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Exploring the Stratosphere: What We Missed by Shooting for the Moon

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Abstract

Similar to outer space, the stratosphere experiences freezing temperatures, with atmospheric pressures and oxygen levels far below the level required for human survival. Exposure to this environment causes unique injuries to the human body that can be deadly if the correct management is not promptly initiated. The preceding decades are filled with stories of deadly failures from such exposures and marked achievement as we began to explore this section of our outer atmosphere. Through advances in technology, we have developed pressure suits and vehicles used for high altitude and outer space that provide protection and allow us to not only survive, but also explore these dangerous environments. The recent high altitude missions are examples of the remarkable capability of human innovation and ingenuity. These missions have fostered an explosion of interest and wonder, creating new demand for a commercial space industry that was virtually nonexistent in the previous century. Though recent tragedies have temporarily delayed the travel of eager citizens into space, the boom of the commercial space industry is pushing forward with new promises of space exploration available to the next paying customer, anticipated in the next few years.

Keywords: high altitude, ebullism, stratosphere, StratEx, Stratos, pressure suit, commercial space industry

1. Introduction

In 1969, when Aldrin and Armstrong first stepped onto the Moon's surface, the world was ablaze with excitement. This event generated a spark that had nearly vanished among those on earth watching the repetitive orbital missions. People organized "moonwalk" parties while children's imaginations across the world came alive with the thought of being able to float

and bounce above that gray, dusty surface they saw on the television [1]. Yet in our hurry to aim for the lunar surface, we flew right through an unexplored and unconquered area of our own planet: the higher atmosphere.

2. Stratosphere and human physiology

2.1. Stratosphere

The stratosphere is the second lowest layer of Earth's atmosphere, stretching from 12 to 55 km above sea level (**Figure 1**) [2]. For comparison, the Everest summit sits at 8.85 km, and jumbo jets cruise at an average altitude of 12–16 km [3, 4]. To optimize fuel efficiency, the typical commercial airliner cruises at 9–12 km (just above the troposphere in the lower reaches of the stratosphere), where temperatures and air density are lowest [5]. Temperatures in the stratosphere are stratified and, somewhat non-intuitively, increase with higher altitude secondary to ability of the ozone layers to absorb ultraviolet light [5]. Due to increased energy absorption at higher altitudes, the top of the stratosphere remains near 0°C while the tropopause (which occurs between the troposphere and stratosphere) exhibits temperatures of –46 to –57°C [2, 4].

Humans on Earth live well below the altitudes that represent our species' physical limitations. Although only 15.6% of inhabited land occurs below 100 m, in 1994 approximately 33.5% of the world's population lived within these elevations [6]. While human beings can adapt to higher altitudes, the Everest "death zone" (mountain's altitude above 8000 m) earned its name for good reason. When people who are not acclimatized are exposed to equivalent levels of ambient hypoxia that exist at altitudes over 8500 m, they lose consciousness within 2–3 min [3]. Why does this occur and what changes in the environment lead to this? At sea level the average atmospheric pressure is 101.325 kPa, but at higher altitudes air pressure decreases. The mean atmospheric pressure on the summit of Everest is only 33.7 kPa, and atmospheric pressure at the top of the stratosphere is 1/1000 that of sea level [2, 7]. According to Dalton's law, the total pressure of a mixture of gases is made up of the sum of the partial pressures of each individual gas [8]. Given this, it is easier to understand how the partial pressure of oxygen is also much lower at these higher altitudes, which also results in lower partial pressures of oxygen in our blood at these altitudes. A study of the mean partial pressure of arterial oxygen (PaO₂) in the blood gas of Everest climbers taken at 8400 m found their average PaO₂ to be 24.6 mmHg, while normal is considered to be >80 mmHg [3]. But what happens when the human body is exposed to even higher altitudes than we are able to achieve via these hiking expeditions, such as the stratosphere or outer space?

2.2. Physics and human physiology

To understand this question, it is important to understand Boyle's law and the effect of pressure on liquids and gases as well. According to Boyle's law, pressure and volume have an inverse relationship; as the pressure on a given volume of gas decreases, the volume of the gas will increase [8]. This means that there will be fewer molecules of gas occupying any given space. For liquid to transform to vapor, consider vaporization or boiling, molecules on the liquid's surface must be able to leave, which means they either need sufficient energy (added

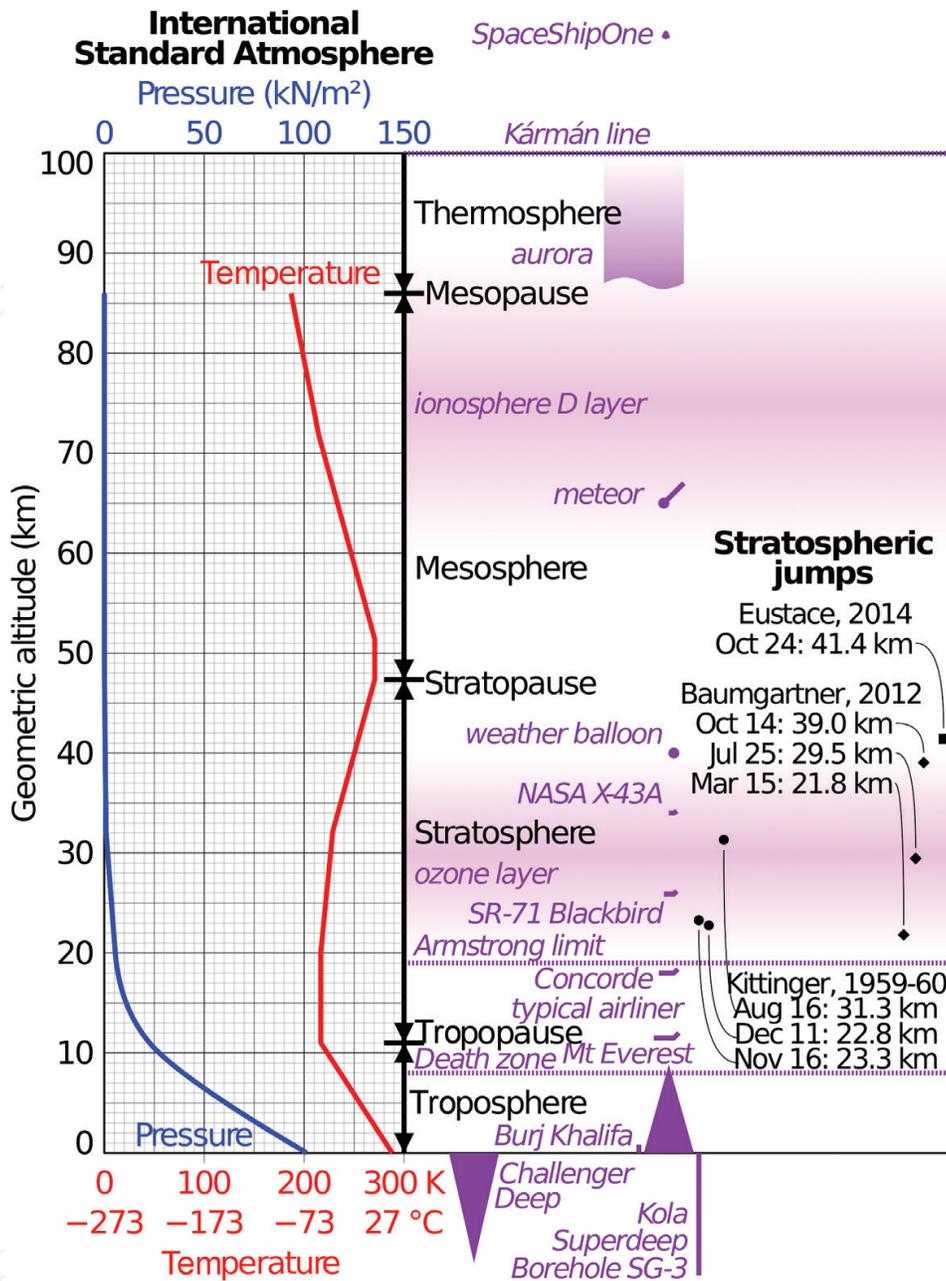


Figure 1. Comparison of international standard atmosphere, temperature and pressure at various altitudes including Armstrong limit and Mt. Everest death zone.

via heat energy water boils), or the number of molecules above the liquid (i.e. vapor pressure) needs to be sufficiently low to allow the surface molecules to escape (achieved by lowering the pressure above the liquid) [8]. Using these two concepts we better understand what happens at higher altitudes, both to the gas filled compartments and the water in our bodies.

2.2.1. Ebullism

A human's normal body temperature is 98.6°F or 37°C, well below the boiling point of water at our usual, livable altitudes. However, a man named of H.G. Armstrong defined the altitude at which the ambient pressure decreases to the point that spontaneous evolution of liquid water to

vapor gas can occur at our body's temperature, a process called ebullism [9]. He coined this altitude "Armstrong's band", which occurs at approximately 18–19 km above sea level [9]. While survival at these altitudes without protection of a pressurized compartment is possible for several minutes, it can quickly lead to dangerous consequences [9]. The human body consists of >50% water, which exists ubiquitously throughout our bodies. During exposure to such low pressures, any water on our skin will vaporize, and resulting pressure in the extremity muscle compartments from the expanding gas can increase to the point that effective blood circulation may cease [10]. Water vapor forms in the thoracic cavity causing vapothorax, increasing intrathoracic pressure, impeding blood flow and inducing vagal stimulation which can lead to bradycardia and decreased blood pressures [9]. Investigations following human exposure have demonstrated intra-alveolar edema, hemorrhagic atelectasis, regional atelectasis, and simple or tension pneumothoraces [9]. A similar process occurs in the abdominal cavity and vapoperitoneum can lead to increased pressure on all the involved organs. In animal models, greater than 2 min of exposure to these simulated pressures led to vascular congestion and hemorrhage in the liver, spleen, kidneys and GI tract, as well as the brain. These findings were more pronounced if the exposure to these pressures was sudden and the decompression was explosive [9].

2.2.2. Anoxia and hypothermia

Tissue damage following exposure to the low environmental pressure above Armstrong's band, or the near vacuum of space, is secondary to more than simply ebullism. The combination of anoxia, gas bubble formation, gas expansion and rapid fluid loss underlie the array of injuries seen after these incidents. The extremely low partial pressure of oxygen at these altitudes can quickly lead to anoxic anoxia, which is most prominently demonstrated by cerebral hypoxia [9, 11]. The time of useful consciousness following exposure to this low pressure is approximately 9–11 s, at which time they lose voluntary control of their muscles, vomit, lose bowel and bladder control and collapse [9, 11]. Within 30 s severe neurologic manifestations ensue including tonic-clonic seizures which progress to spastic rigidity and eventually total flaccid paralysis [9, 11]. Hypothermia is also likely, and ensuing tissue damage depends on the length of exposure as well as the temperature [10]. Although actual tissue freezing is not commonly seen, the increased evaporative cooling on mucosal surfaces has been found to lead to ice formation in those areas [10].

2.2.3. Decompression illness

Gas bubbles form in three different ways: vaporization of water within tissues (previously discussed), evolution of dissolved gas in the vasculature (decompression illness), and direct injection of gas via ruptured alveoli, resulting in venous and arterial embolism [10]. Decompression illness (DCI) is related to diving, however a similar process can occur any time the body experiences significantly decreased ambient pressures. In a manner similar to ebullism, pressure decreases to the point that dissolved gases in the blood spontaneously evolve out and form small bubbles that can become trapped within the smaller capillaries of the skin and organs including kidneys, brain and lungs [9]. Skin findings are more prominent in DCI with divers, but neurologic findings are more common in high altitude exposure [12]. DCI should be suspected in anyone with such exposure who displays altered mental status or abnormal neurologic findings that persist despite initial supportive treatment [9]. These

bubbles can also have a significant effect on the heart. Irritation of the myocardium caused by these bubbles has been demonstrated in animal models to lead to various life threatening cardiac dysrhythmias such as ventricular fibrillation and heart block [9]. It was once believed that placing the exposed person on their left side with their lower body elevated above the heart was the optimal position, and would help prevent any arterial and venous gas emboli from entering cerebral circulation. Animal studies have demonstrated little utility to this approach. The key to treating neurologic DCI is to provide 100% supplemental oxygen and repressurization via a hyperbaric chamber as soon as possible [9].

Decompression injury is most concerning for astronauts during their extra-vehicular activities, but fortunately is rare in space travel. There are only three astronaut deaths reportedly due to decompression from space exposure. On June 30, 1971, *Soyuz 11* was re-entering the atmosphere when the ship depressurized, leading to the death of the three crew members [13]. Two others experienced decompression during training missions in a chamber but for less than 5 min and survived without neurologic sequelae [14].

2.2.4. Barotrauma

Barotrauma occurs as decreased ambient pressures lead to increased volumes of gas within our gas-filled cavities, including the sinuses, ears and thoracic cavity. Usually, barotrauma to the sinuses and ears is less likely when the Eustachian tube and sinus passageways are functional; they act as connections between these cavities and the outside environment and normally allow any expanded volume of gas to exit before causing significant damage [9]. Typically, our airway acts in a similar fashion, but if a person were to hold their breath at the time of exposure, the closed glottis would not allow air to escape from the lungs, and air in the tiny alveoli of lung tissue would expand until their thin walls broke. The direct injection of a large volume of bubbles into the vasculature can result from the rupture of these alveoli, which directly exposes the nearby blood vessels [9]. This massive bubble load can proceed in a retrograde fashion to the right side of the heart and slow blood transport in the major veins, leading to congestion in the capillaries and subsequent tissue damage [9, 11]. As the bubbles prevent forward flow of blood, venous pressure increases and eventually equals that of arterial pressure, at which point cardiac output decreases and there is no effective circulation [11]. This can occur within 1 min of exposure and is a catastrophic condition known as 'vapor lock' [9, 11].

3. High altitude exploration

3.1. Pressure suits

The goal of the first high altitude explorers quickly became focused on finding a way to survive brief periods in this extreme environment. As stated earlier, a protective barrier is needed to survive the life-threatening pressures and temperatures, and so imaginations became focused on how to solve these challenges. Engineers designed pressurized suits which could prevent injuries such as ebullism; but the first suits were heavy, restricted movement and caused high thermal load [9]. Full pressure suits were such units, designed to be pressurized externally and then hold pressure

for prolonged periods of time. They are typically used for routine operations in hazardous environments [9]. In contrast, partial pressure suits have a low baseline profile and are worn overtop elastic undergarments which provide passive mechanical counter pressure. They are pneumatic and inflate when activated to provide near-instant pressurized conditions. They are less cumbersome than full pressure suits, but are not ideal for prolonged, routine activity, and are better used as a redundant protective measure in the event of a vehicle hull breach [9].

Pressure suit design is a very specialized field and the David Clark Company Incorporated (DCCI) has pioneered the field starting in the 1940s by developing partial pressure suits both for NASA as well as full pressure suits for the D558-2 and North American X-15 research aircraft [15]. DCCI created some of the first pressure suits used in high altitude missions, which then became the basis of the suits used by NASA for the space shuttle missions [15, 16]. The pressure suit designed for NASA, termed the Launch Entry Suit (LES), was modeled after the high-altitude protective outfit due to its combination of comfort and protection that could be provided in a short time. The LES was a counter-pressure garment with two separate bladders: one for acceleration, one for altitude protection [16]. The first worn by astronauts is made of athletic underwear, over which the counter-pressure garment fits. A nylon restraint layer is worn overtop which allows the counter-pressure garment to push inwards when inflated. The outer, waterproof, nomex cover is worn over this and is bright orange to assist in search and rescue operations [16]. The astronauts have a parachute harness, flotation devices and other supplies on the outside of their suit. The helmet is connected via a bearing assembly and gloves also strap on separately. The LES was used on 42 Space Shuttle missions from 1988 to 2001, at which time the new, full-pressure Advanced Crew Escape Suit was designed. It was lighter, less bulky, cooler and more comfortable with better physiologic protection and mobility [16]. This model was used through the discontinuation of the Shuttle program in 2011. It was developed in parallel with the S1034 PPA which became the standard pressure suit used by the United States Air Force and Department of Defense [15]. The S1034 and S1035 were the basis for the specialized suits developed for the latest high altitude missions, StratEx and Stratos [15].

3.2. Early near misses and failures

The modern quest to explore high altitudes began with Paul Bert in 1878, who developed the first altitude chamber complete with supplemental oxygen [17]. He was followed by Wiley Post, who in 1934 developed and demonstrated the effectiveness of the first pressure suit for high altitude flight [17]. New pressure suits that were thinner and more comfortable continued to feature improvements, and they became regular equipment for all high altitude pilots. In 1966, during a failed flight test of the Blackbird aircraft, one of these new pressure suits led to the safe landing and survival of its pilot, Bill Weaver. Weaver was piloting the Blackbird at Mach 3 and 75,000 ft when a structural failure caused the cockpit to detach from the fuselage [16, 18]. He was wearing the new S901 pressure suit, and after being violently ripped away from the disintegrating aircraft and ejection seat, he lost consciousness in free fall. His small drogue chute opened automatically, followed by his main chute at a lower altitude. He regained consciousness during the main parachute deployment, but his visor had completely frosted over and he could not see anything around him [15, 18]. After landing he noted that one of the two oxygen lines supplying his pressure suit had detached, and the second was

barely connected. If it had detached, the suit would have depressurized [16]. It was then that he realized that this suit had protected him from the life-threatening low pressures and extreme cold. He referred to the suit later as his 'own escape capsule' [15].

However, as with most great feats, examples of exemplary achievement are likewise met with examples of great tragedy and failure. Pyotr Dolgov, a Soviet Air Force colonel, was part of a unit designing a pressure suit to allow for safe high altitude pilot bail-outs. In 1962, during field testing of this suit at an altitude just over 28.5 km, he attempted to exit the gondola when he accidentally hit his helmet on part of the structure, cracking the visor which caused immediate suit depressurization. This led to catastrophic ebullism and hypoxia resulting in death [4, 12]. Another instance (1966), a Houston technician in a low-pressure chamber was testing a space suit when the suit suddenly lost pressurization. The technician was immediately exposed to atmospheric pressures equivalent to an altitude of 120,000 ft, and quickly lost consciousness. The chamber was repressurized and he awoke as the monitor read 14,000 ft. He reported recalling the feeling of saliva boiling off his tongue just before he passed out [17]. Amazingly, the technician had a quick recovery and did not require any hospitalization nor had any neurologic sequelae from the exposure. A similar incident occurred in 1982 when a technician was inside of a decompression chamber that unexpectedly began dropping pressure [17]. The technician experienced pressures correlating with altitudes greater than 74,000 ft for over 3 min, and was held at the maximum altitude for over 60 s. The chamber manager was forced to kick in the glass ionization gauge to repressurize the chamber by letting air in [17]. By the time the technician arrived at the hospital he was noted to be cyanotic, frothing at the mouth, bleeding from the lungs and had severe barotrauma in both ear drums. However, as serious as his presentation appeared, within 24 h he was awake and alert, and by day five he had been extubated. He, too, suffered no long term neurologic sequelae [17].

3.3. Nick Piantanida and Strato Jump I-III

Nick Piantanida, a truck driver from New Jersey with virtually no experience or training, became obsessed with the idea of high altitude jumps and breaking the world free fall record [12, 19]. He rallied a large amount of sponsor money and a group of volunteers to help him achieve this goal. However, his first attempt in 1965 with balloon ascent failed when wind shear tore off the balloon's top at 23,000 ft, forcing him to parachute into a nearby city dump [19]. During his second attempt, he successfully climbed to 123,500 ft but could not disconnect his oxygen hose from the gondola's oxygen supply in order to connect to a portable tank, and therefore he could not exit the capsule. Piantanida was then instructed by his ground crew to re-attach his seat belt and re-secure the belt across the capsule door, but his bulky gloves made this an impossible task [19]. He was forced to wedge himself inside as the gondola tipped forward at a 45° angle during its 15 s free-fall at 600 miles per hour, then brace inside the open gondola to avoid falling out when the cargo chute opened [20]. He reportedly said afterward: "If only I had a damned \$1.25 wrench, gravity would have done the rest" [19]. His third and final attempt took place on May 1, 1966. Piantanida ascended uneventfully in a styrofoam-insulated gondola (**Figure 2**) when a loud 'whoosh' of rushing air was heard over the communications link by his ground crew, followed by the cut-off call of Nick's voice saying "Emerg-!" [19, 20]. The balloon was cut away and the mission immediately aborted. The gondola, with the pilot still inside, fell



Figure 2. Styrofoam-insulated gondola used by Nick Piantanida during the Strato Jump III mission. Now on exhibit at Smithsonian Institution’s National Air and Space Museum.

for an agonizing 26 min descent from a height of 56,000 ft using the gondola’s own emergency parachute. By the time the crew made it to the downed gondola Nick was outside the capsule, barely alive and conscious [19, 20]. Piantanida lapsed into a coma before arrival to the nearest hospital, and the doctors, with very little knowledge or training on high altitude pathology and management, did their best to help him [19, 20]. He had experienced massive tissue damage and brain injury secondary to emboli. He died 4 months later, never having come out of his coma [19]. While the exact circumstance that led to the incident may never be known, it is believed that Piantanida, who frequently reported discomfort from his pressure suit and had been known to quickly open and shut the faceplate to quickly depressurize the suit, had in fact opened his faceplate at that high altitude and experienced explosive decompression illness [19].

3.4. Joseph Kittinger and Project Excelsior

“There is a hostile sky above me. Man will never conquer space. He may live in it, but he will never conquer it. The sky above is void and very black and very hostile.”

—Joseph Kittinger (12)

Colonel Joseph Kittinger is a pilot who personally understands the dangers of high altitude flight. He is a retired United States Airforce Colonel and, like Piantanida, desired to break

the previous records for high altitude free fall [4]. During his first high altitude jump in late 1959 at just over 23 km, his drogue chute malfunctioned and deployed early causing him to go into a flat spin [12, 21]. A flat spin occurs in free fall when your body is horizontal and essentially spins in a cartwheel motion. A jumper can spin at a rate of up to 180–250 rotations per minute; the centrifugal force from a rapid spin creates negative G's that draw the blood to stagnate in the feet and head [4]. This can lead to headache, shortness of breath, vision failure, altered mentation, and loss of consciousness [4]. This is exactly what happened as Kittinger lost consciousness shortly into his flat spin, but was rescued by the automatic opening of his emergency parachute at 10,000 ft [12, 21]. Following this incident, Kittinger decided to have his small drogue chute open automatically after he jumped from the capsule, which helps to stabilize him in free fall and prevent flat spins. This slows freefall somewhat, but provides an extra layer of safety during that dangerous period [4]. His second jump proceeded uneventfully, however he did not achieve his desired altitude [22].

His third attempt on August 16, 1960, would be his final, and although this jump at 102,800 ft (**Figure 3**) was ultimately a success, it was not without problems [22]. During the ascent at approximately 43,000 ft, Kittinger noticed that his right hand began to feel strange. On inspection, he noticed the glove's airbladder was not inflated and realized that the pressurizing mechanism in his glove had malfunctioned. He decided not to notify ground control, knowing that he could still operate all of the necessary components of the gondola with minimal hand function since most of the controls were operated by a flick of a switch or nudge of the hand [21]. As he ascended higher his hand became increasingly swollen causing him extreme



Figure 3. Joseph Kittinger just after jumping from his capsule during the record-breaking skydive mission, Excelsior III.

pain and losing most of its circulation. By the time Kittinger made it to the ground, his right hand was nearly twice the size of his left due to swelling. However, 3 h after landing his hand had returned to normal size with no residual pain or deficits [21]. He would hold this record for many decades, until 2012 when another adventurous explorer would come along.

3.5. Felix Baumgartner and the Red Bull Stratos mission

On October 14, 2012, history was made as the Red Bull Stratos Capsule Jump set a precedent for high altitude exploration. The mission was no small feat; the goal was to safely ascend beyond Kittinger's previous altitude in a capsule and then free fall in a specially designed pressure suit, eventually using a parachute to descend the remaining elevation [22]. It was a huge success. The ascent was uneventful and the exit altitude for the pilot, Felix Baumgartner, was 127,852 ft (38.97 m). His maximum vertical speed was 843 miles per hour, at Mach 1.25 (377 m/s), making Baumgartner the first person to break the speed of sound in a freefall [22]. He was supersonic for 30 s of his 4 min 23 s freefall, during which he fell 119,431 ft (36,402 m). Other records broken during this jump include the largest balloon flown with a human aboard and the highest manned balloon ascent without a vehicle [22].

Unlike Joseph Kittinger's jump, the capsule (**Figure 4**) was pressurized, which allowed for continuous pre-breathing of oxygen throughout the entire ascent. Pre-breathing oxygen helps to decrease the risk of decompression illness. Increasing the amount of time the pilot can pre-breathe oxygen closer to the actual jump time increases the safety profile of the jump [22]. Using a pressurized capsule also prevents the discomfort and exertion of having to pressurize the suit prior to egress. The capsule provided thermoprotection; the lowest temperature



Figure 4. Gondola and pressure suit used by Felix Baumgartner during the Red Bull Stratos Mission. Now on exhibit in the National Air and Space Museum.

recorded inside the capsule was 13°F (-10.5°C), while the lowest recorded outside the capsule was -95.62°F (-70.9°C). The capsule consisted of fiberglass composite housing, with a hingeless acrylic door designed to pressurize at launch [22]. The capsule housing material selection was very important, as it would need to accommodate significant expansion and contraction expected with extreme variations of temperature. The hingeless door allowed for maximum range of movement within and outside the capsule, and was designed to maximize efficiency and ease of opening [22]. The capsule contained redundant life support systems including 10 h of breathable oxygen, glove and foot heaters, carbon dioxide and water scrubbers, among other systems. It would descend using a 100 foot diameter parachute; the typical landing shocks ranged from 4.5 to 8.0 G [22].

Baumgartner's pressure suit (**Figure 4**) was specifically designed to facilitate the capsule egress and exit. The major challenges of suit design were to provide adequate protection and life support during freefall yet allow the transition from sitting to standing, provide thermal protection, mitigate visor fogging, and create a system to sense and prevent the potential violent flat spin that trapped Kittinger. Baumgartner wore a baseline suit with standard undergarments which provided necessary thermal protection [15]. His chest pack contained three GPS units, an accelerometer, a mach speed indicator, a camera, a battery to heat the face plate and a power supply [22]. He also had an emergency cutaway knife in case the reserve chute opened at too high altitude, which would cause a slow descent and probably oxygen shortage. The helmet acted as an airtight gas container, impermeable to nitrogen and oxygen, yet breathable to allow water vapor to pass out and prevent fogging. The exterior of the suite included a fireproof cover [22]. Underneath he wore a fully integrated medical diagnostic tracking unit (Hidalgo Equivital) which provided continuous information on heart rate, respiratory rate and acceleration [22]. Taking another lesson from Kittinger's jumps, Baumgartner decided not to have a drogue chute deploy at the beginning of the jump, as this added unacceptable drag and he would not achieve his desired speed nor hope to achieve a new speed record [4]. Instead he wore a safety device on his right wrist which measured the amount of G-force throughout the entire mission. If he were to fall into a flat spin similar to Kittinger, and the device measured 3.5 G or higher for six continuous seconds, his drogue chute would automatically deploy, which would act to stabilize and pull him out of the spin [22].

The balloons used for these high altitude missions are also specially designed (**Figure 5**). They are made of thin plastic film, no more than 0.0009 inches (0.02 mm) thick [4]. As Piananida learned on his first failed ascent, the material needs to be thin and light enough to optimize the weight to lift ratio, but also needs to have a high drag limit (the point at which upward velocity creates drag strong enough to threaten damaging the balloon) to withstand the high winds of the upper altitudes [4, 21]. A lower drag limit could be mitigated by slowing the ascent, but only to the extent that the life support systems could allow. The Stratos balloon was made of 40 acres of polyethylene, at launch was twice as tall as a Saturn 5 rocket, and used 180,000 cubic feet of helium to launch [22]. Restraining fabric was placed around it for the initial ascent, holding the circumference to just under 17 ft. The balloon was released at 20,000 ft (6000 m) to allow its full expansion to 100 ft (30 m) diameter [22].



Figure 5. The balloon used for the StratEx mission being filled just as dawn breaks. The restraining fabric can be seen tied near the bottom, restricting the fill of the lower part of the balloon.

3.6. Gary Eustace and the StratEx mission

The StratEx (Stratospheric Explorer) mission (**Figure 6**) would take place just over 2 years following Stratos, and though one goal was to break Baumgartner's record, a new dream was about to unfold. Unlike Stratos, a highly publicized project, StratEx was a privately financed scientific endeavor with focus on creating new technology to allow a less expensive, reusable way to explore the stratosphere without need for a constrictive and cumbersome capsule. Alan Eustace, the son of an aerospace engineer, worked as Google's senior vice president at the time of StratEx's development [23]. His vision was to use a balloon ascent system to transport a pilot, independent of a capsule, in a self-sustained pressure suit complete with all necessary life support systems for both ascent and descent [24].

The pressure suit designed for this mission required three distinct components: the actual pressure suit itself, an equipment module, and the parachute pack. The pressure suit was sandwiched between the equipment module in front, and the parachute pack in back. The pressure controller was housed inside the pressure suit, and the helmet was specially designed to force exhaled air down a valve and away from the facemask. The suit and helmet were essentially separate pressurized chambers, but the helmet had a suffocation valve that



Figure 6. Gary Eustace begins his ascent for the StratEx mission. He is barely visible in his special pressure suit secured to the bottom of the large balloon.

would allow for air passage into the helmet from the suit in an event of depressurization [25]. The equipment module included the life support and electronic support machinery which was primarily located in a large chest plate. The oxygen supply used a demand regulated system similar to SCUBA systems, where gas is supplied only when the pilot takes a breath and is not free flowing. Oxygen use was calculated beforehand based on suit pressure, suit temperature and pilot metabolic rate (breathing rate) during the various stages of the flight process. The oxygen cylinders used were modified standard aerospace composite cylinders [25]. The thermoregulatory system used a cartridge heater to heat a water-based fluid which was then pumped through a liquid thermal garment in order warm the pilot at high altitudes and cool the pilot while on the ground. This liquid cooling system was also used to help regulate the temperature of the electronic systems housed in the equipment module. This module also housed a power supply along with the voice and data communications hardware. The main parachute design was based on the Sigma tandem system, the most widely used tandem parachute [25]. These parachutes are normally built to support an instructor/student pair weighing up to 500 lbs, and fulfilled the needs of the StratEx system which weighed approximately 430 lbs (including the pilot). The parachute pack also acted as a suspension point during ascent, which provided the ideal 45° angle. The ascent balloon was similar to

those used previously, however was much larger than Stratos, reaching 400 ft high at launch and spanned 275 ft in diameter at the maximum altitude [25].

A total of five test runs were performed, the second of which had to be aborted due to rising suit pressures caused by freezing with in the pressure control device [25]. The mission successfully concluded on October 24, 2014, when Eustace ascended to an altitude of 136,410 ft (41.5 km), and was released at 135,897 ft (41.4 km) to take the 9 min and 52 s ride back to earth. His free fall lasted 4 min and 27 s and spanned over 123,435 ft (37.6 m) [24].

3.7. Emergency medical planning for high altitude missions

The principles of medical coverage for this type of mission revolve around planning for the conventional expected injuries of a traumatic accident and well as those injuries specific to high altitude exposure. Medical conditions like those listed above are not routinely covered in medical training, so having a team of professionals familiar with the management of those specific injuries is paramount. Given the potential variability in landing location based on ascent time, wind speed and direction, as well as responding to emergency bail outs, having multiple recovery crews in a variety of vehicles is ideal. For instance, the StratEx mission utilized four vehicle chase teams, including two ground teams driving Suburbans, a helicopter and a fixed wing aircraft, which would deploy an additional parachutist to assist the StratEx pilot to identify a landing zone (limited sight due to the helmet design made clear ground views challenging) [24]. A central Mission Control coordinated these field teams, monitored all communications and worked to anticipate and mitigate any failures throughout the mission [26]. All chase teams included a combination of suit technicians, who specialized in rapid removal of the pressure suit, and volunteer medical personnel (mainly physicians and EMS) who were prepared with large selections of equipment to rapidly stabilize a downed pilot [24]. Each chase team had redundant means of communication including cell phones, laptops and tablets, in case of poor cellular signal [26]. Due to the well-supported utility of ultrasound in remote environments, two machines were carried along with the chase teams in order to perform a rapid, pre-specified, diagnostic and therapeutic assessment in the worst case scenario of an unstable, unconscious pilot [12]. One of the greatest challenges of these high altitude flights is the austere location of the launches in relation to medical facilities. The StratEx flight launched at a remote location in New Mexico, 500 miles from the closest hyperbaric chamber and 175 miles from the nearest level 1 trauma center [24]. Air transport was available in case of severe injury, but actual transport time was still daunting [26].

4. Commercial space industry

With the broadening scope of these high altitude missions, a new kind of space race has taken the Earth by storm, full of wealthy entrepreneurs who are now leading the commercial space industry [27]. In the 1980s two companies, Society Expeditions and Space Travel, proposed to NASA to begin offering passenger tickets aboard the space shuttle, but both were rejected. Through time, the once imagined concept of 'orbital space tourism' slowly shifted to 'suborbital space tourism', and the idea of experiencing longer time in lower earth orbit became a more feasible business strategy [28]. From that dream, companies emerged with the goal of

providing wealthy ticketed passengers a few days of space training camp to then board a private spacecraft and float weightless for several minutes before returning to earth [27, 28].

In 2011, NASA began to lose much of United States government funding and was forced to shut down many programs and projects [29]. The new budget set forth by President Obama cut out the Constellation program, canceling the creation of the Orion spacecraft and Ares rockets. These crafts were supposed to replace NASA's three space shuttles which were set to retire that year. This effectively ended the shuttle missions, and NASA became more dependent on Russian colleagues for transport to the ISS, where they continued to perform many active research projects [30]. During this time the government has attempted to facilitate formation of the commercial space industry by providing only loose regulations, allowing an extended 'learning period' in order to support growth and practice of the companies [27].

4.1. Commercial space companies

4.1.1. *Vulcan Aerospace*

The first commercial aerospace vehicle, known as SpaceShip One, reached space in 2004. Developed by a Paul Allen (cofounder of Microsoft), in partnership with Burt Rutan, the project won the Ansari X contest which came with a 10 million dollar prize [27]. Their company, Vulcan Aerospace, has since begun building Stratolaunch, set to be the world's largest airplane with a wingspan wider than a football field, including the end zones. It is designed to carry a rocket tethered to its belly to an altitude of 35,000 ft, which then drops away and fires its engines to perform an 'air-launch' into orbit [27].

4.1.2. *Space X*

Space X, another growing commercial space company, was founded by Elon Musk, who made his first fortune on Zip2 and Paypal. However, Musk's dream extends beyond many other companies, with his main focus on eventual transport to Mars [27]. His goal is to build a 'Union Pacific' to Mars which would open entrepreneurial opportunities to anyone willing to make the journey. The initial plan of the company was to have its first unmanned flight to Mars by 2019, which would make Space X the first commercial space flight company to dare such a feat [27]. He also stated his next goal would be to execute a manned landing on Mars within the following 20 years [31]. Up to this point only 18 of the 43 robotic missions to Mars have been successful, including flybys [27].

Some of the newly developed technology from Space X includes the Dragon Spacecraft (**Figure 7**), selected as one of five competitors for NASA's commercial orbital transportation service to take astronauts to the International Space Station (ISS). With the NASA contract, Space X is granted the ability to use Kennedy Space Center's Launch Complex 39A, the same complex that launched Neil Armstrong and Buzz Aldrin to the moon in 1969 [27]. Following the discontinuation of NASA's shuttle program, US astronauts have become increasingly reliant on Russian flights for this transport service. The Dragon Spacecraft is approximately 9.5 ft in height, 11.8 ft in diameter, and weighs 9260 pounds. It contains a solar array, giving the



Figure 7. SpaceX's Dragon spacecraft pictured in Orbit.

aircraft a longer in-orbit duration which allows it to remain on the ISS for 1 week with astronauts aboard, or 1 year with only cargo aboard [31].

Space X has also developed a new rocket system. Their Falcon Heavy rockets (**Figure 8**) are designed to be twice as powerful as others currently in use, and can reach a maximum altitude of 75.8 miles. The goal for these rockets is to achieve high altitude and then arc parallel to the Earth's surface at 5 miles per second in order to stay aloft, which would allow them to circle the Earth in less time than it takes to watch a Star Wars movie [27]. However, their story has been laced with challenges. In 2016 one of the Falcon 9 rockets intended to transport cargo to the ISS incurred a malfunction which caused it to explode on the launchpad. That incident led the company to delay all further launches for 6 months, and created a backlog of over 70 missions, costing the company more than 10 billion dollars in revenue [27]. According to Musk, the company hopes to send two civilians around the moon in late 2018. Musk reportedly said this was "an important milestone as we work towards our ultimate goal of transporting humans to Mars" [32].



Figure 8. SpaceX's Falcon 9 v1.1 rocket being wheeled to the Cape Canaveral Space Launch Complex in preparation for the April 27, 2015 launch.

4.1.3. *Blue Origin*

Another giant of the commercial space industry is Blue Origin, founded by Jeff Bezos who made his fortune as founder, chairman and chief executive officer of Amazon.com and in 2013 purchased Washington Post. There appears to be some tension between Blue Origin and Space X, and Bezos and Musk have been known to make harsh comments about each other's accomplishments. The focus of Bezos' company is more to reduce the cost and increase the reliability of the commercial spacecraft, intended to open the opportunity for a suborbital experience to a greater consumer market [27]. His goal is to 'build a highway to lower orbit' so that temporary infrastructure can be used by the next generation's entrepreneurs to further develop new technology and expand the space market. Blue Origin's rockets are designed to be fully reusable and can achieve a maximum altitude of 62.4 miles [27]. Their first unmanned test flight took place in April 2015, achieving an altitude of 93 km (57.8 miles) and speed of Mach 3. Since then, the same booster has been reflown four times during subsequent test flights from their secured launch space in Cape Canaveral [28]. However, Blue Origin has yet to send a rocket into space, and does not currently possess a rocket that is qualified to carry people [27].

4.1.4. *Virgin Galactic*

Virgin Galactic, a competitive entity in the commercial space industry, was developed by Richard Branson. Their spaceport is located in New Mexico, and Branson's stated goal is to be the first large volume commercial space line [27]. The company's main spacecraft is the SS2/WK2, a combination spacecraft and mothership design. The SS2 is an air-launched glider with capacity to carry six passengers and two pilots, and contains a rocket motor and extra systems for spaceflight [28]. Some 700 people jumped on the company's pre-sale tickets, some paying as much as \$250,000. However, a tragic accident in 2014 involving one of their aircraft led to many delays in the planned flights [27, 28]. The incident occurred in California's Mojave Desert, involving a test pilot who was operating one of Virgin Galactic's newest spacecraft, SpaceShip Two [28]. According to the official report released by the National Transportation Safety Board, the pilot was believed to have unlocked the spaceship's 'feather system' prematurely, causing the vehicle to break apart in-flight, killing both the pilot and co-pilot [28, 33].

Three years from that tragic day, Virgin Galactic has yet to test any further powered spacecraft flights. Its newest vehicle, Spaceship Unity, has performed only a small number of glide flights. The company anticipates returning to unmanned, powered flights in late 2017 or early 2018. During the downtime, Virgin Galactic created a spin-off company called Virgin Orbit, which develops air-launched platforms for small satellites, with plans to begin launching 300 kg missions to Earth's lower orbit by 2018 [33]. The ultimate goal of Virgin Orbit is to distribute satellites around the solar system, starting with the low-Earth orbit constellation [33, 34]. This constellation will be part of the larger SpaceBelt satellite system, and will serve as a space-based data storage network. The company plans the first rocket test in 2018, using the Boeing 747-400 as part of its two-stage LauncherOne system, providing both an expendable and reusable air-launched platform [34].

4.1.5. *Sierra Nevada Corporation, XCOR and other commercial space startups*

There are a number of other smaller commercial space flight companies vying for position in this competitive market. Newer engineering including electronics miniaturization, advanced

design of stronger and lighter materials, and new standards make it feasible for many of these developing companies to enter a market previously available only to those with the billionaires' backing. From 2007 to 2017, roughly 115 space-related companies were founded, with nearly 84 focusing on satellite technology [35]. The development of newer "microsatellites", weighing as little as 22–220 pounds, and "nanosatellites" which weigh less than 22 pounds, are sold by many of these companies. Roughly 2400 are projected to be launched within the next 6 years. The Cubesat is one satellite example, which weighs two pounds, is the size of a baseball and costs less than \$100,000 to build [35].

Sierra Nevada Corporation (SNC) Space exploration a model company, with its Dream Chaser spacecraft (**Figure 9**) [28]. This winged spacecraft will reportedly allow for flexible, trustworthy, and affordable transport. This craft won NASA's Commercial Crew Integrated Capability award in 2012 as a potential spacecraft to provide transport of crews to the ISS, however SNC did not win NASA's commercial crew contract in 2014. The craft experienced some issues during a 2013 test flight in which the landing gear failed to deploy and sent the craft skidding off the runway after landing. Despite this setback, the company continued development of the a Dream Chaser cargo version and secured a Commercial Resupply Services-2 contract with NASA as one of three companies (including SpaceX's Dragon) to deliver cargo to and from the ISS from 2019 to 2024 [36]. SNC partnered with the United Launch Alliance, announcing in 2017 that they would employ the use of the Atlas 5 rocket, which includes 5 strap-on boosters and a twin engine upper stage, to send the first two Dream Chaser cargo aircraft to the ISS in 2020 and 2021. Utilizing these powerful rockets, the aircraft will be able to deliver nearly 12,000 pounds (5500 kg) of equipment and supplies on each non-piloted mission [37].

XCOR is a smaller commercial spaceflight company whose primary focus is a higher tempo flight operation. Their spacecraft, the Lynx Suborbital Vehicle, is a two seated, piloted transport with room for one pilot and one passenger or a specified payload [38]. XCOR plans to have a fast flight turnaround time and will prioritize low cost operations with minimal maintenance necessary for the fully reusable rockets between flights. This would potentially allow their goal of offering up to four flights per day. They are the first, and at the present time, the only, company to have successfully passed the Federal Aviation Administration's licens-



Figure 9. Dream Chaser spacecraft being lifted by an Erickson Air-Crane helicopter during a captive-carry flight test.

ing process for these aircraft. However, the actual two-seated rocket that XCOR plans to use remains under development in their Mojave, CA warehouse [38].

Naveen Jain, another visionary, plans to launch the Moon Express in late 2017 in an attempt to win Google's Lunar Xprize, a \$20 million award for the first company to successfully land a robotic spacecraft on the moon and accomplish a variety of technical challenges. After landing, the Moon Express will need to extract iron ore, water, minerals and precious metals from the lunar soil, as well as capture nitrogen and hydrogen. Jain's vision is that the moon will one day become a fuel depot for spacecraft to dock and resupply before heading out on longer journey's [35].

Robert Bigelow, owner of Bigelow Aerospace which produces inflatable space habitats, has a similar vision. He even asked for government assistance to develop a 'lunar depot' that orbits the moon to allow for easier access to the lunar surface [39]. His company is currently testing a prototype, Bigelow Expandable Activity Module on the ISS, and has demonstrated free-flying prototypes in orbit. This could potentially give Bigelow a huge future advantage in the area of space tourism hotels.

Interorbital Systems, a small 12-person operation, is also based in the Mojave desert. Cofounders Roderick and Rnada Milliron started the company with the personal goal to eventually live on the moon. They also plan to compete for the Lunar XPrize. Currently, Interorbital Systems primarily sells satellites, with plans to launch more than 100 in the next year to provide revenue for equipment needed to achieve their moon landing goal [35].

4.2. Future of commercial space industry

Considering these commercial space industry startups, where will the next decades take us? Axiom Space, a Houston-based company, has partnered with Made In Space, a California company that specializes in 3D printing products. This partnership is intended to help facilitate Axiom's goal to develop a commercial version of the ISS, proposed as an outpost for private individuals and companies to conduct research and space exploration [40]. Its ultimate purpose is to help grow the space-tourism business. Made In Space's involvement is to expedite the logistics of creating an actual in-space factory that can produce equipment without the burden of transport from Earth's surface to the station [40]. Axiom has NASA backing; the current ISS has available funding currently to carry only through 2024. The full ISS expense cannot be overlooked; each day an astronaut is housed on the ISS costs roughly \$7.5 million. The hope is that this deadline will be extended by at least 4 years, however there is a looming possibility that this extraordinary \$100 billion structure will be brought down from orbit just over 25 years following its initial launch [35]. Axiom's current plan is to attach its first commercial module directly to the ISS in 2020. Upon ISS decommissioning, the module would detach and begin formation of the Axiom commercial space station [35].

Beyond a commercial ISS, plans to place orbital hotels have been the dream of many countries for some time. Consider the Space Hotel Berlin and Space Hotel Europe, which share a similar circular design with individual pods on the perimeter; each would provide accommodation for about 50 tourists [41]. A group from MIT won a NASA sponsored competition in early 2017 by designing a luxury space hotel purposed to help offset the cost of NASA research

through commercial rental income [42]. The project, known as the Managed, Reconfigurable, In-space Nodal Assembly (MARINA), would be commercially owned and include a luxury hotel to serve as the primary anchor and a separate hub to serve as a temporarily co-anchor for NASA. The innovative aspect of MARINA is the external International Docking Adapter ports which allow modular service pods to connect to various points and, if standardized among space vehicles, would allow companies of all sizes to provide and request products and services from other companies in space [42].

5. Conclusion

Twenty-first century space exploration has transformed and taken on new meaning. What was once thought to be travel only to the moon or nearby planets now includes stratospheric exploration and commercial high atmosphere flights. Experiences available to only a select group of people with years of advanced training, are now close to being offered to a much wider group of eager customers.

Human ingenuity prevails yet again; we have developed technology to keep us safe in one of the most hostile environments of our home planet. As we continue to explore, we must never lose the sense of awe and respect for those visionary pilots and adventurers that helped us better understand and appreciate this aspect of our Earth. As Col. Joseph Kittinger said upon landing from his final mission: "Now that I am safely down, I realize once again how dependent upon the protection of the Almighty are all seekers of the unknown" [21].

Conflict of interest

There are no conflicts of interest to declare.

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