks made for cold weather exposure were also worn. The LTG was also used to supply cooling to the pilot prior to flight and for ground testing.

External to the suit a heavily insulated pair of mountaineering boots, cold rated to -90˚F, were worn on the feet, Phase VI Extravehicular Mobility Unit (EMU) style gloves covered by a modified commercially available actively heated pair of gloves were worn on the hands, and the entire suit was then covered with an insulated and impact/cut resistant cover layer. Thermal mitts based on the EMU thermal over-glove design were later added to the flight system as a result of thermal chamber testing. A second polycarbonate bubble was also added to the helmet design over the top of the actual pressure bubble (reference Figure 6) to add a ‘dead space’ layer of insulation between it and the atmosphere. This thermal bubble was made to be easily removable and replaceable so that it could also serve as a consumable means of impact protection for the pressure bubble as required. Standard, proven EMU materials with known thermal limits were used where possible however, commercially available materials were identified and used as necessary.

III. Ground Testing

Prior to flight testing, the following ground tests were conducted as part of the design and development process and to certify designs as flight worthy.

A. Vertical Wind Tunnel Testing

The first major test conducted as part of the suit architecture selection process was a vertical wind tunnel test conducted at SkyVenture Colorado located in Denver, Colorado using an ILC Dover Launch, Entry, and Abort (LEA) I-suit. Both Dr. Eustace and a similarly sized professional skydiver took turns flying the suit in order to determine the flight characteristics of a pressurized pressure suit, and to examine the change in those characteristics under various conditions of mass and volume distribution around the suit. This testing helped the program decide that descent with an attached life support system was indeed a viable option and the best configuration of that life support equipment mass. From a suit configuration standpoint it also aided in the decisions to change the shoulder joint to upper torso angle to be more ‘freefall position’ friendly, and to eliminate both a waist and hip joint as part of the StratEx architecture as it appeared that they would not be utilized due to the size and position of the front mounted life support system.

Figure 8. Vertical Wind Tunnel Testing[6].

B. Thermal Testing

Five thermal suit tests over three test sessions were conducted in order to qualify the pressure suit for flight worthiness. These tests were conducted in a 10 ft x 10 ft x 12 ft insulated chamber located on site at Paragon SDC in Tucson, Arizona. Consideration was given to finding and using a thermal vacuum chamber, however the cost of using such a facility in conjunction with the lengthy schedule required to reserve a time slot was considered prohibitive. Additionally, separating out the thermal testing and performing it at near sea level atmospheric conditions was a conservative test approach that fell in line with the safety oriented program philosophy. Testing in nearly one full atmosphere for the whole temperature profile, as opposed to doing the same thing at diminishing pressures simulating an increase in altitude, meant that the rate of heat loss at any specific part of the temperature profile would be greater than if pressure suit hardware was subject to that same temperature at a lower equivalent atmospheric pressure. Thus designing for this conservative test case would provide confidence in the thermal integrity of the hardware during all phases of actual flight operations. The risk assumed with this philosophy was that the test would prove too conservative and that unnecessary development cost and schedule would result.

The flight temperature profile was maintained during the tests by injecting liquid nitrogen into the closed chamber and using circulating fans to evenly mix the air temperature. Published standard atmospheric temperatures together with an assumed 1000 ft/min ascent rate were used to build a temperature versus time profile that was followed for the test period (see Figure 9 for a typical test profile). Large, high speed fans were initiated to simulate air movement during the free fall portion of the flight.

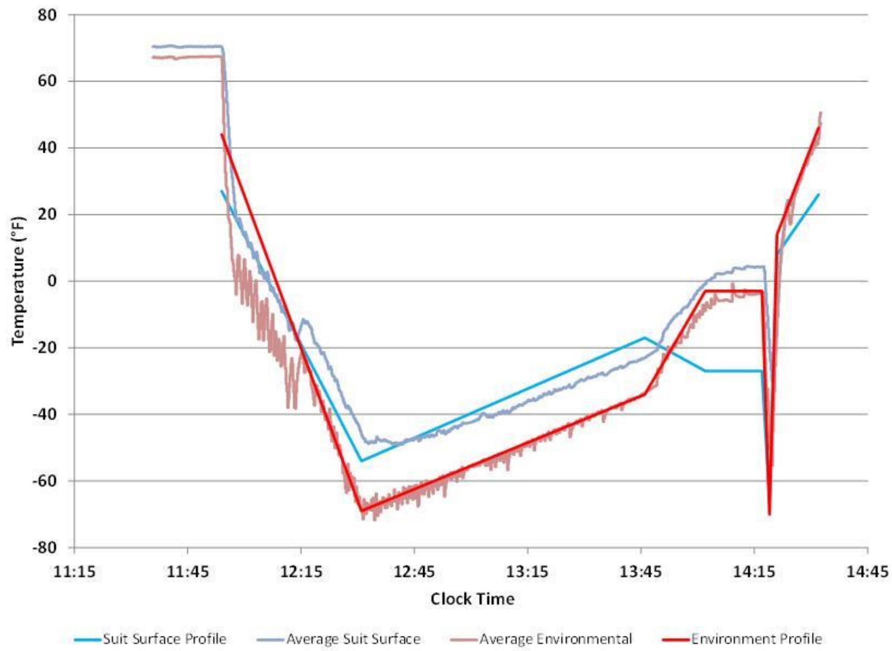

Figure 9. Typical Thermal Test Temperature Profile[6].

The following system changes were made as a result of thermal testing:

1) Insulation was added to the push to talk (PTT) switch:
   During testing the pilot noted that the continual use of the cold PTT switch caused the thumb and index finger used to actuate the switch to be cold.

2) EMU style thermal 'over' mitts were added:
   Although the pilot's hands did not get dangerously or prohibitively cold, they were cold enough to warrant an additional layer of insulation over the top of the heated gloves. This addition was debated prior to actual altitude test flights however, because of the known conservative nature of the test and the decrease in tactile feedback produced by the additional thermal layer when they were used. These outer gloves were eventually retained for flight, however additional human factors testing was required to train the pilot to operate all suit components with them in place.

3) Additional insulation was added to the DSC:
   Early termination of one of the test sessions was required when the suit pressure began to increase suddenly. Investigation led to the conclusion that there was a potential for ice to form at the outlet of the DSC which controls the differential pressure set point of the suit. A heavily insulated layer was added over the DSC which prevented its surface temperature from dropping below the freezing point of water.

4) A Second pair of socks was added internal to the boots:

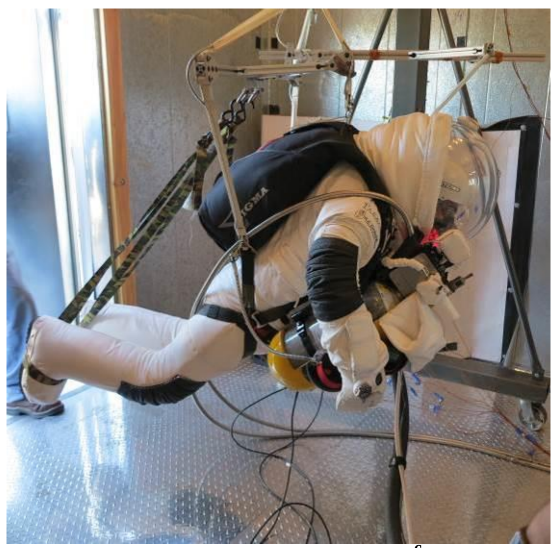

Figure 10. Thermal test chamber[6].

As with the hands, the pilot observed that although his feet were not prohibitively cold they were more uncomfortable than he liked. A second pair of socks was added to the flight configuration to provide additional thermal comfort.

5) Pilot heating philosophy established:

Another item noted through the course of thermal testing was that if the pilot was allowed to get too cold then the heat produced by the LTG was only enough to keep him from getting colder, but not enough to re-heat him to the point of feeling thermally comfortable. There was no provision for cooling the pilot if he were to somehow get too hot so the original philosophy was to keep the pilot slightly on the cool side of comfortable and only add heat when the pilot requested it. However, because it was observed to be difficult to make up heat loss the new philosophy became for flight controllers to add heat in anticipation of pilot needs rather than wait for the pilot to ask for it. This new philosophy was used throughout the duration of the flight test campaign and found to be successful.

C. Unmanned Altitude Chamber

Prior to subjecting the suited pilot to the dangers associated with altitude chamber testing the pressure suit assembly was first thoroughly checked out in an unmanned setting. This test was completed using the Environmental Control and Life Support System (ECLSS) Human Rating Facility (EHF) vacuum chamber located on-site at Paragon SDC in Tucson, Arizona. While not currently a man rated chamber, it was sufficient to perform the unmanned test plan. The purpose of this test was to demonstrate that suit pressure control functioned as designed, to serve as the 'hot' stressing case for pressure suit and life support hardware since it was performed at room temperature (much warmer than the flight case), to demonstrate proper operation of the purge valve, and to demonstrate the proper operation of the dual helmet regulators including their ability to free flow makeup gas for an equivalent quarter inch sized simulated suit leak. For the purposes of this test the pressure profile and duration was the same as expected during actual flight, once again assuming an ascent rate of 1000 ft/min.

Figure 11. Paragon's ECLSS Human Rating Facility (EHF)[6].

The result of this test was that all pressure suit pressure regulating valves operated as expected. The DSC controlled the suit pressure to 5.4 psig as expected and the helmet regulators responded to a simulated suit leak and open purge valve by free flowing to allow no less than a minimum suit pressure of 3.0 psia during these simulated off-nominal events. The simulated mission also demonstrated that the pressure suit could withstand a full mission profile and that the avionics temperatures stayed controlled, even in a non-convective environment at room temperature. No major pressure suit or life support system changes were made as a result of this test.

D. Manned Altitude Chamber

After suit operations had been verified in the unmanned altitude chamber pressure profile test the pressure suit and pilot underwent manned pressure profile testing at the Arizona State University Del E. Webb Altitude Chamber in Mesa, Arizona. The maximum simulated altitude of this chamber was approximately 85,400 ft (chamber pressure of 0.30 psia) however; this only translates to a real difference in absolute pressure of about 0.25 psi as opposed to the atmospheric equivalent of the 135,000 ft flight goal. This difference was considered negligible for the purposes of this test. From a human standpoint, this also served as the first full scale test of the approved oxygen pre-breathe protocol. This test also stressed the suited pilot for an entire mission equivalent duration and allowed him to experience purge valve operation at flight equivalent pressures. Pilot oxygen consumption data was also taken as part of this test.

As with the unmanned altitude chamber test all mission objectives were met throughout the course of this test. The pre-breathe protocol was properly executed and no signs or symptoms consistent with decompression sickness were manifest at any time either during or after the test. Additionally, the pilot was in good health for the duration of the test and no adverse effects of the mission profile were reported. At full altitude the pilot was able to demonstrate the ability to operate the purge valve and all pressure regulation equipment functioned appropriately for this simulated off-nominal test. No major pressure suit or life support system changes were made as a result of this test.

IV. Flight Testing

The successful completion of ground test activities, along with completed design iteration as required, culminated in the launch of the manned test campaign which included five total airplane jump tests and three altitude flight tests. Each of these tests will be discussed in detail below.

A. Airplane Jump Test – Coolidge, AZ

Airplane jumps were conducted with the objective of testing all of the flight and recovery systems, and to provide the pilot with experience using the equipment in the presence of safety skydivers prior to performing actual high altitude flights. The first of these jumps was conducted in May of 2013 at a remote drop zone in Coolidge, Arizona. At the time of this jump the StratEx program was still young and did not have a lot of experience on the difficulties associated with integrating a pressure suit, a life support system, and a parachute. All three of these systems had just completed their initial design and manufacturing phase and the mindset at that time was that there was no reason that an airplane jump test shouldn't be conducted. At that time the pilot had very little experience wearing the suit and the importance of extensive human factors testing was not well understood at a programmatic level. Additionally, all aspects of the jump test had not been well thought out and little or no practice of those items that could be practiced on the ground had been conducted.

At the outset of this first jump the lack of preparation became instantly apparent. The idea had been for the safety skydivers to carefully maneuver the pilot to the edge of the aircraft door at the tail of the plane, and then to gently rock him over the edge and into freefall. In reality there was little room inside the aircraft to maneuver the four hundred pounds of suited pilot and the skydivers were not able to be as careful or gentle as had been hoped. Upon egressing the airplane, the base of the EM rolled across the edge of the aircraft door frame and the Global Positioning System (GPS) and data antennae were sheared from their mounting supports. After egress the pilot was able to practice performing some maneuvers, however when it came time to pull the parachute ripcord he was unable to pull it far enough to release the parachute and one of the safety skydivers had to pull it for him. After parachute opening the pilot reported that he was unable to reach both of the steering toggles and that he was also unable to locate and use the suit depressurization valve. At that time the depressurization valve was still located on the side of the suit and there had been little training to access that valve. Because of his inability to control the parachute the pilot landed several miles off the airfield and into the Arizona desert. To further complicate the situation, the jerk from the parachute opening loads caused a solder joint on the speaker wire to fail which resulted in the inability of the pilot to hear communications after which he assumed that all communications had been lost. Although the mission control vehicle could still hear the pilot, the pilot ceased to communicate under that assumption. Additionally the support skydivers were all using small, sport parachutes as opposed to the large tandem parachute being used by the pilot. These smaller parachutes took the support skydivers quickly to the ground where they were unable to follow the suited pilot during his much slower descent.

Figure 12. Coolidge, AZ jump test[6].

The result of all these complications led to a situation where the pilot landed fully pressurized in an unknown desert location where he was not attempting to communicate, and could not be tracked via GPS because the antenna had been sheared off. Fortunately there were helicopter training exercises underway on the airport runway and mission control was able to communicate with one of them who had seen the pilot's descent from the air. When contact with Dr. Eustace was finally made he was found in good health and with plenty of remaining oxygen; however, had outside air support not been available the outcome could have been much more negative. Post-flight equipment examination also revealed some material stressing at the mounting holes of the neck dam.

The biggest lessons taken away from the events of this jump were the importance of extremely thorough test planning and rigorous human factors training prior to testing. Accounting for these things alone would have negated most of the problems encountered with this jump. The hardware changes to the pressure suit that resulted are as follows:

1) Internal helmet speaker wire reinforcement and the addition of wire strain relief

2) Reinforcement of the neck dam mounting holes

3) Relocation of the depressurization valve to a visible and more accessible location

4) Relocation of the purge valve to a visible and more accessible location

5) Re-design of the purge system to allow it to be used for emergency breathing of external air

Changes were also made to the parachute and life support systems; all of which were extensively tested prior to further airplane testing.

B. Airplane Jump Tests – Roswell, NM

The final series of airplane jump tests did not happen until more than a year later in August and September of 2014 in Roswell, New Mexico. At this point the system had been through all ground testing and associated re-design and the pilot had been through all requisite human factors training. With a well thought out test plan and appropriate available recovery resources four additional airplane jumps were conducted over the course of several weeks as weather allowed. For these jumps the complete pressure suit assembly was as flight like as could be made possible. One exception to this was the addition of wheels to the front of the life support system which allowed the pilot to be easily rolled out of the rear airplane hatch.

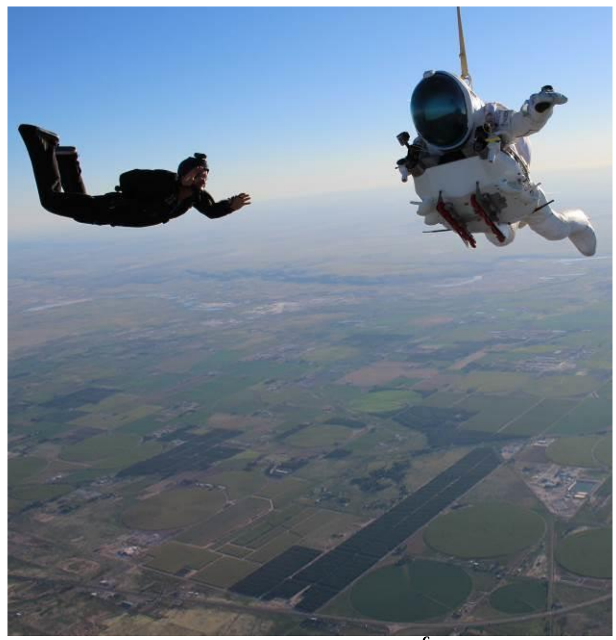

Figure 13. Roswell, NM test jump[6].

These jumps were observed to be generally successful, and served to provide the pilot with the confidence necessary to complete high altitude missions. The biggest item of concern that required discussion, however, was the landing impacts observed at the end of each jump (Refer to Section II.C. and Table 1 for further discussion of landing loads). Fortunately these impacts did not cause even minor injury to the pilot; however they did necessitate very close evaluation of the suit and EM components between flights in conjunction with pressure and leak checks. Through these evaluations no damage was noted beyond the ability to recover full flight capability within just a few hours. No major changes to the system were required as a result of the airplane jump tests and the program was able to flow directly into high altitude balloon jump testing.

C. Manned High Altitude Testing

The final test of the StratEx pressure suit came in the form of actual manned stratospheric flight demonstration of the entire system. This took place with a series of three test flights that increased in altitude and duration over the course of a three week test period. The altitude of each progressive flight was determined by a combination of balloon availability and the desire to minimize added risk, while still increasingly stressing the system in a systematic fashion. This was also the first real look at actual oxygen consumption rates under flight conditions. Table 1 summarizes the ascent time, time in freefall, freefall distance, top speed, and balloon size for each of the flights. To note, several unmanned flight tests using a mass and volume equivalent pilot simulator took place to test and enhance all flight operations prior to manned flight testing.

1. 56,867 ft Flight, October 4, 2014

The first and lowest of the three manned test flights flew to just under 57,000 ft and used a relatively small 3,000 m^3 (106,000 ft^3) balloon. The test was approached as a cautious, end to end test of the entire system with a man in the loop. Using this 'small' sized balloon simplified launch operations, kept the flight short in duration, and ensured that the distance of the balloon drift over the course of the flight would be minimized which would ease recovery operations. At the same time the altitude of this flight was an increase of four times the altitude of the airplane jump tests which increased the freefall time and speed and provided the pilot exposure to the resulting higher aerodynamic loading.

An additional few thousand feet in altitude could have been achieved prior to descent however, the pilot was released before the balloon achieved its maximum float altitude in order to ensure landing in an 'ideal' location that had been previously identified. One thing noted by the pilot during the course of freefall was that at the higher freefall speed achieved very small arm movements could result in large body position changes. This made it difficult for him to move his arm to read his wrist mounted altimeter without inducing some kind of unwanted motion. At the pilot's suggestion an additional analog altimeter was mounted to the top of the EM for the remaining two flights to allow him constant insight into his altitude without having to change the position of his arm during freefall.

2. 105,771 ft Flight, October 15, 2014

The second manned flight was an increase in altitude to just under 106,000 ft and made use of a 48,000 m^3 (1,700,000 ft^3) balloon. This flight further increased demands on the flight system from both an aerodynamic loading on descent and a consumables standpoint. Freefall duration was increased by nearly a minute and a half over the previous flight and maximum freefall speed more than doubled. A noteworthy achievement for this flight was that it broke the unofficial world altitude record for a drogue assisted skydive set by Joe Kittinger in 1960 as part of the Air Force Excelsior program.

For this flight the only anomaly associated with the pressure suit assembly occurred pre-flight and during suit donning operations when the pilot had difficultly donning one of the pressure suit gloves. Subsequent investigation revealed that tapes used to index the glove bladder to the glove restraint had allowed slippage between these two layers, likely due to storage at elevated desert temperatures over an extended period of time. These layers were carefully re-indexed in the field and were successfully used for this flight, however the tapes were completely replaced and the bladder/restraint layers completely re-indexed prior to the subsequent and final flight.

3. 135,890 ft Flight, October 24, 2014

The third and final flight used a 328,000 m^3 (11,600,000 ft^3) balloon to achieve its altitude, which was the largest balloon purchased for use on the StratEx project. For reference, this was about three times the size of the balloon used for Kittinger's Excelsior III flight, but only about one third the size of the balloon used for the third and final Red Bull Stratos flight. At a flight payload mass of only just over 600 lbs it is estimated that use of a balloon the size of the one used in the Red Bull Stratos program could increase the achievable altitude of the StratEx system to near 150,000 ft, thus opening access to the stratosphere even further than was demonstrated by this manned test campaign.

A notable achievement for this flight was that, because of the additional thirty seconds of freefall duration, supersonic speeds were

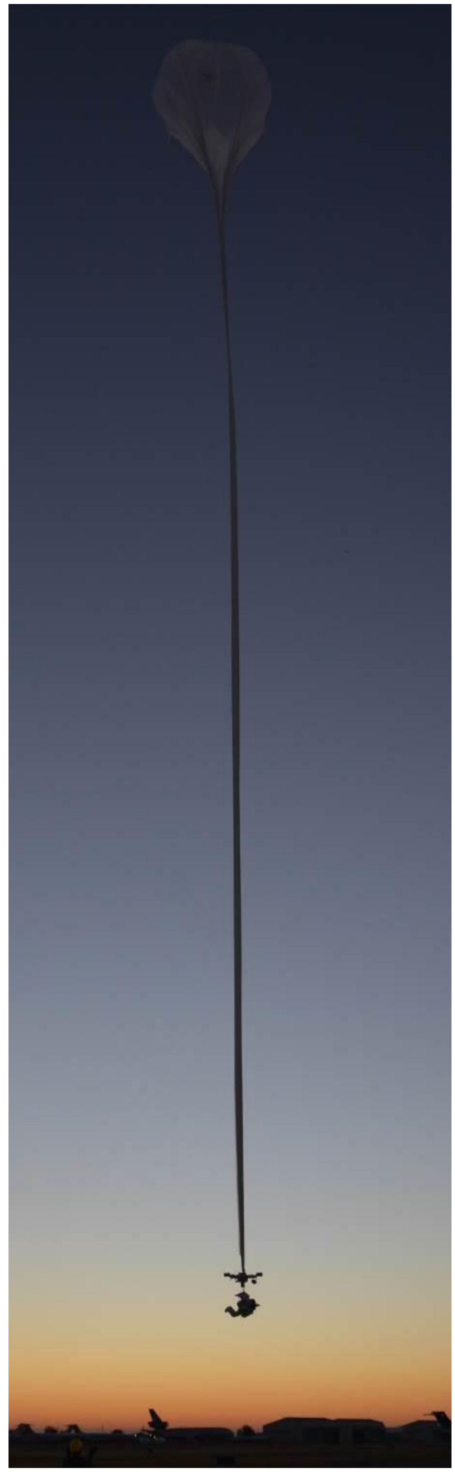

Figure 14. Dr. Eustace embarks on his record breaking flight[6].

achieved in the thin upper atmosphere. This new paradigm stressed the suit system at a whole new level and demonstrated even further the durability of the system. The performance world records claimed during the course of this flight were highest exit (or release) altitude for a skydiver, vertical distance of fall, and vertical speed attained with a drogue/stabilization device (see Table 2).

No pressure suit anomalies were reported over the duration of this flight.

Flight	I	II	III
Date	10/4/14	10/15/14	10/24/14
Altitude (ft)	56,867	105,771	135,890
Ascent Duration (min)	53	99	126
Freefall Duration (sec)	150	236	267
Freefall Distance (ft)	40,215	91,416	123,414
Max Freefall Speed (mph)	258	607	822
Balloon Volume (ft^3)	106,000	1,700,000	11,600,000

Table 2: Stratospheric Manned Flight Data Summary

V. Lessons Learned/Future Development

While the StratEx program was successful in the goal of demonstrating a viable flight system for extravehicular, stratospheric exploration, there were several lessons learned that are worth noting for the development of future systems with similar objectives.

1. Decrease Mass/Volume of Life Support EM

As explained in Section II, a demand breathing system architecture was chosen for use in this program. The nature of this architecture is such that all exhaled gasses are vented overboard, including the unused oxygen expired in the exhalation cycle of each breath. While it was originally deemed too complex for the purposes of this program, consideration should be given to a re-breather style architecture where CO_2 and humidity are scrubbed from the exhaled breath of the pilot and the unused oxygen is recirculated back through the suit ventilation loop. Such a system could dramatically reduce the mass and volume of the oxygen tanks required for flight operation. These tanks ultimately drove the volume of the life support system as flown. The total trade would have to include provisions for CO_2 and humidity removal as noted however, the StratEx team believes the trade for mass and volume would fall in favor of a re-breathing architecture.

2. Improve Landing Capability

The biggest driver for reducing the size of the EM is the ability to land the suit in a more controlled fashion than was demonstrated through the course of the StratEx flight program. The volume of the EM prevented Dr. Eustace from being able to raise his legs to attempt a seated landing, and the front mounted mass prevented the pilot from being able to adequately attempt a back landing as was the original intent. Reducing the mass required for the EM, and possibly re-distributing some of the internal components to make a less front heavy system would allow a pilot enough room and stability to raise his or her knees high enough to perform a more controlled, seated landing.

Figure 15. Dr. Eustace under parachute[6].

3. Integrate Parachute

The StratEx program chose to use standard parachute harnessing for attaching the parachute to the pressure suit system. This decision was made given the long successful history of this type of harnessing; however it was problematic in several regards. First, strapping the parachute harness over the top and bottom halves of the suit added additional complexity to the problem of extracting the pilot in the event of an emergency; second was the problem of transferring the EM loads to the parachute while being hard mounted to the suit; and the third was the operational overhead of having to don and doff the parachute each time the suit was likewise donned and doffed.

Instead of repeating these issues with standard style parachute harnessing the parachute could be integrated into the hard framework of the suit just as the EM was ultimately integrated. This arrangement would be more of a 'bolt-on' system that could be attached to the upper half of the suit prior to suit donning and would not be in the way of doffing operations in the event of a time critical extraction. An integrated parachute system would also better lend itself to volume sharing with life support system components should there be an effort to transfer some of the life support mass from the front to the back of the pilot.

4. Increase Suit Pressure

A large part of the preparation activities for the pilot on flight day revolved around the four hours of pre-breathe that occurred before flight in order to mitigate DCS risk. In an effort to reduce or eliminate the overhead associated with pre-breathe the operational pressure of the suit could be increased to as high as 8.3 psid. This has been a standard operating pressure in a laboratory environment for prototype ILC Dover spacesuits for nearly a decade and represents current technology that could be used to reduce DCS risk in future flight systems. While the decision to increase suit pressure came too late in the StratEx program to fully use this technology, it could be utilized on future flight systems.

VI. Conclusion

As a precursor to the StratEx program Dr. Eustace posed the question, "What if you could design a system that would allow humans to explore the stratosphere as easily and safely as they do the ocean?" Through the course of successfully designing, developing and flight testing a high-altitude stratospheric exploration system the StratEx program demonstrated that long duration, extravehicular exposure to stratospheric conditions is possible and can be done repeatedly and safely. And while the type of flight system demonstrated for this program probably can't yet be called 'easy', it is certainly a step toward the development of a system that simplifies access to the stratosphere. By designing and demonstrating a first order, robust single person system that requires minimal pilot interface and is capable of quick flight turnaround with minimal support personnel, the StratEx team has shown that the vision presented in the question posed by Dr. Eustace may indeed one day be realized.

Acknowledgments

The authors wish to acknowledge the hard work and effort made by the employees of ILC Dover LP, Paragon SDC, United Parachute Technologies, ADE Aerospace Consulting, and all others who dedicated their time and energy to the successful development and execution of the StratEx program. Thanks also to Dr. Alan Eustace for having the vision to look ever upward and for involving us all in that vision. This work was performed by ILC Dover and Paragon Space Development Corporation under contract from Alan Eustace.

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