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StratEx Mission Overview

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The StratEx (Stratospheric Explorer) project's primary goal was to create a system that allowed an individual to travel to, explore, and return from the stratosphere analogous to how a SCUBA suit allows one to explore the ocean depths. It was a rare opportunity for a team to take a system of this scope from high level concept to world record breaking fruition in a span of 34 months. This paper is an overview of the project from beginning to end with a focus that includes requirements definition and implementation throughout the life of the program, major subsystems, the development program, the testing program, and the operations program. The major systems include the Pressure Suit Assembly (PSA) consisting of the Pressure Suit, the Equipment Module pack with all ECLSS, Thermal and Avionics equipment necessary to complete the mission, and the recovery system that safely brings the pilot back from the stratosphere; the Launch System that includes the Balloon Equipment Module for control of the balloon flight vehicle, the ground hardware and system to launch the flight vehicle; as well as the Mission Control system that coordinates all aspects of the operation pre-launch through to recovery, and the Chase / Recovery system that must promptly get to and safely recover the pilot upon landing. Additionally a focus will be on the interplay between development, testing, and operations that allowed for the rapid product life cycle needed to implement the ever-evolving design through the completion of the StratEx program.

Nomenclature

AAD	=	Automatic Activation Device
AGL	=	Above Ground Level
ATCS	=	Active Thermal Control System
BEM	=	Balloon Equipment Module (comprised of BEM-SS and AM)
BEM-SS	=	BEM Support Structure
CHASE	=	Chase team lead
COMM	=	Communication
ConOps	=	Concept of Operations
COTS	=	Commercial Off The Shelf
DAB	=	Data Acquisition Board
DHR	=	Dual Helmet Regulator
DOC	=	Medical Team Doctor
DSC	=	Dual Suit Controller
DZ	=	Drop Zone
ECLSS	=	Environmental Control and Life Support System
EM	=	Equipment Module

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°F	=	degrees F
FAA	=	Federal Aviation Administration
FAI	=	Fédération Aéronautique Internationale
FMEA	=	Failure Modes and Effects Analysis
FSDC	=	Flight System Data Commlink
ft	=	feet
ft^2	=	square feet
ft^3	=	cubic feet
ft/min	=	feet per minute
GC	=	Ground Cart
km	=	kilometer
kPa	=	kiloPascals
lbm	=	pound mass
LTG	=	Liquid Thermal Garment
LS	=	Launch Site
m	=	meter
m^2	=	square meter
m^3	=	cubic meter
m/s	=	meters per second
MC	=	Mission Control
MED	=	Medical Technician
min	=	minute
mph	=	miles per hour
MSL	=	Mean Sea Level
NAV	=	Navigation
nm	=	nautical miles
NM	=	New Mexico
NOTAM	=	Notice to Airmen
O_2	=	Oxygen
PLT	=	Pilot
PS	=	Pressure Suit
PSA	=	Pressure Suit Assembly
psf	=	Pounds per Square Feet
psi	=	pounds per square inch
psia	=	pounds per square inch absolute
psig	=	pounds per square inch differential
psig	=	pounds per square inch gauge differential
RS	=	Recovery Suit
SAEBER	=	Stiff Anti-Entanglement Bridle Ejecting Rod
SCUBA	=	Self-Contained Underwater Breathing Apparatus
StratEx	=	Stratospheric Exploration
US	=	United States

I. Introduction

IN December of 2011, Alan Eustace posed the question to Taber MacCallum the CEO of Paragon Space Development Corporation what if, using a zero pressure balloon as a launch vehicle, you could get to and explore the stratosphere in a suit that was analogous to a SCUBA suit? This would greatly simplify the system, and drastically reduce launch mass of the existing and historical capsule-based systems used to perform manned flights to these altitudes. Was it feasible to do this safely, quickly, and with a relatively small team? Could we develop and thoroughly demonstrate a self-contained system so humans could explore the stratosphere as easily and safely as we do the ocean?

Just 34 months later, on October 24th, 2014 at Roswell International Air Center, the StratEx (short for Stratospheric Exploration) team launched a 328,000 m^3 (11.6 million ft^3) balloon whose lone passenger was the pilot Alan Eustace. He was protected only by a custom space suit with a flight system consisting of the components that were part of the space suit and a separate, avionics module attached to the base of the balloon. The flight went to a peak altitude of 41,578 m (136,410 ft), and after a short float period the pilot was released from the balloon at an altitude of 41,422 m (135,899 ft). With only a small drogue shoot to stabilize his descent, the pilot reached speeds of 1,320 km/hr (820 mph, Mach 1.22) during a free fall that lasted 4 minutes 27 seconds and covering a vertical distance of 37,623 m (123,435 ft) before deploying his parachute. 9 minutes and 52 seconds later he completed the flight coming to terra-firma 125.2 km east of where he started the journey.

This was a culmination of a dedicated effort that encompassed conceptual design and requirements definition, hardware and operations development, System Development Testing, and a Manned Flight campaign. Prior to the manned flight campaign, 5 major systems had to be produced from the ground up; (1) the Pressure Suit Assembly, (2) the Flight Vehicle & Balloon, (3) the Launch System, (4) Chase & Recovery, and (5) Mission Control. In all, 49 integrated system level tests were performed to stress the system and operators, and allow for design iteration.

This process resulted in a very robust system that could be rapidly cycled between tests, as evidenced by the unprecedentedly short manned flight campaign that achieved 3 flights (including the final record flight) in a period of 20 days[**], the span of which was dictated by waiting for favorable weather opportunities for flights.

II. Requirements

One of the first tasks performed was to determine the requirements for executing this endeavor. The historical systems (and especially failure modes) used to date were leveraged to drive many of the requirements. For an introductory background summary of the historical manned, stratospheric flights performed prior to this effort see Ref. 1. Requirements for the program were defined to communicate the scope, constraints and goals of this effort. The overall goal was to develop and demonstrate a self-contained system so humans can explore the stratosphere as easily and safely as we do the ocean. Specific narrowing of scope was required to focus the team on achievable goals, while leaving the questions of application for this technology for those that come after.

Six Program and Architecture Functional Requirements were defined as follows:

The StratEx architecture shall provide the capability to:

1. maintain the health of the pilot during the mission
2. maintain pilot comfort during the mission
3. conduct a high altitude sky dive
4. conduct a jump at any altitude up to and including 40.5 km (133,000 ft)

The StratEx architecture:

1. shall be at least one fault tolerant for all functions whose failure would result in a catastrophic event
2. fault tolerance for catastrophic events shall be provided without the use of emergency equipment and subsystems
3. shall utilize industry standard specifications for the individual subsystems

III. System Description

A. Major Subsystems

The StratEx Architecture is comprised of the StratEx Flight System and the Ground Elements. The StratEx Flight System is further divided into six system modules. (1) the Pressure Suit Assembly that includes the pressure suit; the Equipment Module (EM), which provides a mounting location for components from a variety of subsystems; and the Flight Recovery system includes the harness, drogue, main and reserve parachutes. (2) The Flight Vehicle module is the balloon and all of its associated components, including dedicated avionics & power. The other four modules remain on the ground. (3) The Balloon Launch Equipment is all items needed to unfurl and inflate the balloon prior to launch. (4) The Ground Cart provides oxygen, cooling, electrical power and communications while the pilot undergoes the pre-breathe process. (5) Mission Control houses all of the equipment needed to track the mission and communicate with the pilot. Finally, (6) Chase / Recovery includes the vehicles and people to pick up the pilot and all equipment. One way to think of the StratEx System is that it is all of the equipment that will have to be moved should the launch location change.

[**] In comparison Kittenger's, with project Excelsior, manned flight campaign spanned 274 days[1], and Baumgartner's, with Red Bull Stratos spanned 213 days[2].

Looking at it from a functional perspective, the StratEx System also consists of various subsystems. The Environmental Control and Life Support Subsystem (ECLSS) provides thermal control, oxygen, pressurization and other functions to keep the pilot alive and comfortable. The Launch Balloon Subsystem provides the means to lift the pilot to the desired altitude. The Pressure Suit isolates the pilot from the outside environment. The Avionics subsystem provides communication and tracking, receives and issues commands and monitors sensors in other subsystems. The Power subsystem provides the electrical power to all electrical components that need it. The Recovery subsystem includes the harness, parachute and reserve parachute.

The Ground Elements include all equipment and infrastructure to support the mission. This includes cargo vans, lift gas trucks, storage facilities, helicopter pads, etc.

1. Pressure Suit Assembly

The Pressure Suit Assembly (PSA) was a collaboration between ILC (the pressure suit), United Parachute Technologies (the flight recovery system), and Paragon Space Development Corp. (integration, Equipment Module & Ground Cart). This is the first, truly new space suit design in 30 years, and is the highest operating pressure (37.2 kPa / 5.4 psia) for a suit manufactured in the United States. A detailed discussion of the design and performance of the PSA is contained in Ref. 4.

The PSA (Figure 1) consists of the Equipment Module (EM), Pressure Suit (PS), Flight Recovery System (RS) and Ground Cart (GC).

- PS
  - The suit protects the pilot (PLT) from the harsh environment in the upper atmosphere, and interfaces with all the necessary ECLSS components required to keep the PLT alive throughout the operation.
  - The suit maintains an internal pressure of 37.2 kPa (differential) (5.4 psig). The suit is pressurized via the PLT's exhalation from a one way valve interfacing the helmet bubble with the rest of the suit, and is relieved using the purge valve, depress valve, or Dual Suit Controller (DSC).
  - The ECLSS of the suit is controlled and sustained by the EM as described below. Oxygen flows directly into the helmet via a demand regulator (Demand Helmet Regulator [DHR]) and the thermal system interfaces with a liquid thermal garment (LTG) worn by the PLT.
  - This section includes the glass of the helmet bubble, as well as glare protection for the PLT.

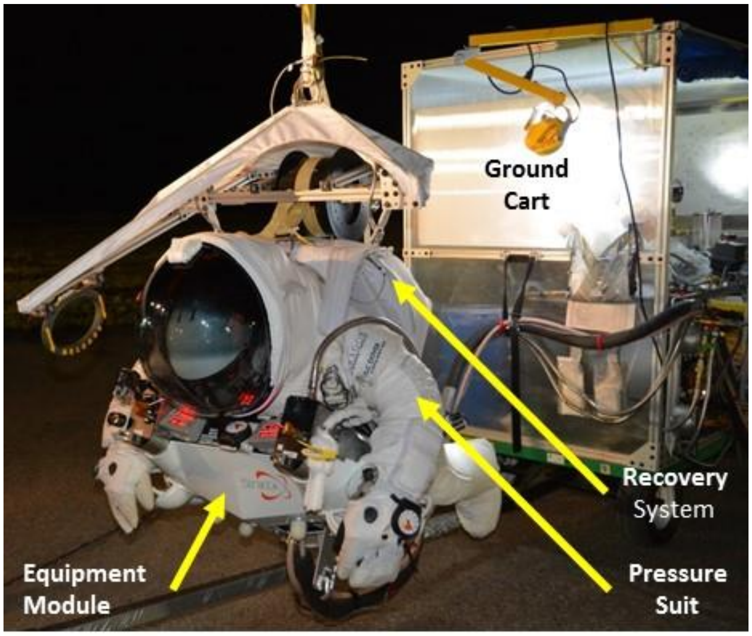

Figure 1. Space Suit Assembly & Ground Cart. During transport from the suit-donning facility to the launch site.

- EM
  - The equipment module includes the physical container that resides on the pilot's chest, the structure that attaches that container to the PS and any interfaces on other systems. It consists of three subsystems and the batteries to power them.
  - Two tanks mounted to the equipment module, provide oxygen for the PLT to breathe. Each tank is pressurized to an initial pressure of 227,500 kPa (3300 psi).
  - A pumped fluid loop include a pump to circulate water around the avionics and the PLT, several thermocouples to measure the temperature, one heat exchanger to heat the water and two heat exchangers to control the oxygen temperature. The pump includes an accumulator to regulate the pressure throughout the flight. The PLT can control the temperature using a

toggle switch attached to the LED Display. Mission Control (MC) also has the ability to control the temperature.
    - The Avionics system encompasses all the electronics on both the EM and PS. This includes all sensors; telemetry; the SPOT GPS (A GPS tracking device) and the StratEx communications system (Flight System Data Commlink [FSDC]); GPS; and all communication systems and data acquisition through the FSDC.
    - Before takeoff the electronic systems of the PS and EM are powered by the Ground Cart (GC). After takeoff the power is provided by four packs of seven lithium-ion batteries each.
- FR
    - The Flight Recovery system allows the PLT to execute the descent portion of his flight.
    - The drogue chute is a small quasi-round parachute that stabilizes the PLT and extracts the main parachute from the pack (Figure 2). Concerns about the Drogue deployment led to the design of the Stiff Anti-Entanglement Bridle Ejecting Rod (SAEBER) System. The SAEBER system is a stowed stiffening device used to control the drogue parachute bridle line and drogue parachute so as not to allow it to wrap around a pilot during times of low dynamic pressure.

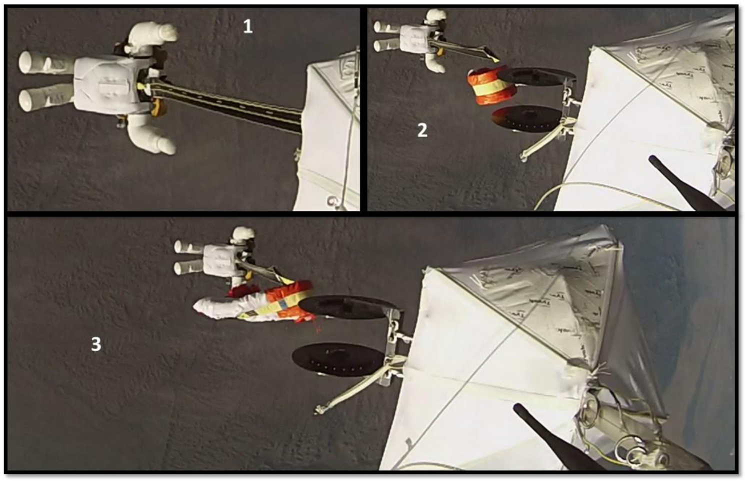

Figure 2. SAEBER System: *Deployed drogue pole does not tangle on rotating test article in free fall.*

    - The main parachute consists of a 33 m^2 (360 ft^2) parachute and parachute pack. It is deployed by pulling an attached rip cord.
    - The backup parachute consists of a 33 m^2 (360 ft^2) parachute. The backup parachute will only be deployed if there is a malfunction with the main parachute or if the PLT fails to deploy the main parachute. It is deployed by pulling an attached rip cord, or by the Automatic Activation Device (AAD).
    - The AAD consists of a controller and a cutter. The controller tracks the altitude and rate of descent of the PLT and sends a signal to the cutter if the PLT reaches a pre-determined altitude at a certain descent rate. When the signal is sent the cutter activates and deploys the backup parachute.
- GC
    - The GC supports the PSA prior to launch by providing all functions of the EM and allowing for the preservation of flight consumables
    - The GC oxygen supplies the PLT in the suit but prior to liftoff.
    - The GC thermal control consists of a chiller, pressure gauges, and pump/motor and maintains the temperature of the suit prior to launch.
    - The Ground Power Supply consists of a DC transformer which will convert the power for the EM, and a generator to power the GC during mobile operations.

2. Flight Vehicle

The StratEx Flight Vehicle consists of the envelope (balloon) and the Balloon Equipment Module (BEM), which supports flight avionics, digital camera capture and transmission hardware, and mechanical and electrical interfaces to the Power, Avionics, Recovery, and Launch Balloon Subsystems.

- Balloon (Figure 3)
    - The balloon consists of the envelope, Crown Valve, and Base Fitting

- The envelope is a unique polyethylene material that has been developed specifically for zero pressure balloons. It is made up of numerous "Gores" which compose individual sections of the envelope.
- The crown valve is a servomotor-actuated valve that allows for the venting of lift gas. The valve is controlled by the Avionics Module (AM).
- The base fitting is the point where all the gores come together and are attached to create the envelope. It is equipped with a bolt to which all supporting equipment, including the payload will be attached.
- Destruct System
  - The balloon is deflated by tearing a sizable hole in its structure thereby allowing the helium to vent. This hole is created using a weight attached to the balloon's structure, called the gore weight. The AM is used as the gore weight.
  - As a backup to this system fuse material is attached around the crown valve which can be ignited using an Iridium modem command to arm (opening a shorting fuse) and separately fire the system.

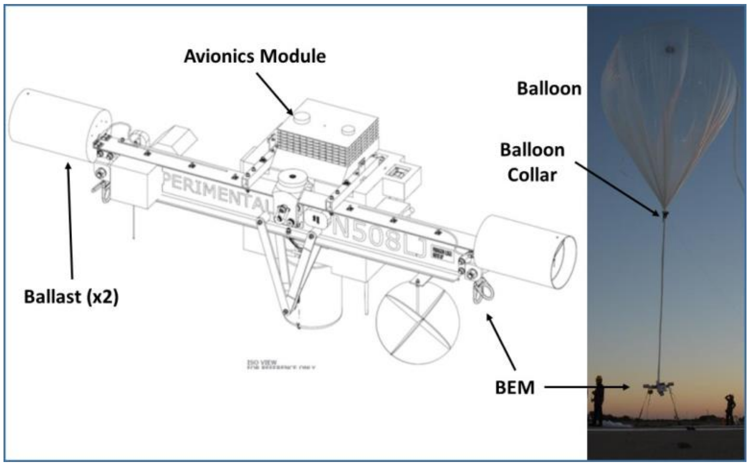

Figure 3. Flight Vehicle: *Balloon and Balloon Equipment Module (BEM)*

- BEM (Figure 3)
  - The BEM interfaces between the Balloon, the PLT, and ground; it houses the Avionics Module (AM), the Mode S Transponder, antennae, radar reflector, and ballast.
  - The AM consists of one FSDC, a transponder, video transmitter, and two Data Acquisition Boards (DABs). This system allows Mission Control to track the flight vehicle, receive telemetry from and send commands to the Flight Vehicle.
  - Ballast attached to the end of the BEM is deployed in low lift scenario. During nominal flight the ballast is deployed at the top of the Tropopause.

3. Launch System

The StratEx Launch System consists of all ground equipment that supports the launch of the flight vehicle. This includes equipment that is used to secure the flight vehicle to the ground, equipment to fill the balloon, the equipment to stand the balloon, and the launch sedan, which is used to support the pilot on the launch pad.

A new static launch method enables safe balloon flight to the stratosphere for humans, by allowing the balloon to be stood up to a static condition and inspected prior to pilot hook on and launch.

- Balloon Support Equipment entails all the equipment necessary to layout the balloon in a manner which prevents damage to the balloon.
- The balloon will be deployed from the balloon box which will be placed on a trailer hitch towed by a pickup truck.
- Helium Fill Equipment
  - The balloon envelope is fitted with two fill tubes in which the lift gas can be put into the balloon.
  - The lift gas used during operations is helium. The Helium Supply System is made up of five major components; the helium gas trailer, main hose, helium manifold cart, fill hoses (2x), and the gas diffuser assembly (2x) which interface to the fill tubes.
- The Spork vehicle is a CASE 621D wheel loader. The Spork vehicle is equipped with a spool-fork assembly (Spork) used to raise and standup the balloon in a controlled fashion.

- The Launch Plate anchors the BEM after the fill has started and keeps the BEM and balloon fixed to the ground up to launch.
- The Launch Sedan supports the PLT on the ground and translates laterally during launch to keep the PLT under the balloon during the launch process.

4. Chase

The primary goal of the Chase Team is to arrive promptly at the landing location of the pilot (PLT) and safely transport him away from the landing site. If the PLT is OK, he would be transported back to the launch site. If he had been seriously injured he would be flown to an appropriate medical facility. Implicit in this goal was the ability to manage suit (PSA) operations and to handle medical emergencies that may arise.

A secondary goal was to recover any equipment, including the AM, BEM Support Structure (BEM-SS), balloon envelope, PSA components, and any other equipment that may land.

A further secondary goal was to serve as a backup Mission Control (MC) if all communication were to go down at primary MC, or if for any reason MC was unable to function effectively.

The Chase Team was formed largely from members of the Launch and PSA teams once the launch phase had been completed and the PLT had safely left the ground. A Recovery/Medical Support team from ADE Aerospace provided medical assistance and other vital functions. The team included a team leader (CHASE) who coordinates activities and communication with the Flight Director (FLIGHT) in MC.

The Chase team operated several vehicles () to deploy to the landing site, aid the PLT as needed, recover the PLT, provide backup support, and recover equipment. For manned operations, two helicopters and two ground vehicles served as primary and backup chase elements, supplemented by a fixed-wing aircraft to deploy one or more para-jumpers, and a medical helicopter on deployed standby.

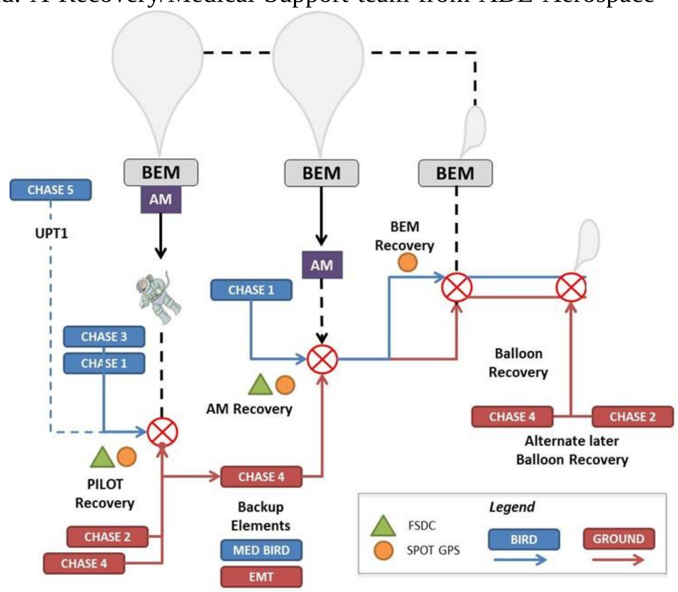

Figure 4. Chase ConOps Schematic

<u>4.1 CHASE 1 Team (helicopter)</u>

• NAV1 is the navigator who provides information to the helicopter pilot on the desired direction of flight and landing locations. NAV1 was in radio contact with NAV in MC. This person was from ILC to serve as a suit technician at the landing site. A tablet computer provides NAV1 with information regarding the absolute and relative positions of the helicopter and PSA. Also, a hand-held GPS unit was available for backup and guidance to locations such as refueling points.

• PSA1 monitors the data coming from the PSA FSDC using a laptop and ground station in the helicopter and issues any commands as needed should MC have technical issues. PSA1 listened to the pilot voice comm channels to stay abreast of the mission status. This person is also responsible for assisting the PLT with helmet doffing (if needed) and shutting down the PSA if CHASE 1 reaches the PLT first, as is expected. This person will assist the medical team as directed. PSA1 will be in charge should the vehicle lose contact with MC and CHASE.

• DOC1 is the Field Medical Director. This person will evaluate any PLT injuries prior to suit doffing and request emergency medical assistance.

• MED1 is a medical technician who will support DOC1.

• Either DOC1 or MED1 sits in the front seat of the helicopter to help provided visual information to the pilot (birds, power lines, etc.) and for visual acquisition of the pilot under parachute.

<u>4.2 CHASE 2 Team (Pickup Truck)</u>

• DRIVER2 is the person who drives the CHASE 2 truck.

• NAV2 is the navigator who provides information to DRIVER2 on the desired direction of travel. NAV2 will be in radio contact with NAV in MC. A laptop computer will show NAV2 the absolute locations of the BEM and truck. Also, a hand-held GPS unit is provided for backup and guidance to locations such as refueling points.

• BEM2 will monitor the data coming from the BEM FSDC using a laptop and ground station in the truck and will issue any commands as needed should MC have technical issues.

• CHASE is the leader of the Chase team and takes over if MC losses contact. CHASE will listen to the pilot voice comm channels to stay abreast of the mission status. CHASE will be in charge if the vehicle loses contact with MC.

• CHASE will also communicate with the other Chase assets via Motorola or aviation radios.

4.3 CHASE 3 Team (helicopter)

• NAV3 is the navigator who provides information to the helicopter pilot on the desired direction of flight and landing locations. NAV3 will be in radio contact with NAV in MC. NAV3 will also listen to the pilot voice comm channels to stay abreast of the mission status. This person must be from ILC to serve as a suit technician at the landing site. NAV3 will be in charge should the vehicle lose contact with MC and CHASE. A tablet computer will provide NAV3 with information regarding the absolute and relative positions of the helicopter and PSA. Also, a hand-held GPS unit is provided for backup and guidance to locations such as refueling points.

• DOC3 is a medical team doctor. If CHASE 3 arrives at the PLT landing location first this person will evaluate any PLT injuries prior to suit doffing and direct any emergency medical assistance.

• MED3 is a medical technician who will support DOC3.

• Either DOC3 or MED3 sits in the front seat of the helicopter to help provided visual information to the pilot (birds, power lines, etc.) and for visual acquisition of the pilot under parachute.

4.4 CHASE 4 Team (Pick-up truck)

• DRIVER4 is the person who drives the CHASE 4 truck.

• NAV4 is the navigator who provides information to DRIVER4 on the desired direction of travel. A laptop computer will show NAV4 the absolute location of the truck. Also, a hand-held GPS unit will be provided for backup and guidance to locations such as refueling points.

• NAV4 will be in radio contact with NAV in MC. NAV4 will listen to the pilot voice comm channels to stay abreast of the mission status. NAV4 will be in charge should the vehicle lose contact with MC and CHASE.

4.5 CHASE 5 Team (fixed wing aircraft)

• NAV5 is the navigator who provides information to the airplane pilot on the desired direction of flight. NAV5 will be in radio contact with NAV in MC. NAV5 will listen to the pilot voice comm channels to stay abreast of the mission status. NAV5 will be in charge should the vehicle lose contact with MC and CHASE.

• An experienced sky diver from United Parachute Technologies (UPT) will jump from CHASE 5 to assist the PLT with landing. If the PLT is conscious and in control this person will guide the PLT into landing, if not he will stay behind him and land next to the PLT.

5. Mission Control

Mission Control encompasses the hardware, software, and personnel involved in directing the execution of all flight procedures from flight planning through recovery. Mission Control personnel include a flight director, mission meteorologist, Flight Surgeon, navigator, ECLSS specialist, recovery system specialist, avionics specialist and flight vehicle specialist. The flight director was responsible for communication with ATC and the launch director. Procedures to be executed include, but are not limited to, weather forecasting, medical oversight, flight operations, ECLSS, recovery and launch hardware check and preparation, launch operations, system monitoring, and ground and air-based flight recovery.

Mission control is broken up into a main room that houses all nominal, required mission equipment and personnel, while a backroom has technical specialists that supply support in the event of an off-nominal operation. Specific positions are as follows:

- Main Room: Flight Director (PLT communication, decision authority), Safety (independent check), Flight Surgeon (medical & PLT health), ECLSS Engineer (Pilot Comfort), Flight Engineer (Avionics & Flight control), Navigation (Chase team coordination), Meteorology (Weather and FAA/Airspace coordination), and a Communications Engineer (computer & network systems)
- Backroom: Balloon specialist, Suit specialist, FAI observer (records monitoring), Parachute recovery system specialist, Crisis management / external communication,

B. Concept of Operations (ConOps)

The purpose of the StratEx system is to bring a human safely to the stratosphere utilizing a space suit as protective vehicle for life support. At altitude return of the pilot will be done by releasing from the balloon and sky diving to lower altitudes where a parachute can be deployed to finally bring the pilot back to terra-firma.

The desired altitude for the flight & release is 135,000 feet. In order to get the pilot to this altitude, a zero pressure helium balloon will be utilized. The pilot will be attached to the balloon via a tether with only a space suit to protect him from the near space environment

The pilot will require several subsystems to complete the mission. In order to survive the extreme altitude, the pilot will wear a pressure suit similar to those worn by astronauts. The ECLSS will maintain the pilot's health by supplying heating, providing oxygen and removing carbon dioxide, and maintaining a pressurized environment. An avionics system will monitor sensors and provide uplink and downlink communications. The recovery system will consist of a parachute and harness that hold the pilot and equipment module together, and it utilizes a drogue parachute and a parafoil to help the pilot glide safely back to earth.

1. Mission Timeline

Figure 5 shows the top level milestones of the mission and their timing (Actual) relative to the predicted schedule (Est.) for the final flight on October 24th, 2014.

Task Name	**Time**	
	Est.	**Actual**
MC Operations Start	0:32	0:30
FV Operations Start	1:22	NTR
PSA Operations Start	1:56	NTR
PLT PB start	2:45	2:30
PS Ready for Donning (Go/No-Go Poll)	3:58	3:48
PS Helmet Bubble Seal	4:18	NTR
Balloon Unpacking Go/No-Go	4:32	4:13
PS Donned	4:47	4:28
PS Tests Complete	5:17	NTR
PLT Ready for Mobile Ops	5:17	5:00
Balloon Fill Go/No-Go (Check pre-breathe time)	5:57	6:15
PLT at Launch Site	5:57	5:33
Balloon standing, PLT on site	6:37	6:50
Contact FAA for permission to launch	6:37	NTR
Conduct Hook-up Poll	6:37	NTR
FV Ready for Launch	6:43	NTR
Launch	6:45	7:00
Altitude call [102.8K ft MSL passing Kittinger's record]	8:27	8:36
Altitude call [105,884 ft MSL you have broken Kittinger's record (ASSUMING 3%)]	8:30	8:39
Altitude call [127,851 ft MSL Passing Red Bull Stratos record]	8:53	8:57
Altitude call [131,686 ft MSL you have set a new manned balloon altitude record (ASSUMING 3%)]	8:57	9:01
Get FAA permission to release PLT	9:06	8:57
Record Altitude Achieved	9:20	9:06
Go poll for release	9:20	9:07
PLT Released	9:20	9:09
PLT on the Ground		9:23
PLT Located - Extraction	9:35	
Get FAA permission to Release AM and destroy balloon	9:37	NTR
Arm AM Release and Release AM	9:40	9:15
AM Away	9:40	9:15
Balloon on ground	10:20	9:57
AM on ground	10:20	9:57
PLT on Chase	10:22	NTR
PSA Recovered	10:22	NTR
AM Recovered	12:15	NTR
Balloon Recovered	13:15	Next day

NTR = No Time Recorded

Figure 5. Predicted Mission Timeline for October 24th, 2014 record flight

2. Pre-Launch

Preparations prior to flight day are encompassed by a phase 0 operation that sets up all hardware in a ready state so that a flight can be executed when a suitable weather window has been identified. Phase 1 starts with a mission briefing held at least 18 hours prior to an identified launch window. Operations / procedures during this phase were organized around the four operational teams; PSA team focused on the PLT and getting the suit ready and bringing the PLT to the launch site; Launch team focused on balloon and Flight Vehicle preparation, identifying the layout direction, placing of the launch equipment, laying out the balloon, then filling and standing it up; Chase team readying chase vehicles and equipment; finally Mission Control coordinating all operation, tracking mission timeline milestones, and resolving delays and conflicts.

Figure 6. Balloon Fill & Standup

3. *Ascent*

Take-off was at Roswell, New Mexico (elevation 1,100 m [3671 ft.] above mean sea level). The nominal ascent rate was assumed to be 5 m/s (1000 ft/min), although with the 14% free lift the rate was sometimes higher. During the ascent phase as temperature inversions are encountered (such as above the tropopause) ballast deployments will be used to improve the ascent rate.

Under the nominal ascent rate, it was expected to take about 2 hours and 12 minutes to ascend from the ground to the target altitude of 41.1 km (135,000 ft).

4. *Loiter*

Originally it was expected that the pilot would want to linger at altitude for up to 1.5 hours to enjoy the view. Manned suit testing dampened his enthusiasm for staying in the suit longer than necessary. Mission planning did assume 15 minutes at the loiter altitude of 41.1 km (135,000 ft). This allowed for any preparation for descent, if required.

5. *Descent*

A drogue parachute is deployed when the pilot releases from the balloon. This drogue chute will stabilize the pilot and prevent tumbling and spinning during the descent.

The pilot will deploy the main parachute

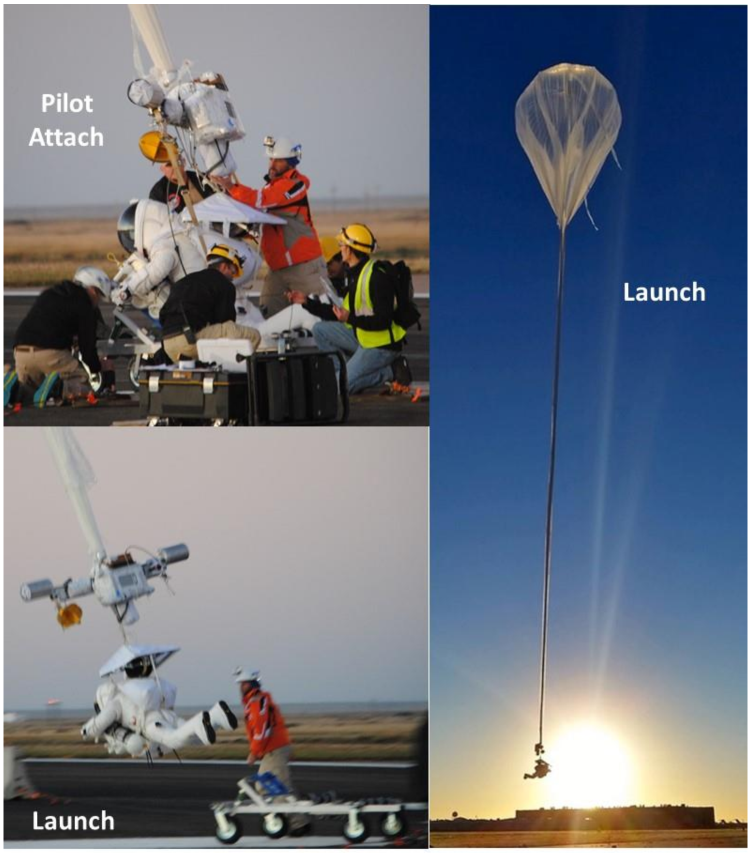

Figure 7. Pilot Attachment & Launch.

at an altitude of 5120 m (16,800 ft) above sea level (MSL). The parachute ConOps requires that the AAD for the reserve be set to activate 670 m (2200 ft) above the highest geographical point in the projected flight path. In order to ensure that the main parachute fully deploys and slows the skydiver sufficiently to prevent the reserve from deploying, the main must be deployed 1524 m (5000 ft) above the AAD set point (or 2195 m [7200 ft] above the highest geographical point in the flight path).

After parachute deployment the pilot will depressurize the suit to improve mobility for landing. If the helmet bubble is fogged and the pilot cannot see, he will have the option to either re-pressurize the suit and land blind or remove the helmet bubble to provide visibility at the expense of physical protection.

Landing will be in the vicinity of Roswell, NM, most likely to the east of the city.

6. Landing

The ConOps called for the pilot to land with the suit un-pressurized. The idea is that the unpressurized suit will provide additional mobility allowing the pilot to better control the parachute. After landing the pilot could take off the helmet bubble.

7. Mission Abort ConOps

Once the pilot has reached 610 m (2000 ft) ground altitude and above, any abort merely replicates the descent portion of the nominal mission, corrected to the abort altitude. The decision to abort will be made by either the pilot or the Flight Director. The pilot can initiate an abort based on his own knowledge of the circumstances, but he cannot over rule a Flight Director's decision to abort.

Detailed abort criteria were included in the Flight Manual to determine when an abort takes place, however some likely scenarios that could drive an abort are:

- Power failure
- A suit leak
- An unconscious pilot
- Loss of communication with the pilot
- Loss of avionics.

For the case of a suit leak, it is assumed that it will take 5 minutes for the pilot and ground personnel to determine that a leak exists and abort the mission.

IV. Development

The focus for development was to use Commercial Off The Shelf (COTS) equipment as much as possible. The goal was to rapidly development and manufacture the system so that testing and vetting of the system could occur. With the preference to build and test hardware, analysis was minimized, except for the following areas:

- Thermal analysis on suit during flight
- Structural analysis of EM & BEM structure
- Analysis of Suit Aerodynamics

Due to the easy access to flight testing via latex weather balloons, and payloads under six pounds (under the FAR Part 101 rules exceptions), rapid development of component hardware was driven by performance in flight. This was a welcome deviation from the extensive analysis and design process that is necessary for space-flight hardware, and this was critical for development of the communications equipment (primary, and backup systems) on the ground and in the air, as well as balloon destruct hardware, as well as being quite useful for Chase / Recovery hardware & operations development.

Early on Operations was identified as an area that would require significant effort. As such, it was decided to develop and train the operations early on at the same time as system testing was begun. As much as possible, a fully operational crew for the final manned flight tests was included during the first system level testing. This allowed the team extensive opportunity to exercise procedures, and exercise the information flow and command structure that would be required for the final flights. Ample practice over the time spanned by the tests allowed the team to become a well-oiled machine, able to handle serious deviations with a practiced precision.

V. Development & Testing

The goal was to rapidly development and manufacture the system so that testing and vetting of the system could occur. Extensive analysis was minimized, with the preference to build and test the hardware; Thermal analysis was performed on the suit, structural analysis of the EM and BEM structures, and some aerodynamic modelling of the suit was also performed.

Early on operations was identified as an area that would require significant effort. As such, it was decided to develop and train the operations early on at the same time as system testing was begun. Extra effort and personnel participated in integrated testing so that the team would become proficient well in advance of manned flights.

At the outset the test program was designed to build on each test performed. Subsystem tests would mitigate risks, validate analyses and prove out design concepts. This would lead to a final subsystem design. The system level tests are used to verify requirements and functionality and to identify unknown problems early. Ground tests are done for safety and unmanned balloon flights are conducted before attempting manned flights.

It is important to note that each of these tests was looked at as a series of technical objectives that must be achieved and evaluated prior to moving on to a next, dependent step. While these tests would fall into a natural schedule, the technical objectives are what are important, and a test was repeated until the test team agreed that the technical objectives have been met. As the program was executed this was an important point which had to be kept in mind as development and test went hand in hand, in a multiplicity of iterations with parallel paths and branches that needed to be brought to a close in order to ready hardware and personnel for manned flight tests. In the end subsystem testing, system level tests, ground testing and flight testing were performed concurrently as issues were identified; at time including performing system level tests multiple times as subsystem designs were revised and updated.

A. Mission Phases

To keep this brief, the focus will be on the StratEx system level tests. The purpose of these tests is to verify the performance of the StratEx system under conditions that simulate the pressure and thermal conditions that the pilot and the flight vehicle will see during the mission to 41 km (135,000 ft). The mission is divided into one preflight phase (Phase 0) and six flight phases (Phases 1 through 6). The six flight phases are:

1 Pre-launch
2 Launch
3 Ascent
4 Loiter
5 Descent
6 Post-landing

Each of these stages has different environmental conditions that must be considered. In addition off-nominal operations will need to be considered.

1. Pre-Launch

The pre-launch phase includes all activities until inflation of the balloon begins. From a thermal and vacuum testing perspective the most important activity is the start of pre-breathe. This phase is expected to take place during pre-dawn hours as launch will be early in the morning when winds are lightest. The pre-launch phase will be performed in test flights and prior to any vacuum testing, but special test conditions will not be required or applied.

- Pressure - During this time the pilot will experience a constant outside air pressure assumed to follow the 1976 US Standard Atmosphere and, while inside the pressurized suit, the suit will control the pressure to 37.2 kPa (differential) (5.4 psig).
- Air Temperature - For most of this phase the pilot is expected to be in a controlled environment and attached to a ground cart that will provide thermal comfort. There will be a period (currently assumed to be 15 minutes) between the time the ground cart is disconnected and the actual launch. At this time the pilot will have the ability to apply heat, but not cooling.
- Convective Heat Transfer – Convective heat transfer is not significant during this phase.
- Radiative Heat Transfer - Radiative heat transfer is not significant during this phase.
- Duration – Pre-breathe will be 4 hours, primarily based on the pre-breathe protocol developed.
- Structural - There are no significant structural loads expected during this phase. The pilot may be outside the suit, hanging in the suit (1g) or lying on the launch sedan.

2. Launch

The launch phase begins with the inflation of the balloon and continues until the balloon has exited the black zone approximately 610 m (2000 ft) above ground level. The pilot will be disconnected from the ground cart and attached to the balloon during this phase. The pilot will transition from a controlled inside environment to ambient outside conditions. As such, there may be a change in environmental temperature but no change in pressure (ignoring the effects of rising 610 m [2000 ft]). Once the pilot is disconnected from the ground cart cooling for the LTG will no longer be available. It is anticipated that the pilot will be “pre-cooled” prior to disconnect.

• Pressure - During this time the pilot will experience a constant outside air pressure assumed to follow the 1976 US Standard Atmosphere with the pressure inside the suit controlled to 37.2 kPa (differential) (5.4 psid). There will be some decrease in ambient pressure as he rises to 2000 ft above ground level.
• Air Temperature –The pilot will transition from a controlled inside environment to the outdoors. The outside air temperature will not be known, but will be consistent with fall weather in Roswell NM.
• Convective Heat Transfer – Convective heat transfer will be assumed as equivalent to 0.5°C (31°F) with a 5 m/s wind (1000 ft/min) after the balloon is released. As the pressure suit is designed for much colder conditions, this is not expected to be a stressing condition.
• Radiative Heat Transfer - Radiative heat transfer is not significant during this phase.
• Duration – This phase will last on the order of 30 minutes.
• Structural - There are no significant structural loads expected during this phase. The actual launch is expected to be smooth and the pilot will go from resting on the launch sedan to hanging from the balloon.

3. *Ascent*

The ascent phase begins when the balloon exits the black zone at 2000 ft above ground level. The balloon will take the pilot to a height of 41 km (135,000 ft) above mean sea level. The balloon may travel over 161 km (100 miles) down range during this phase of the mission.

• Pressure - During this time the pilot will experience an ever decreasing outside air pressure assumed to follow the 1976 US Standard Atmosphere with the pressure inside the suit controlled to 37.2 kPa (differential) (5.4 psid).
• Air Temperature – The surrounding air temperature is assumed to follow the 1976 US Standard Atmosphere. During ascent, the pilot will be in the wake of the balloon which may modestly affect the temperature the pilot experiences.
• Convective Heat Transfer - A maximum ascent rate of 6 m/s (1200 ft/min) is assumed, which will provide some degree of convective cooling, particularly in the lower tropopause.
• Radiative Heat Transfer - Solar flux will increase as the air thins and the sun rises further above the horizon. Radiative cooling to the sky will increase with altitude. Albedo and Earth IR will decrease with altitude.
• Duration – The nominal anticipated ascent rate is 1000 ft/min, meaning this phase would last just over 2 hours. However, lower ascent rates could mean that this mission phase could last up to 3 hours.
• Structural - There will be some structural load during launch but are not expected to be significant compared to loads encountered during other phases.

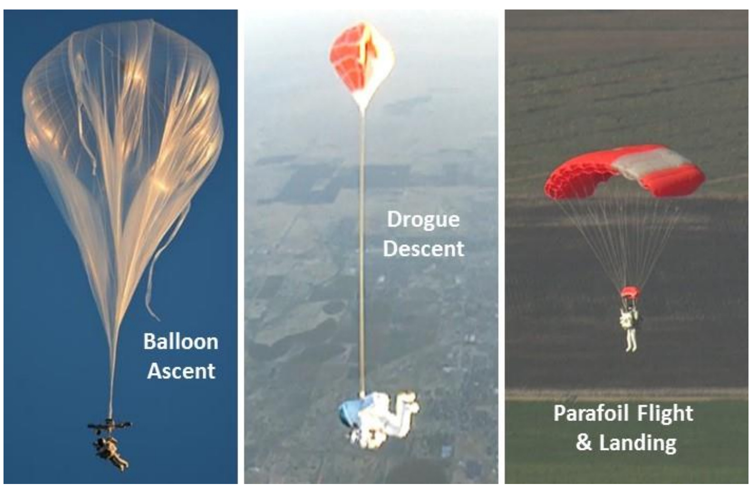

Figure 8. StratEx Flight Modes.

4. *Loiter*

As the balloon approaches an altitude of 41 km (135,000 ft) the helium inside of the balloon will expand and passively vent from the balloon. Once enough helium vents the balloon will stop rising and float at 41 km (135,000 ft). This begins the loiter phase of the mission.

• Pressure - During this time the pilot will experience outside air pressure assumed to follow the 1976 US Standard Atmosphere. At 41 km (135,000 ft) this is 234 Pa (0.034 psia) with the pressure inside the suit controlled to 37.2 kPa (differential) (5.4 psid).
• Air Temperature - The surrounding air temperature is assumed to follow the 1976 US Standard Atmosphere. At 135,000 ft this is -19°C (-2.8°F).
• Convective Heat Transfer – The outside air temperature will be cold (-19°C / -3°F), but the air density will be so low that any impacts from convective cooling should be negligible. Also, the balloon will be moving with the air so the relative air velocity will be very low.
• Radiative Heat Transfer - During this phase the pilot will be exposed to high solar fluxes and a very cold sky. Some reflective solar radiation (albedo) and IR heat from the earth will be present.
• Duration - This phase will be minimized, with an assumed loiter time of 15 minutes.

- Structural - There are no significant structural loads expected during this phase.

5. *Descent*

The descent phase can be further subdivided into a free fall phase and descent under parachute. A drogue release will occur upon pilot release from the balloon and will remain deployed during the entire free fall.

Free Fall

At the end of the loiter phase the pilot will release from the balloon and free fall towards earth with the SAEBER system providing stability.

- Pressure – During this time the pilot will experience an ever increasing outside air pressure assumed to follow the 1976 US Standard Atmosphere with the pressure inside the suit controlled to 37.2 kPa (differential) (5.4 psid).
- Air Temperature – The surrounding air temperature is assumed to follow the 1976 US Standard Atmosphere.
- Convective Heat Transfer – During this phase, the driving thermal consideration is convection. At the higher altitudes the pilot will feel very little aerodynamic effects and hence convection will be low. As he descends towards the tropopause the air pressure will increase and the air temperature will decrease. The convective cooling will be maximized at around 11 km (35,000 ft) at the bottom of the tropopause with the combination of cold air (-57°C / -70°F), noticeable air pressure and high air speeds. Once the pilot enters the troposphere the pressure will increase but so will the temperature.
- Radiative Heat Transfer - The pilot will experience the same solar and radiative conditions at the beginning of free fall as during loiter.
- Duration – The free fall is expected to last approximately 260 seconds, assuming a main parachute deployment at 4000 m (13,200 ft) AGL.
- Structural - The pilot's maximum speed will occur around 30 km (98,000 ft) and his maximum deceleration will occur around 23 km (76,000 ft). This could be up to 1.7 g's of deceleration. The aerodynamic drag forces will concentrate on the Equipment Module outer shell. The pressure distribution from the drag forces will need to be considered.

Descent under Parachute

When the pilot gets close to the ground he will deploy the main parachute to start the final phase of the flight (the exact altitude of deployment will be determined by local geography and the desire to allow the pilot to have as much horizontal flying range as possible). The parachute will slow the pilot down to a descent rate of approximately 5 m/s (1000 ft/min). The temperature and pressure will be increasing as the pilot descends so this should not be a driving thermal case in comparison to the free fall phase. The parachute deployment could cause up to 5 g's of deceleration with reserve deployment accelerations even higher. The landing loads may be as high as 5 g's or more during an uncontrolled landing (demonstrated during testing). A perfectly controlled landing in a benign landing zone may result in very low landing loads.

- Pressure – During this time the pilot will experience an ever increasing outside air pressure assumed to follow the 1976 US Standard Atmosphere with the pressure inside the suit initially controlled to 37.2 kPa (differential) (5.4 psid). As the pilot prepares for landing the pressure inside the suit will be equalized to the surrounding air pressure to allow for greater flexibility during landing.
- Air Temperature – The surrounding air temperature is assumed to follow the 1976 US Standard Atmosphere.
- Convective Heat Transfer – Given the warmer temperatures of the lower atmosphere and low descent rates, this is not expected to be a driving case.
- Radiative Heat Transfer – The pilot will be exposed to solar fluxes consistent with mid- to late-morning. Heat transfer to the sky should not be a driving factor.
- Duration – The descent under parachute is expected to last 10-15 minutes depending upon the elevation above ground when the parachute is deployed.
- Structural – Significant structural loads from parachute deployment and landing must be considered. The magnitude of these loads has been demonstrated during unmanned tests by UPT, and manned tests by Paragon.

6. *Post-Landing*

After landing the pilot will remove the helmet bubble. By this time the support crew should be arriving to assist the pilot in removing the rest of the suit. The heating may likely be turned off (as early as just before pilot release from the Balloon) as the thermal environment is most likely too warm for the cold biased pressure suit. No structural loads are expected post-landing.

- Pressure – During this time the pilot will experience outside air pressure assumed to follow the 1976 US Standard Atmosphere. During a nominal landing the suit will be depressurized. In the event of an unconscious pilot the pressure inside the suit would be 37.2 kPa (differential) (5.4 psid).

- Air Temperature – Ground air temperatures could be highly variable depending upon the time of day and natural variation.
- Convective Heat Transfer – Not expected to be significant.
- Radiative Heat Transfer – Solar heating could be significant, but not driving.
- Duration – This phase could last up to 60 minutes in the case of an unconscious pilot making an uncontrolled landing in an area where the Chase teams may have difficulty finding him.
- Structural – No structural loads are anticipated.

B. Ground Tests

The goal of ground testing was to verify the function and operation of the Flight System before the pilot was subjected to flight tests. Ideally all conditions expected in the flight profile would be exactly replicated.

1. Long Range Communications Testing

The purpose of this test is to demonstrate that the communications and telemetry functions work properly when the Flight System is in is flight configuration (BEM with Pressure Suit Assembly [PSA] attached via flight rigging). The Flight System was located in a location that had an unobstructed view of a location 110 km (70 miles) away, where Mission Control was set up. Experience has shown that if all communications functions can occur at distances greater than 80 km (50 miles) then there should not be issues seen during flight from much greater distances.

2. System Thermal and Vacuum Proto-qualification Test

The purpose of this test was to simulate the pressure and thermal conditions that the pilot will see during the mission to 41 km (135,000 ft). It was decided that the thermal and vacuum tests would be separated into two separate tests; the thermal-cold test is performed at conservative temperatures at ambient ground pressure, and the vacuum tests (representing a thermal hot case, and pressure case) are performed in vacuum / altitude chambers. For a more detailed discussion please see Ref. 5.

Figure 9. Thermal – Cold Testing in the FЯANKENFЯEEZEЯ: *Left, testing underway under careful supervision of the team; Right: at 57°C (-70°F) a simulated altitude of 20 km (65,000 ft)*

The thermal – cold testing is done using the FЯANKENFЯEEZEЯ (a 12’ x 12’ x 12’ outdoor freezer, Figure 9). After the test unit is installed liquid nitrogen is injected into the chamber to cool the environment. Control thermocouples allow the temperature to be varied by changing the rate at which the nitrogen is injected.

Figure 10. Manned Vacuum – Hot / Pressure Testing: *Left, Pilot in the chamber ready for doors closed; Right, team in front of the Chamber after the successful test*

Vacuum testing is done either unmanned using a Paragon chamber or manned using the Arizona State University Del E. Webb High Altitude Training Chamber (Figure 10). In these tests the pressure profile is set to match the expected flight profile.

3. Pilot Training & Human Factors Tests

A need for detailed pilot training and human factors testing was identified during early systems testing. As such a series of objectives and training milestones was developed, and proficiency in all tasks needed to perform the final mission flight was required. These tests included pulling parachute handles, the manual release handle, heater and voice communication switches, depressurization and purge valves, reaching the riser handles and removing the helmet bubble.

C. Flight Tests

1. Pilot Jump Tests

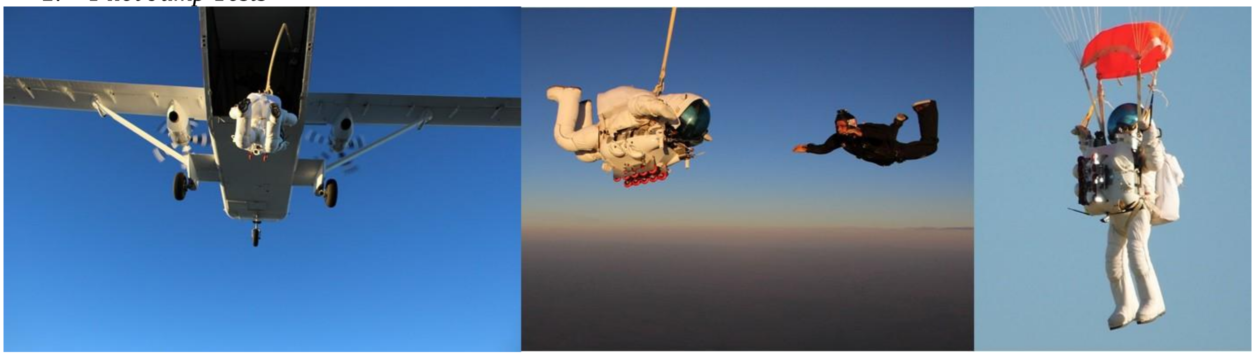

Figure 11. Airplane Jump Tests: *Left, Exiting the plane; Middle, Drogue descent; Right, Parafoil flight*

The purpose of these tests was to train the pilot to carry out the tasks of the descent phase in real world conditions. This includes the separation from the balloon, free fall with the equipment module and suit, deployment of the parachute and landing. The training will go in steps of increasing complexity.

This started with Tandem Jump training as an instructor that was done by UPT. Airplane jumps were then performed with a test rig and Equipment Module simulator to get the pilot used to the mass of the system. The pilot would then perform jumps with the Flight System including the Pressure Suit, Equipment Module, and Flight Recovery system.

2. Unmanned Balloon Flights

The primary purpose of the unmanned flights was to serve as a final check of the launch system and the flight vehicle, as well as serve as a high altitude demonstration of the SAEBER drogue system. All aspects of a manned flight were simulated, but the pilot and PSA were replaced by an iron dummy for the actual flight.

This test would occur prior to having a fully trained Operations team and will also be used to gain additional training and experience for StratEx operations team; for example, Phase 1 operations (everything but attaching the

Figure 12. Unmanned Flight System

pilot to the balloon) of the PSA, coordinated through mission control, exercise of the chase vehicle systems and operations, etc. will be done.

3. Manned Balloon Flights

At least one manned flight test was planned to be conducted prior to the record breaking attempt to be made. As a prerequisite, all other tests must have been completed prior to the first Manned Balloon Flight. This flight test would expose the entire system to very low pressure environments and the significant convective cooling of the tropopause.

The full flight configuration would be utilized and all pre-launch protocols were followed. The balloon would lift the pilot to the desired altitude at which point the release mechanism will be activated (manually or remotely). The pilot free falls to the designated deployment altitude at which point he manually deploys his main parachute.

To determine the number of manned flights, things like pilot safety, balloon availability, schedule impact and technical details needed to be considered. Regardless of the number of manned jumps before the record breaking flight, the following graph (Figure 13) was considered to help select the jump altitudes.

Figure 13 shows five parameters plotted versus the jump altitude. First is the amount of time spent at or below 0.1g, which is considered the limit of "weightlessness". The second parameter is the time spent falling with a dynamic pressure that is less than 50% of the dynamic pressure experienced at terminal velocity at 3050 m (10,000 ft) (approx. 1050 Pa / 22 psf), designated "<50% DP 10k". The third parameter is the time spent falling with dynamic pressures greater than 115% of terminal velocity at 3050 m (10,000 ft). Next, the percentage that the peak dynamic pressure is greater than the terminal dynamic pressure at 10,000 ft is plotted. Lastly the maximum Mach number during descent is shown. Also plotted on the curve is Armstrong's Line, which is defined as the altitude at which water boils at body temperature. This is considered a maximum altitude at which a human could survive without a pressure suit. Note, both the 50% and 115% limit values are somewhat arbitrary. The curve above also assumes a constant drag coefficient that is unaffected by Mach number.

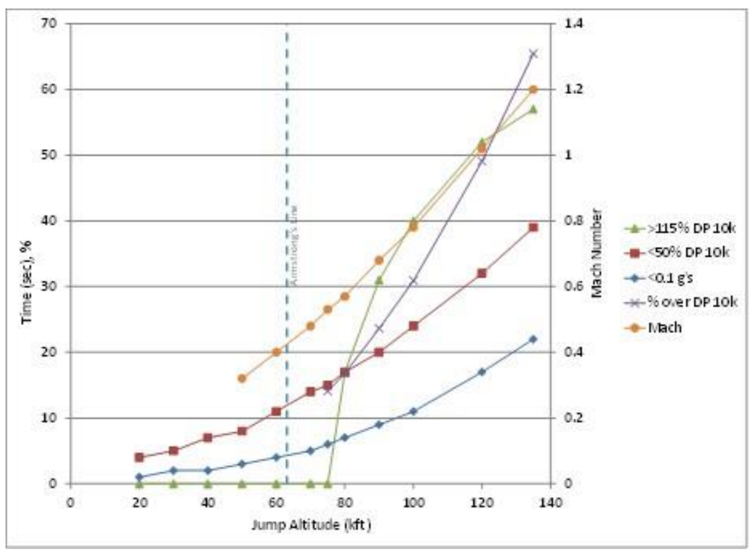

Figure 13. Effect of altitude on freefall characteristics.

The figure was used to infer the following series of manned flights. First would be a jump from below Armstrong's Line (~ 19 km / 63,000 ft). This would expose the pilot to some weightlessness and low dynamic pressures but yet add a perceived improvement of safety; and, in the end, a deciding factor for this test was to build pilot confidence and comfort in the system, as this was much like an extended version of the Airplane Jump Testing that had been recently completed. Next a jump from around 30 km (100,000 ft) would provide additional time of weightlessness and low dynamic pressure as well as expose the pilot to dynamic pressures up to 30% over that of terminal velocity for over 30 seconds.

D. Test Results

Not including small component tests that were done throughout the program, the StratEx program performed 49 tests for this 34 month program, all but one of which happened in a span of 18 months. The overarching approach for the program was to rigorously hold to a milestone based approach to test progress. A specific test that was deemed dependent on another test, would not be able to be performed until that test had met all of its primary objectives. As can be seen in the table below, multiple testing was performed in parallel; this allowed for a shortened schedule, but this was a conscious decision for tests that were not dependent on each other. Objectives were rigorously evaluated after each test to determine if it was safe to move on to the next test.

	Test Date	Location	Test Category	Test Description	Comments	Duration	DZ range from LS
1	2012.04.30	Lone Tree, CO	Wind Tunnel				
2	2013.04.10	Tucson, AZ,	Vacuum Chamber	PSA Unmanned Pressure #1	Completed DSC aneroid test & DHR aneroid test		
3	2013.04.11	Tucson, AZ	Vacuum Chamber	PSA Unmanned Pressure #2	Completed pressure profile		
4	2013.04.18	Tucson, AZ	Vacuum Chamber	BEM Unmanned Pressure #1	Completed pressure profile no-insulation,		
5	2013.04.22	Tucson, AZ	Vacuum Chamber	BEM Unmanned Pressure #2	Completed pressure profile with-insulation,		
6	2014.05.28	Tucson, AZ	Vacuum Chamber	BEM Unmanned Pressure #3	Test to hotcase-thermal & pressure qualify FSDC		
7	2013.04.24	Tucson, AZ	Human Factors & Pilot Training	Manned Systems Checkout #1			
8	2013.04.25	Tucson, AZ	Human Factors & Pilot Training	Manned Systems Checkout #2			
9	2013.04.26	Tucson, AZ	Human Factors & Pilot Training	Manned Systems Checkout #3			
10	2013.10.24	Roswell, NM	Human Factors & Pilot Training				
11	2014.07.21	Roswell, NM	Human Factors & Pilot Training				
12	2014.07.22	Roswell, NM	Human Factors & Pilot Training				
13	2013.05.02	Tucson, AZ	Thermal-Cold	PSA Thermal #1	More O_2 use than expected (test cut short due to this), Helmet fogging, DSC got cold --> increase in suit pressure		
14	2013.05.03	Tucson, AZ	Thermal-Cold	PSA Thermal #2	Abort, due to lost COMM right before descent profile		
15	2013.07.28	Tucson, AZ	Thermal-Cold	PSA Thermal #3	Abort due to fluctuation in system voltage		
16	2013.07.30	Tucson, AZ	Thermal-Cold	PSA Thermal #4	Abort due to pressure rise in suit		
17	2013.08.09	Tucson, AZ	Thermal-Cold	BEM Thermal #1	Completed profile, but lots of component failures		
18	2013.08.16	Tucson, AZ	Thermal-Cold	BEM Thermal #2	Completed profile, still component failures, but less		
19	2013.08.20	Tucson, AZ	Thermal-Cold	BEM Thermal #3	Completed profile, still component failures, but less		
20	2013.08.23	Tucson, AZ	Thermal-Cold	BEM Thermal #4	Completed profile, Iridium modem still failing		
21	2013.08.26	Tucson, AZ	Thermal-Cold	BEM Thermal #5	Completed profile, Iridium modem still failing		
22	2014.01.15	Tucson, AZ	Thermal-Cold	PSA Thermal #5	Completed Successfully		
23	2014.05.29	Tucson, AZ	Thermal-Cold	BEM Thermal #6	Test to coldcase-thermal qualify FSDC		
24	2013.05.08	Coolidge, AZ	Airplane Jump	Jump #1	Turning point: pilot couldn't steer during freefall, couldn't do main parachute pull, not able to reach toggles under canopy.		
25	2014.08.19	Roswell, NM	Airplane Jump	Jump #2	Assisted main canopy pull, did navigate under parachute, Safe if ugly landing		
26	2014.08.20	Roswell, NM	Airplane Jump	Jump Attempt	Abort due to high winds		
27	2014.08.21	Roswell, NM	Airplane Jump	Jump #3	Trouble steering during freefall, did pull parachute, good canopy control, safe but ugly landing		

	Test Date	Location	Test Category	Test Description	Comments	Duration	DZ range from LS
28	2014.08.22	Roswell, NM	Airplane Jump	Jump Attempt	Abort due to high winds Instead did pilot spin & pull training		
29	2014.09.02	Roswell, NM	Airplane Jump	Jump #4	Pilot start & stop turns during freefall, Safety diver pulled main canopy, good canopy control, safe but ugly landing		
30	2014.09.03	Roswell, NM	Airplane Jump	Jump #5	The pilot executed sufficient freefall stability and was able to pull his own parachute.		
31	2013.09.09	Roswell, NM	Long Range Comm	Manned Flight System Test #1	Abort, due to interference between Telemetry & Voice communications		
32	2013.09.23	Roswell, NM	Long Range Comm	Unmanned Flight System Test #1	Abort		
33	2013.09.24	Roswell, NM	Long Range Comm	Unmanned Flight System Test #2	successful test		
34	2014.06.07	Roswell, NM	Long Range Comm	Manned Flight System Test #2	Redone due to addition of FSDC flight computer		
35	2014.06.07	Roswell, NM	Long Range Comm	Unmanned Flight System Test #3	Redone due to addition of FSDC flight computer		
36	2014.09.09	Roswell, NM	Long Range Comm	Manned Flight System Test #3	Redone due to addition of Mode S transponder		
37	2014.09.09	Roswell, NM	Long Range Comm	Unmanned Flight System Test #4	Redone due to addition of Mode S transponder		
38	2013.10.08	Roswell, NM	Flight	Unmanned T22K / 93,000 ft flight	First successful large balloon flight		
39	2014.06.18	Roswell, NM	Flight	Unmanned T120K / 119,704 ft flight	Tycho payload		45.3 nm, 320.5°
40	2014.06.29	Roswell, NM	Flight	Unmanned T412K Launch Attempt	Abort to high winds and Balloon Collar failure		
41	2014.07.03	Roswell, NM	Flight	Unmanned T120K / 120,790 ft flight		2 hrs	32.4 nm, 250°
42	2014.09.26	Roswell, NM	Flight	Unmanned T22K Training / Mission Simulation Launch Attempt	Phase 0 & Phase I completed, Abort due to failure of Balloon Collar to release		
43	2013.12.10	Del E. Webb Altitude Chamber, Mesa, AZ	Vacuum Chamber	Manned Altitude Chamber	First manned vacuum chamber test of a fundamentally new space suit in almost 40 years.		
44	2014.02.19	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #1			
45	2014.02.20	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #2			
46	2014.02.20	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #3			
47	2014.03.19	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #4			
48	2014.03.19	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #5			
49	2014.03.19	Coolidge, AZ	Airplane Drop	Unmanned Dummy Drop #6			
50	2014.10.04	Roswell, NM	Flight	Manned Flight #1, T3K / 57,000 ft		70 min	31.8 nm, 118.0°
51	2014.10.15	Roswell, NM	Flight	Manned Flight #2, T48K / 106,000 ft		116 min	14.1 nm, 101.2°
52	2014.10.20	Roswell, NM	Flight	Attempt, T312K	Abort due to inadvertent actuation of the Tertiary balloon destruct fuse		
53	2014.10.24	Roswell, NM	Flight	Manned Flight #3, T328K / 136,000 ft		151 min	67.6 nm, 98.1°

VI. Conclusion

The three manned flights concluded the testing and the program. These occurred in a span of 20 days and included one aborted record launch attempt due to a tertiary balloon destruct inadvertently firing prior to filling the balloon, and to higher than predicted winds that thwarted using a backup balloon on that day.

Still, on October 24th, 2014, from Roswell International Air Center, the StratEx team launched a 328,000 m^3 (11.6 million ft^3) balloon with Alan Eustace attached in a custom made space suit and recovery system. The flight went to a peak altitude of 41,573 m (136,395 ft), and, after a short float period, he was released from the balloon at an altitude of 41,422 m (135,899 ft). The freefall got to a speed of 1,320 km/hr (820 mph, Mach 1.22), lasted 4 minutes 27 seconds and a spanned a total distance of 37,623 m (123,435 ft) before deploying a parachute. 9 minutes and 52 seconds later he completed the flight, landing 125 km (67.6 nautical miles) east of where he started the journey.

StratEx created a new class of stratospheric exploration vehicle - designed for an altitude range that is too low for orbital-dynamics and too high for practical aerodynamic flight. Among other things, the project achieved the following milestones:

- Developed a self-contained flight system useable in many configurations
- Developed a stable, safe, drogue system suitable for high altitude bailout that removes many of the previous systems safety hazards
- Operational efficiency - entire manned flight campaign completed in 20 days (one suit)
- Peak altitude of 41,573 m (136,395 ft)
- New World Record Exit Altitude above sea level: 41,422 m (135,899 ft)
- New World Record for Vertical Speed with Drogue: 1,321 km/hr (821 mph), Mach 1.22
- New World Record for Freefall distance with drogue or stabilization device: 37,617 m (123,415 ft)
- No pilot safety backup systems were used, and there were no injuries to pilot or crew.
- Nominated for the 2014 Collier trophy
- The Collections Committee of the Smithsonian National Air and Space Museum voted unanimously [and with virtually no debate] to accept the StratEx flight system into the national collection.
- Finally, World View's Voyager capsule and stratospheric exploration is a direct application for this technology

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References

[1] Lee, G. R., Graziosi, D., and Leidich, J., "The Design and Development of an Extravehicular, Stratospheric Exploration (StratEx) Pressure Suit", 45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, ICES-2015-63

[2] Craig, R., The Pre-Astronauts, Manned Ballooning on the Threshold of Space, Bluejacket Books, Annapolis, 2003.

[3] Hensley, D., From the Edge of Space, Felix Baumgartner's Stratos jump from 24 miles up [Kindle Edition], 2012. Retrieved from http://www.amazon.com

[4] Leidich, L., Maccagnano, Z., McFatter, D., Lee, G.R., Hahn, N., StratEx Pressure Suit Assembly Design and Performance, 45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, ICES-2015-138

[5] Bode, R., Hahn, N., StratEx Environmental Testing, 45th International Conference on Environmental Systems, 12-16 July 2015, Bellevue, Washington, ICES-2015-136