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THE DEVELOPMENT OF AN EMERGENCY RESPONSE PLAN FOR MEDICAL CONTINGENCIES DURING COMMERCIAL SPACEFLIGHT AT THE HOUSTON SPACEPORT

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by

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THE DEVELOPMENT OF AN EMERGENCY RESPONSE PLAN FOR MEDICAL CONTINGENCIES DURING COMMERCIAL SPACEFLIGHT AT THE HOUSTON SPACEPORT

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Abstract: Commercial spaceflight has grown increasingly prominent over the last decade. Yet despite the obvious successes, commercial spaceflight is still in its relative infancy, and mishaps in the industry may be enough to lose the trust of consumers and shut down the market altogether. This is especially true in the event of a medical disaster. In order to protect the commercial spaceflight industry in the event of a medical catastrophe, should it occur, it is necessary to have the appropriate infrastructure in place to properly respond to an event and mitigate or minimize the harm to person and property that could occur as a result. Doing this will help to salvage the trust of consumers (and the public as a whole) in the utility of commercial spaceflight, and may help prevent the collapse of the industry before it has established itself. The purpose of this project is to aid the Houston Spaceport, a new spaceport located at Ellington Field in Houston, Texas, in developing a medical response plan for contingency scenarios during its mission operations. With appropriate infrastructure

development, the Houston Spaceport could become a leader in the commercial spaceflight industry and act as a model for space safety.

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List of Abbreviations

FAA	**Federal Aviation Administration**
NASA	**National Aeronautical and Space Administration**
G	**Gravity**
EMS	**Emergency Medical Services**
STS	**Space Transportation System**
SMAC	**Space Maximum Allowable Concentration**
COPD	**Chronic Obstructive Pulmonary Disease**
RLV	**Reusable Launch Vehicle**
LLC	**Limited Liability Company**
CDC	**Centers for Disease Control**
FBI	**Federal Bureau of Investigation**
BPR	**Basic Priority Rating**
GPS	**Global Positioning System**
UTMB	**University of Texas Medical Branch**
ACLS	**Advanced Cardiac Life Support**

Chapter 1: Introduction

Specific Aims –

Because of the narrow envelope within which one must operate during space travel, mishaps may be unavoidable. Because of this, the only way to inoculate against these mishaps and prevent the collapse of the entire commercial space industry as a result, is to have the infrastructure in place to properly respond when an event occurs to mitigate or minimize the harm to person and property that could occur, and in so doing, salvage the trust of consumers and the public as a whole in the utility of commercial spaceflight. This infrastructure includes a well developed medical contingency plan for medical disasters, in the event they occur during commercial spaceflight operations, during training, during any activity that occurs on spaceport grounds, or during any other spaceport activity that could lead to injury or death to crew, spaceflight participants, ground workers, or bystanders at the spaceport, surrounding areas, or anywhere else that could be in the path of harm in the event of off-nominal and catastrophic mission operations. The purpose of this project is to aid the Houston Spaceport in developing a medical response plan for contingency scenarios during mission operations. This plan will encompass the following categories: (1) Identify major medical risks associated with spaceport activities, (2) identify appropriate medical and other resources needed to manage these risks (eg. local facilities, medical and other teams, supplies, etc.), and (3) create a medical response protocol [112]. With appropriate infrastructure development, including medical infrastructure, the Houston Spaceport could lead the industry of commercial spaceflight and help move our society into the future with new forms of advanced tourism and travel.

Significance -

Commercial spaceflight, in the form of both government contractors and space tourism, is a blossoming industry that has grown increasingly prominent over the last decade. Companies like Virgin Galactic, Space Explorations Technologies Corporation (SpaceX), Blue Origin Aerospace, Orbital Sciences Corporation, and Sierra Nevada Corporation have established themselves as solvent and self-sustaining enterprises. Yet despite the obvious successes, commercial spaceflight is still in its relative infancy. Many within the field believe that the industry is still somewhat tenuous and that the public at large is not fully convinced of the merits of such an industry. Especially with the case of space tourism, it may be that even minor mishaps may be enough to lose the trust of consumers and shut down the market altogether. This is especially true in the event of a medical disaster, such as a death or serious injury in-flight. Though there have been mishaps that have occurred with commercial space in the recent past, the industry has thus far survived. However, to date, these mishaps have not involved any laycustomers, and even still, many people opted to have their tickets refunded [109].

Up to this point, spaceflight and space travel have primarily been the purview of government entities. Because of this, with only a few exceptions, only the healthiest of individuals have been allowed to travel to space, in order to minimize any risk to mission objectives that could occur with ill or injured crewmembers. With companies like Space Adventures and Virgin Galactic ushering in a new era of space tourism, the industry will see an increasing number of flyers that will no longer fit the mold of the super-health astronaut [160]. Because of the high cost of reserving such a seat (space tourism can range from $100,000 to $35 million depending on the flight profile [57]), many customers are older in age, owing to the fact that it can often take years or even decades to amass the wealth necessary to pay for such an endeavor. Additionally, the Federal Aviation Administration has been careful to limit any mandatory restrictions on qualifying medical criteria for fear of inhibiting the market by limiting the size of the customer base [132]. Thus, this creates an environment where a cadre of individuals, many of which are elderly, with varying levels of fitness and a wide variety of underlying chronic medical conditions, will be exposed to the unique environment of space because the primary gating criteria for reserving a seat on one of these commercial flights will be whether an individual can afford a ticket, and not whether they are fit to fly. It is unclear how these medical conditions will be affected with exposure to radiation, high G-force acceleration, microgravity, and a confined cabin environment. These questions are only now starting to be evaluated [45].

In addition to the risk created by exposure of various medical conditions to the unique environment of space, spaceflight is, itself, inherently dangerous even without any known underlying health risks. Working within the environment of space is a complicated task requiring the proper function of many complicated and interdependent systems. Failures in any one of these many systems can potentially lead to catastrophic results. On April 24, 1967, Vladimir Komarov became the first spaceflight fatality when a failure in his capsule parachute opening during Soyuz 1 resulted in a high velocity impact of the capsule with the ground [63]. On November 15, 1967, Michael J. Williams became the first American fatality during spaceflight when electrical problems with his X-15 rocket aircraft resulted in an uncontrolled spin and inverted dive, leading to structural breakup of the vehicle [4]. Since then, a number of spaceflight-related deaths have occurred during both Russian and U.S. missions, as well as mission training exercises, including the deaths of 14 astronauts on STS-51-L (Challenger) and STS-107 (Columbia). As recent as October of 2014, a catastrophic breakup of Virgin Galactic's SpaceShipTwo lead to the death of Michael Alsbury and the critical injury of Peter Siebold [59]. This disaster, along with the explosive breakup of Orbital Sciences' Antares rocket that same week and two breakups of SpaceX's Falcon 9 rocket months later (all of which were unmanned [29, 68, 140]) demonstrates that the dangers of spaceflight remain very real for the commercial space industry. Additionally, the Houston Spaceport presents unique challenges to commercial spaceflight. Until now, the majority of spaceports and launch sites have been located in remote areas where there is little risk of peripheral damage in the event of a disaster. The Houston Spaceport, however, is located at Ellington Field in a fairly populated area. Though this does provide interesting opportunities in the future for commercial spaceflight activities such as high speed sub-orbital point-to-point travel that would not otherwise be economical in more remote locations, it also creates new issues that must be addressed regarding the management of mass casualty events where not only pilots and spaceflight participants are injured but bystanders on the ground as well. It also raises concerns regarding the best way to manage resources in such a heavily populated urban setting, including what Emergency Medical Services (EMS) services to mobilize and how and where to transport injured persons in the event of a medical catastrophe.

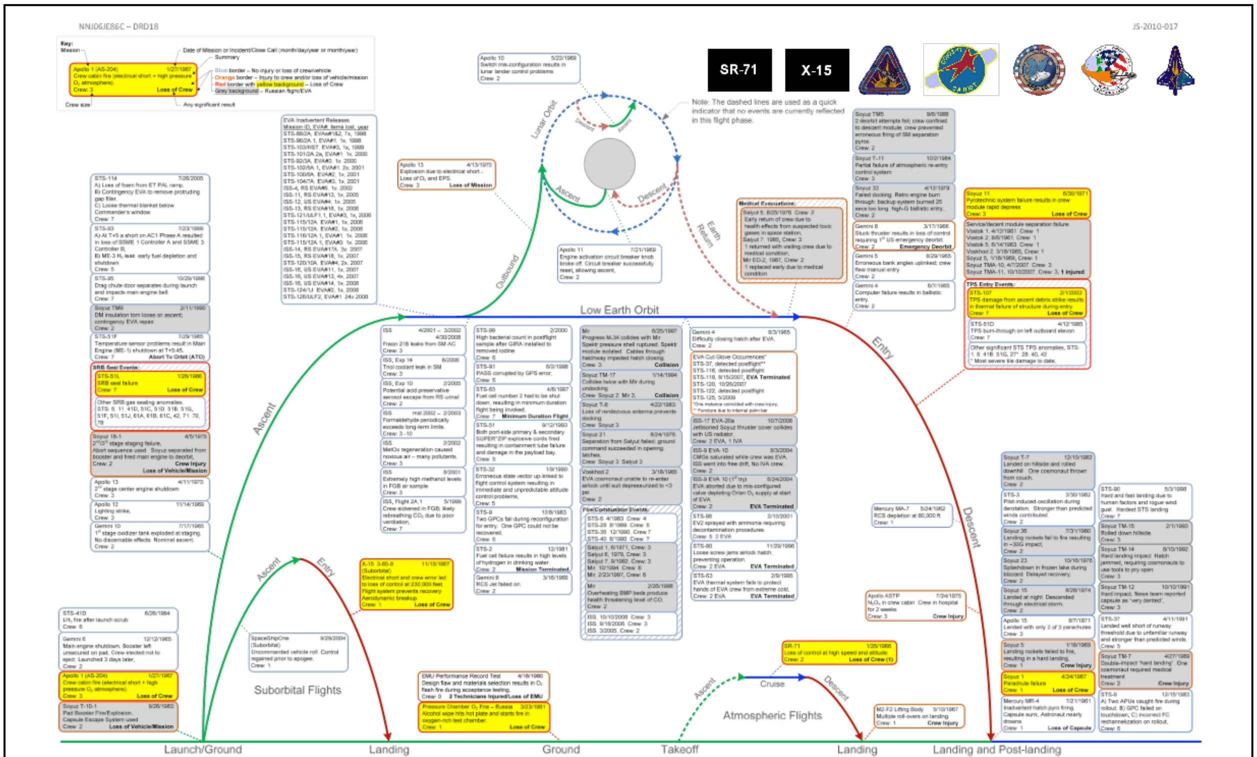
However, despite its complexities, the Houston Spaceport also provides unique and exciting opportunities as well. Given its proximity to NASA's Johnson Space Center, the Houston Spaceport is uniquely suited to act as the hub for commercial spaceflight and all of the other existing spaceports around the country. Additionally, given the proximity of Ellington Field to the city of Houston proper, the Houston Spaceport is an attractive incubator for the blossoming industry of high-speed sub-orbital point-to-point travel, as long as this new form of travel can be demonstrated to be appropriately safe to both the travelers and the lay people that live around the airfield. As stated previously, with appropriate infrastructure development, these exciting opportunities could become a reality. This proposal endeavors to help with the development of a sound medical infrastructure so that the Houston Spaceport can do just that.

Chapter 2: Background and Literature Review

Epidemiologic Description of the Health Problem (Distribution and Determinants) –

It is worthy to note that though there are some data on deaths and injuries that can be directly attributed to spaceflight, the space environment, and surrounding space operations, getting access to these records can be difficult and sometimes even impossible. Many NASA documents regarding these issues are internal and though not classified, can be tightly controlled. Information surrounding United States military space programs may, in fact, be classified and can prove even more difficult to get a hold of. Russian data in this area can also be notoriously difficult to come by, as information regarding spaceflight related mishaps is often tightly controlled by both the United States and Russia because of the potential international embarrassment that often comes with failed missions. That being said, this document attempts to present, as accurately as possible, the epidemiologic data regarding the distribution and determinants of injuries and death associated with space missions. Though potentially incomplete, this data will at least give a sense of the size and scope of this issue, areas of risk that can be associated, and potential solutions for mitigating and minimizing potential issues for the future.

Since the beginning of human spaceflight in 1961, there have been 270 fatalities (32 of which were astronauts and cosmonauts) and 67 other accidents associated with spaceflight, either during flight, during flight training, or in non-astronaut support crewmembers or unaffiliated bystanders due to mishaps surrounding flight operations [93, 130]. Though not fully accurate, this amounts to an incidence of 1.47 mishaps per year and 4.9 fatalities per year. It also amounts to a mortality rate of 3.9 per 1,000 person-years for astronauts and cosmonauts and a total mishap incidence rate of 9.9 per 1,000 person-years, if you assume a total number of fliers of 547 and an average career length as an astronaut or cosmonaut of 15 years [93, 130]. Calculating these same statistics for support crew and bystanders is most likely not feasible given the wide variety of locations that various space related mishaps have occurred, the constant flux in numbers of workers that are employed at any one location, the wide variety of jobs that these workers may be employed in, and the variation in time that any one employee will stay in a particular job. However, for the purposes of commercial suborbital spaceflight, the highest risk of death or injury is associated with in-flight operations for the pilots and space flight participants. Thus, data on flight and training mishaps for astronauts and cosmonauts is most likely sufficient as a first pass for characterizing risk associated with commercial space tourism. Though these incidence rates are not particularly high as compared to other disease processes, the fantastical nature of how these mishaps can unfold (and the panic they can instill), the high cost to life and property that occurs with a mishap, and the fragile nature of the commercial space industry currently suggest that the benefit of implementing mitigation strategies should a mishap occur may be worth the costs of doing so. **Figure 2.1** is a visual representation of all mishaps and close calls associated with United States human spaceflight up through the year 2010. Specific events that are particularly noteworthy are detailed below.



The JSC Flight Safety Office maintains the *Significant Incidents and Close Calls in Human Spaceflight* graphic to provide continuing visibility of the risks inherent with space exploration and provide engineers with a summary of past experience. It is hoped this information will be used to learn from the past and make present and future missions safer.

Figure 2.1: Pictorial representation of all of the "Significant Incidences and Close Calls" associated with human spaceflight, up through the year 2010, organized by phase of flight. Fatal incidences labeled in yellow. Republished from the NASA Johnson Space Center Flight Safety Office (public domain, permission not needed).

There have been 19 fatalities of flight crew documented during flight and 23 documented during training and testing operations [93, 130]. The major causal factors of note that were associated with these disasters were 1) a loss of integrity of the vehicle by either a breach in the pressure cabin or a total vehicle destabilization and structural breakup, or both, 2) trauma related to this loss of vehicle integrity or related to the impact of the crash, and 3) exposure to altitude resulting in hypoxia, decompression injury, ebullism, or some combination of these [93, 130]. As stated previously, Michael J. Williams was the first fatality during spaceflight, during his test flight of the X-15 to an altitude of 266,000 feet, which went off-nominal, resulting in an uncontrolled spin and structural breakup of the vehicle [22]. In the United States, two high profile fatal mishaps have occurred during flight. These mishaps were considered high profile because of the popularity of the two flights at the time, as well as the multiple fatalities that occurred on each flight. The first involved STS-51L (Challenger) in 1986, and killed 7 astronauts when a leaky O-ring allowed heat to escape from one of the solid rocket motors which caused a melting of the attachment strut leading to a shift in the center of thrust such that the shuttle was forced to propel at a non-aerodynamic angle. Because of the shuttle's high velocities at the time of the incident, there was a structural instability of the vehicle, which resulted in structural breakup of the shuttle. The crew was not wearing pressure suits at the time, leading to hypoxia and loss of consciousness. Because of this, they were unable to deploy their parachute systems and were fatally injured from a high-velocity impact with the water in the Atlantic Ocean [25]. The second incident involved STS-107 (Columbia) in 2003, when a piece of foam insulation from the shuttle's main rocket engine broke off during launch and struck the leading edge of the left wing. This created a breach in the structural integrity of the wing, which on reentry, led to hot gases entering and thus damaging the wing. This led to aerodynamic instability and catastrophic breakup of the vehicle. Because of the speed with which this breakup occurred, it was determined that the crew most likely developed rapid onset ebullism from the exposure to vacuum and became incapacitated and died before they were able to prepare their pressure suits [8]. Another high-profile mishap that has occurred as a part of the United States human space program, but during the testing phase of the program, is the Apollo 1 mishap, which occurred on January 27th of 1967. This mishap occurred when an electrical fire ignited in the vehicle during ground testing because of the pure oxygen cabin environment. This fire created a high-pressure environment within the vehicle, which prevented the crew from opening the capsule hatch, which was designed to open inward. The fire and the trapping of the crew led to the deaths of all three Apollo 1 crewmembers involved [20]. A second fatality during testing that is noteworthy, because of how recently the events took place, was the catastrophic mishap of SpaceShipTwo, which took place on October 31st of 2014 during flight-testing that was being carried out by Scaled Composites, LLC. The mishap occurred when the co-pilot, Michael Alsbury, prematurely executed the procedure to feather the tail wing of the vehicle. Because this was done at a high velocity, the wind resistance was much greater than would otherwise have been true if the wings were feathered at the proper altitude near the von Karman Line at the spacecraft's apogee. The drag from this wind resistance led to instability in the vehicle's aerodynamics and ultimately resulted in a structural breakup of the vehicle at an altitude of roughly 55,000 feet. This breakup resulted in the fatality of Michael Alsbury, and the serious injury of the pilot, Peter Siebold [19]. In addition to being devastatingly tragic, this mishap highlights the fact that despite lessons that have been learned regarding space safety over the last 50 years of human spaceflight, space travel remains a dangerous and high-risk enterprise with a narrow envelope of safety. Lastly, another mishap worth noting, because of the potential for a similar mishap during commercial suborbital flights, is the Soyuz 11 mishap. This mishap occurred on June 30th of 1971, when an explosive decompression of the Soyuz capsule occurred when a ventilation valve located between the service and descent modules was shaken open from the force of the pyrotechnics that fired to separate the two modules prior to reentry.

This decompression occurred at an altitude of 551,000 feet, causing the rapid development of ebullism in the crew from exposure to vacuum. All crewmembers were already dead on landing when support crew arrived on scene [26].

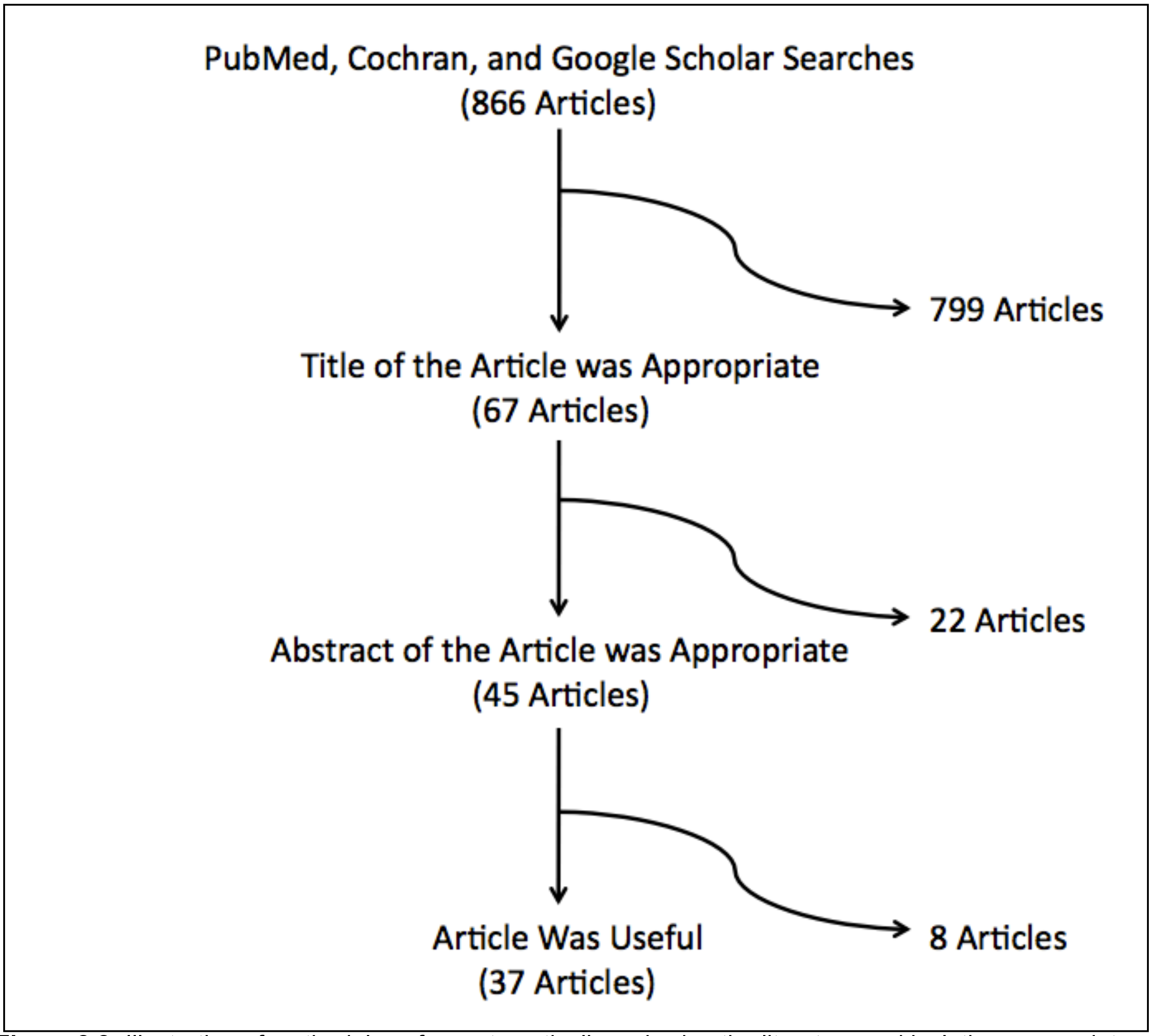
In addition to the fatal mishaps described above, there have also been 32 non-fatal incidences during flight operations and another 35 during training and testing operations [93, 130]. Though too many mishaps have occurred to allow for a complete description of all of them here, below is an account of those mishaps that could occur again during suborbital spaceflight operations and which provide lessons learned for these flights. The major causal factors of note that were associated with these disasters were 1) vehicle sinking and potential drowning during water landing, 2) lightening strikes (often knocking out electronics), 3) trauma, especially related to impacts from loose articles within the cabin environment, 3) oxygen deprivation and exposure to noxious gases within the cabin environment, and 4) fire [93, 130]. Two space vehicles (both capsules) experienced problems during their water landings and ended up sinking in the ocean after splashdown. The first of these involved the fourth flight of the Mercury-Redstone system, and occurred on July 21st, 1961, when the hatch of Liberty Bell 7 prematurely opened and started flooding with water. Gus Grissom, the spacecraft pilot, was able to egress from the vehicle, but his pressure suit, too, began to fill with water and he struggled to remain afloat. Fortunately, rescue helicopters were able to recover Grissom before his suit became completely flooded and he drowned [173]. The second flight, involving Soyuz 23, occurred on October 16th 1976, when the crew landed on a lake and were dragged underwater by their deployed parachute system. After a difficult and prolonged recovery, the capsule was dragged to land by helicopters. The crew remained safe in their capsule while underwater, as there was no breach in the pressurized cabin [9]. Though spaceflight operations out of the Houston Spaceport will most likely consist of horizontal launching and landing (more on this described in Chapter 4) and will not involve water landings nominally, the rocket-powered portion of the suborbital flight profiles planned are designed to occur in designated airspace over the Gulf of Mexico [14, 15] and thus could result in a water landing in a contingency scenario and must be anticipated when considering potential medical risks. There have been three mishaps related to fires onboard vehicles during flight. The first of these, the Soyuz T-10-1, occurred on September 26th 1983, when damage to the rocket engine fuel pump caused leaking of kerosene onto the ground and a launch pad fire. The crew was narrowly saved by activating the pad abort system before the fire ignited the main propellant storage tank in the rocket, causing it to explode [77]. The second, STS-9, occurred on December 8th 1983, when hydrazine leaked to the rear of the shuttle and ignited on a hot surface associated with the auxiliary power unit during reentry. The fire did not interfere with the structural integrity of the shuttle and no one was injured as a result of the incident. The fire was discovered the next day during inspection and maintenance of the vehicle [11]. The last of these mishaps occurred on February 23rd, 1997 aboard the Mir Space Station when one of the oxygen-generating canisters ignited part of its contents, causing a fire fed by the oxygen being released from the lithium perchlorate in the canister. It was later determined that the initial flame leading to the fire started when a retained piece of latex glove (latex gloves were worn when changing out the oxygen canisters) was heated and ignited. No crewmembers were injured, but they were forced to wear personal oxygen equipment while the fire was extinguished and smoke cleared from the station [117]. Another non-fatal mishap occurred November 14th, 1969 when Apollo 12 was taking off and the spacecraft was struck by lightening twice. This resulted in damage to multiple fuel cells and onboard electronics, including the reaction control system and the guidance system [3]. Also during the Apollo 12 mission, on November 24th, 1969 during landing of the crew back on Earth, one of the cameras that was rigged on the inside of the capsule broke loose during splashdown in the ocean and struck Alan Bean in the face causing a concussion and leaving him with a laceration on his forehead [17]. This emphasizes the fact that trauma can be an important source of morbidity related to spaceflight, and loose articles in the cabin can be a potential hazard. This is true for suborbital flight just as it is for orbital missions. Another incident occurred during the Apollo Soyuz Test Program on July 24th, 1975 when nitrogen tetroxide was vented into the cabin, forcing the crew to don emergency oxygen masks. They were unable to get the masks on before being exposed to the noxious gas and later developed acute respiratory distress syndrome and ended up in the hospital [6]. Lastly on September 29th 2004, Scaled Composites' SpaceShipOne, during demonstration flights, started rolling shortly after initiation of rocket-powered flight. These rolls continued until shortly after the vehicle reached peak altitude. They were eventually brought under control by the pilot, Mike Melvill, and he was able to land the vehicle safely and unharmed [24]. However, this again represents a near miss in a commercial vehicle that could have, if this had been a paid flight, exposed the passengers and crew to increased G-forces that could have led to injuries or exacerbations of medical conditions. It also could have led to disorientation of the flight crew that could have resulted in a crash.

There have also been approximately 238 deaths (accounts differ) in non-crew related mishaps. A large percentage of these deaths (213 individuals) are secondary to rocket explosions [93, 130]. Unsurprisingly, the majority of these mishaps occurred during the manufacturing of the rockets, fueling up of the rockets, ground testing, and test launches [93, 130]. What this highlights, however, is the high-risk nature of rocket engine assembly and the potential for injuries, not just during commercial launches, but during all phases of flight including manufacturing and testing, as well as immediately pre-flight. One particular mishap of this nature is worthy to note. On July 26th 2007, three Scaled Composites employees were killed during a testing of the new engines for SpaceShipTwo [168]. This mishap is important to emphasize because, again, this is a commercial spaceflight accident that occurred during testing of a vehicle not dissimilar to one that could potentially operate out of the Houston Spaceport. Indeed, it is possible that Virgin Galactic, itself (the owner of SpaceShipTwo developed by Scaled Composites), could operate out of the Houston Spaceport as one of its bases of operations for suborbital space tourism launches. Of the remaining mishaps, the majority were trauma related and were most frequently the result of falls or related to impacts from high-velocity projectiles when gas pressure buildups occurred during vehicle servicing. Multiple episodes of anoxia have also occurred as a result of nitrogen leaks during vehicle servicing as well [93, 130].

Scientific Background and Rationale –

Given the above information, the rationale for the development of a comprehensive medical support plan and infrastructure for commercial spaceflight operations to deal with a medical contingency scenario in the event one should occur may seem straightforward. Throughout the history of human spaceflight, fatalities have occurred in association with missions or the training for missions at a not infrequent rate. Additionally, there have been a large number of non-fatal mishaps, injuries, and near-misses that have occurred during training and mission operations as well. This is because of the dangerous nature of the environment surrounding spaceflight and the large number of potential hazards that could negatively impact the health of the crew, support team, and even lay-bystanders. Spaceflight is associated with controlled explosions, fire, extreme hot and cold temperatures, high velocities and acceleration forces, toxic materials and fumes, a lack of atmosphere and oxygen, abnormal weather conditions, extreme and often remote environments, and complicated mechanical and electronic equipment that has to work correctly and has a narrow envelop for tolerable failure. And, as is evidenced by the recent mishaps (both manned and unmanned, [19, 29, 68, 140]) that have occurred with commercial spaceflight, it is obvious that there have been no paradigm shifting technological developments that have made spaceflight safer. It is true that each mishap brings lessons learned and changes are implemented following disasters to prevent the same catastrophes from happening again. However, when working in the environment of space, we don’t know what we don’t know, and it is always the failure that wasn’t anticipated or planned for that causes the worst problems. Additionally, human beings are fallible and are prone to complacency and short cuts when operations are running smoothly without issues. Thus, as long as we have humans in the loop for spaceflight operations or until future technologies such as space elevators make significant advances in the state of the art, there will always be a level of cyclical normalization of deviance that occurs, where mishaps will inspire vigilance acutely among operators which eventually tapers off over time as complacency sets in, until the next mishap when the cycle starts over again. This is especially true when there is turnover within the aerospace industry where new operators who lack the experience of working through previous mishaps and thus may be more cavalier and accepting of risk regularly replace more experienced operators that have managed mishaps in the past and may be more risk averse. Thus, there will always be a role for contingency medical support as a metaphorical safety net to manage and mitigate contingencies as they inevitably occur.

In order to evaluate the current state of the fields of space safety, disaster medicine, and mass casualty emergency care, a comprehensive literature search was undertaken. To do this, the PubMed, Cochran, and Google Scholar databases were searched using the search criteria, “medical support”, “spaceflight”, “commercial space”, “airshow”, “air races”, “motor sports”, “Indy car”, “nascar”, “formula one”, “mass gathering”, “mass casualty”, and “disaster”. The returned articles were evaluated and narrowed down to 37 references that were considered to be relevant to the development of this proposal (see **Figure 2.2**). Of note, there is currently a paucity of literature on emergency medical care for mass casualty and disaster settings, both in the number of articles and in the evidence to support particular medical response actions. However, this document attempts to compile the available literature, as well as point out where the literature is lacking and where expert consensus and best practices are used to fill in. The following are the major points presented in these articles. These points are discussed here in brief and elaborated upon further in Chapter 4:



<u>Figure 2.2:</u> Illustration of methodology for systematically reviewing the literature and isolating appropriate articles for review and inclusion in a medical response document for the Houston Spaceport flight operations.

When addressing medical concerns for commercial spaceflight, the unique medical conditions associated with the space environment must be considered. To some degree, these medical risks will vary depending on the flight profile, the specific vehicle being flown, and the surrounding area within which flights are being conducted. Medical conditions that must be considered include ebullism (or the boiling of body fluids because of an ambient vapor pressure below 47mmHg, which is the boiling pressure of water at body temperature [43, 44, 112, 129]), decompression sickness (where supersaturated nitrogen bubbles out of tissues because of low ambient pressure causing tissue damage [44, 76]), exposure to high G-force loads [43, 44, 138], and trauma from off-nominal flight profiles, damage to the vehicle, and/or loose contents within the cabin environment [43, 44]. In addition, crew and spaceflight participants are at risk of developing medical issues even during a nominal flight. Participants have the potential to develop exacerbations of their medical conditions [45], especially exacerbations of cardiac issues from fluid shifts during the microgravity phase of flight [64, 159], ophthalmologic exposures such as foreign bodies in the eye from floating debris during microgravity [159], or the unmasking of psychosocial conditions, such as anxiety, from the stressors related to spaceflight [127, 159]. It is also possible that passengers could develop ailments related to malfunction of their personal medical equipment, such as pacemakers or insulin pumps, potentially related to the increased radiation exposure at altitude. These issues are under investigation [46, 116, 144]. In addition, if there are crowds associated with commercial flight activities, such as having friends and family on hand to witness a space tourist's flight, then other more common ground-based medical conditions in bystanders and spectators must be considered as well [119, 156, 162, 179]. **Figure 2.3** shows a comprehensive list of medical conditions that frequently occur at mass gathering events, based on a comprehensive review of the mass gathering literature [112]. It is also worthy to note that there is a well-known phenomenon that occurs at mass gatherings where the ratio of sick or injured spectators compared to the overall number of attendees increases. This is believed to be the result of a large number of people in a crowded space with limited resources, often with extreme conditions such as increased noise or temperature extremes [21, 32, 80, 162]. Thus, the number of spectators that may require treatment and the resources needed to do so may not be insignificant. The literature suggests that the number of patients averages around 0.5 to 2 patients per thousand spectators [67], and can reach as high as 90 patients per thousand [32].

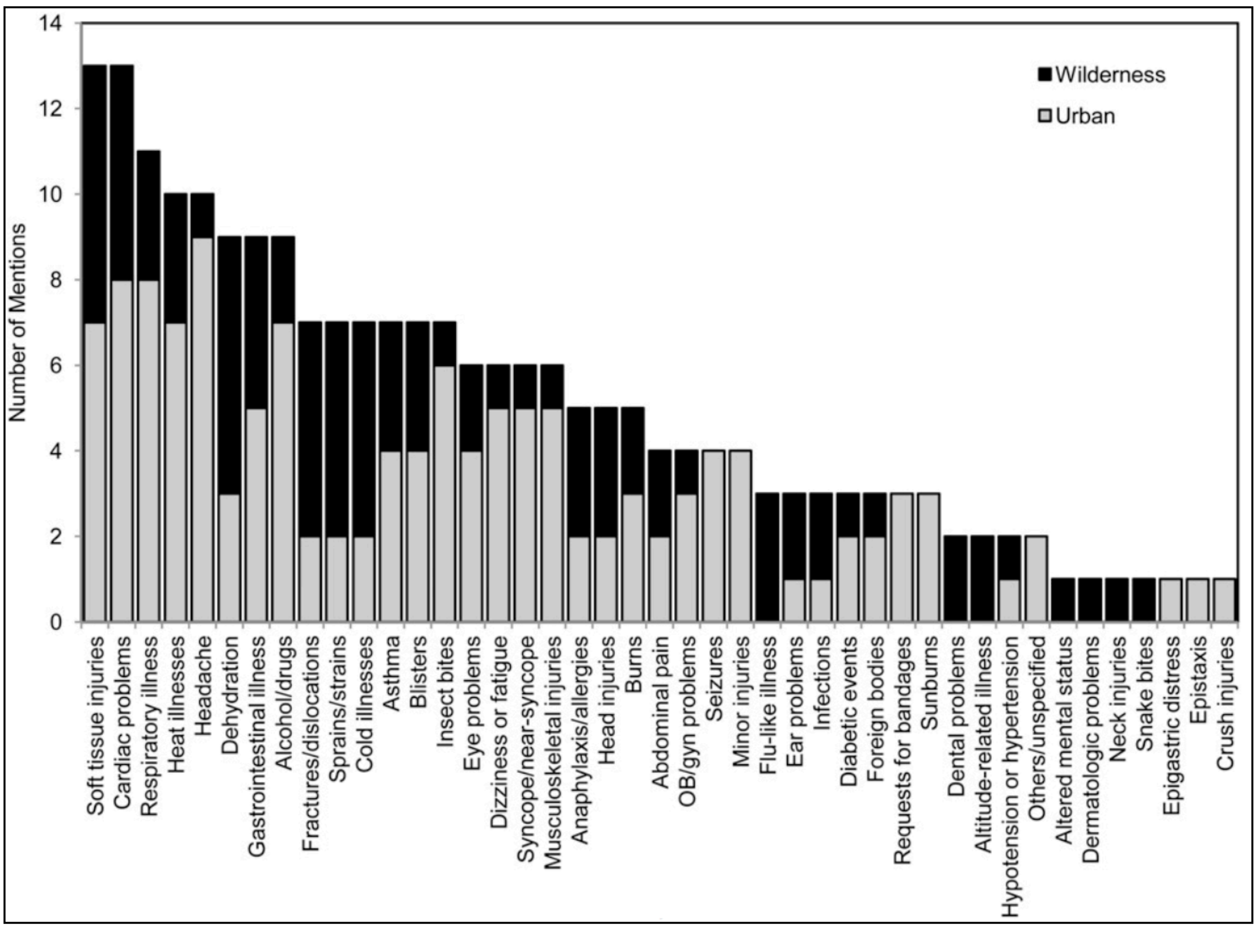


Figure 2.3: Illnesses and injuries to be considered in an emergency medical plan, in descending order of number of mentions in 19 wilderness and urban mass gathering medicine articles reviewed. (Reproduced with permission from the Aerospace Medical Association, [112]).

The elements of a comprehensive commercial spaceflight and mass gathering medical response plan can be broken down into the following categories: 1) event planning (based on flight and mission architecture), 2) medical risk assessment, 3) medical personnel, 4) protocols, 5) medical reconnaissance (including evaluation of access points, barriers to entry, identification of local tertiary care facilities, and coordination with those facilities), 6) equipment, 7) communication, and 8) medical documentation [43, 44, 112, 123].

Event planning should include evaluating the individual medical risks to the passengers and the surrounding bystanders based on the mission profile, the vehicle involved, and the surrounding area where the flight is to take place. This can include ensuring that ground spectators are stationed clear of the vehicle's flight path, clear of any hazardous materials such as fueling stations, and clear of any potential hazards surrounding the launch site, such as trip hazards or dangerous plants and animals [112, 145].

From the standpoint of medical personnel, it is important to have a basal level of medical support for all spaceflight operations that can be ramped up in the event of a high volume of launch attendees [145]. Providers with different levels of medical expertise can be utilized to provide different levels of care depending on need [137]. It has been recommended to have a ratio of medical staff to spectators of somewhere in the range of 1 to 2 physicians per 5,000 to 40,000 attendees [80, 112, 137, 149]. Medical personnel can be deployed in teams of 4 to enable each team to act as a stand-alone unit capable of executing Advanced Cardiac Life Support and Advanced Trauma Life Support care if needed. It is generally recommended that the lead for these field teams be someone with training in emergency medicine and disaster care [43, 44, 119, 145]. An aerospace medicine-trained physician should be stationed in Mission Control as Medical Director and act to monitor all medical responses and coordinate care amongst the different field teams [43, 44, 112]. Additionally, it is worth considering having an FBI official to support launches, so that in the event of a medical emergency off site, it is still possible to rapidly access the crew and passengers in a legal way, when they may have landed on private property or areas where entry may otherwise be unlawful [43, 44]. Additionally, it may be worth considering having designated communications operators assigned to each team to ensure that messaging between teams is implemented in a concise, effective way in order to reduce miscommunications [145]. To accommodate these personnel requirements, additional medical staff can be supplemented using volunteers from local, surrounding medical and academic facilities. Indeed this was used to great effect during Shuttle Operations out of Cape Kennedy. Volunteer medical care providers were oriented to the Kennedy Space Center grounds and were trained on NASA's emergency medical procedures, including donning and doffing of the crew's launch and entry suits. They were required to maintain a currency with NASA procedures through yearly training. If current, they were called upon to help with medical support for Shuttle launches and landings [145]. The Medical Director should dictate what level of care will be provided during flights for bystanders, as well as in the event of a mass casualty event. This level of care should be determined based on what is appropriate given the resources available, and this level of care will drive what protocols will be in place to manage medical events [112]. Additionally, because of the time course for a suborbital spaceflight mission (potentially in the range of several hours), it may be worth considering whether or not to have a level of medical capability on board the flight (as well as whether or not to train the spaceflight participants on life saving measures) in the event that a passenger has a medical event early in the flight, but past the point where an abort is feasible (eg. at the initiation of rocket-powered flight). Life supporting measures such as Advanced Cardiac Life Support could be potentially life saving if implemented appropriately until definitive management can be administered. However, these procedures are not intuitive in a standard clinical care setting (they require a certain level of training) and are made even more difficult by the spaceflight environment [102, 159]. A cost/benefit analysis will need to be assessed to determine if implementing an onboard medical capability is of sufficient value. However, this analysis is beyond the scope of this document. It is mentioned here for completeness sake only. Medical reconnaissance can involve evaluations to determine what the best route of entry to a site of operations is for emergency response personnel in the event that a medical evacuation is needed, as well as an assessment of what medical resources are available to support a mission or mass gathering, including what kind of medical evacuation capability will be supported. Generally, it is recommended to have at least one ground and one air evacuation asset to maximize the probability that the vehicle can be reached in a timely fashion during a contingency when the spacecraft may have flown off course [43, 44, 123]. Additionally, having smaller, more versatile medical evacuation assets, such as golf carts are useful for large crowds when navigating amongst groups of people can be more difficult for larger assets [112]. Reconnaissance also involves evaluating what tertiary care facilities are in the surrounding area (and what capabilities they can support) and contacting those facilities to inform them of the spaceflight activities that are taking place, to determine their willingness and capacity to help in the event of a medical contingency, and to coordinate care during mission operations [112]. Such reconnaissance can also include the establishment of additional, back-up tertiary care facilities to deal with patient overflow in the event of “off-nominal” scenarios that have the potential to overwhelm the first-line tertiary care facilities [137]. Such scenarios could include an accidental mass casualty event where large numbers of individuals are injured and need care or an attack where multiple people are intentionally injured [32]. Medical equipment and facilities can be scaled up or down based on the parameters of the medical care to be provided (eg. based on how many spectators will be in attendance, the size and layout of the facility where launches and landings will take place, and the level of practitioners that will be available to provide medical care) [112, 137, 149]. In addition to basic medical equipment for providing first aid and routine medical care, it may be pertinent to consider proper emergency equipment, such as advanced airway equipment and Advanced Cardiac Life Support resources [112]. Contingency specific medical equipment should also be considered, such as high-frequency percussive ventilation for the respiratory management of a patient that develops ebullism [43, 44, 129]. Lastly, though it is beyond the scope of this document, it may be of value to incorporate preventive measures such as water, earplugs, sunscreen, and misting tents into the medical supplies to have on hand during mission operations, especially in the event that a crowd will be present to observe the proceedings [137].

Organization/Agency Description –

The Houston Spaceport is a subsidiary of Ellington Airport, which is a part of the Houston Airport System. Ellington Airport consists of 2,590 acres and is made up of three runways. The first, 17L/35R is a 4,609 x 80 foot runway, the second, 17R/35L is a 9001 x 150 foot runway, and the third, 4/22 is a 8001 x 150 foot runway [10]. The Houston Spaceport will occupy a 483-acre plot of land on the southeast section of the airfield (see **Figures 2.4-2.8**) [14, 15]. The Houston Spaceport was created in June of 2015 after the City of Houston received approval for a commercial spaceport license from the Federal Aviation Administration. The Houston Airport System is ranked fourth in the country compared to other airport systems with regards to size. It is also sixth in the world [13]. The Airport System has a yearly operating budget of approximately $450 million [7], and has so far dedicated $6.9 million to the development of the spaceport, for land purchase and the purchase of an aerospace engineering building [23], with the intent of returning Houston to a position of leadership in aerospace innovation, making Houston the hub of commercial space transportation around the United States and around the world, and enhancing the economy of Houston by bringing in new businesses within the aerospace industry [14, 15]. The Concept of Operations for the Houston Spaceport, including planned flight profiles and spacecraft types is described in detail in Chapter 4.

Figure 2.4: Arial view of the Ellington Airport, facing North. The Southeast Airside plot of land (highlighted in orange) will be the site of the future Houston Spaceport. (Reproduced with permission from the Houston Spaceport, [16]).

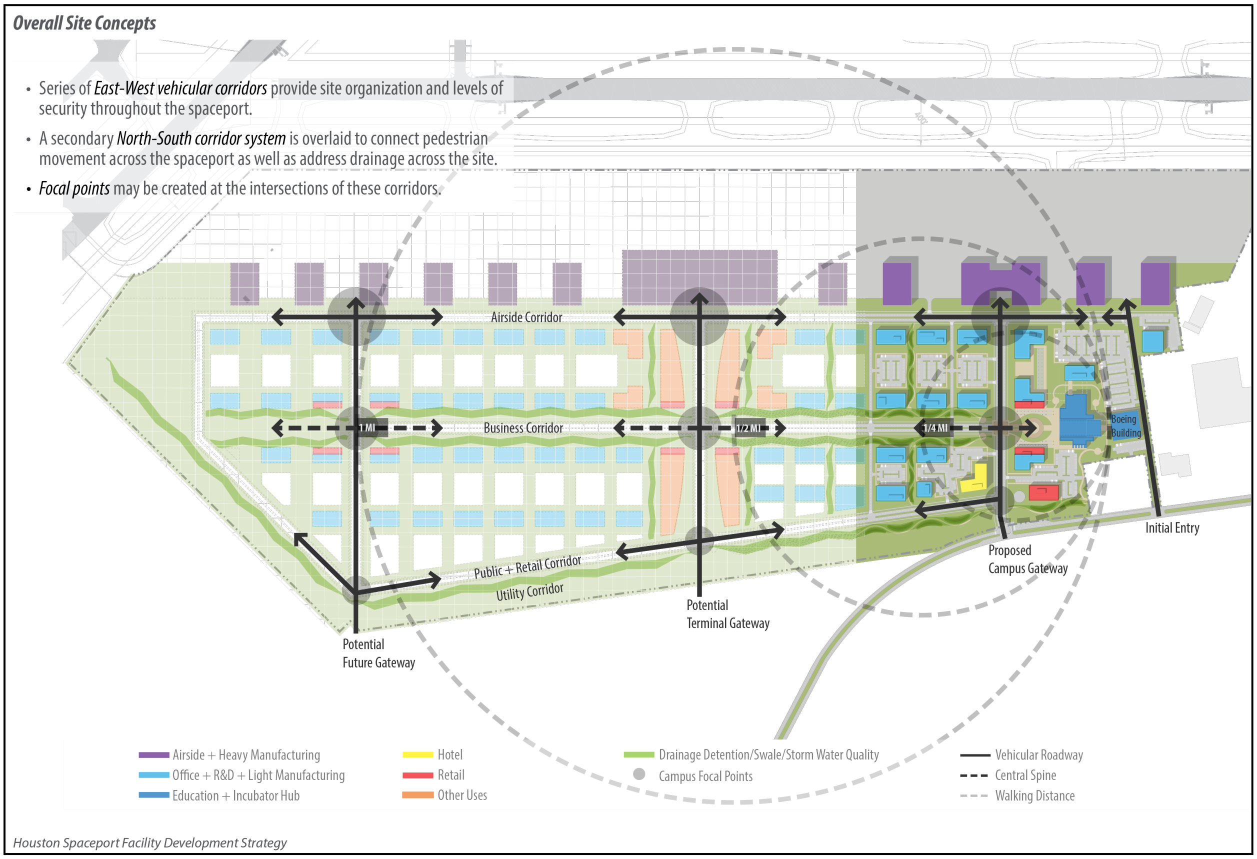


Figure 2.5: Overall site concepts for the Houston Spaceport. The diagram is oriented with the direction of West facing up. Phase 1 of the plan includes the area of land shaded darker to the right of the diagram. The future flight line will be located to the West of the Spaceport. Space Center Boulevard can be seen running along side (and splitting off from) the East side of the Spaceport, on the bottom right of the diagram. (Reproduced with permission from the Houston Spaceport, [14, 15]

Figure 2.6: Overview concept art for the Houston Spaceport once it is fully established. The image is oriented such that east is facing up. The spaceport flight line can be seen at the bottom of the image. Space Center Boulevard is highlighted (in orange) running parallel to the spaceport at the left of the image before branching off and traveling toward Johnson Space Center at the top-center of the image. Highway 45 South can be seen highlighted (in blue) along the top right of the image. (Reproduced with permission from the Houston Spaceport, [16]).

Figure 2.7: More detailed concept art of the Houston Spaceport. Image is oriented with the top facing a Northwesterly direction. Space Center Boulevard can be seen at the bottom right of the image. (Reproduced with permission from the Houston Spaceport, [14, 15].

<u>Figure 2.8</u>: More detailed concept art of the Houston Spaceport. Image is oriented with the top facing north. The main North-South Corridor System can be seen running along the middle of the image from top to bottom. Space Center Boulevard can be seen at the top-right of the image. (Reproduced with permission from the Houston Spaceport, [14, 15].

Chapter 3: Methods

Needs Assessment –

Below is a six-step process for assessing need for a medical response infrastructure for commercial spaceflights out of the Houston Spaceport, based on previously reported and validated techniques [122]:

Step 1: Determining the Purpose and Scope of Needs Assessment – The ultimate purpose of initiating a needs assessment is to make the commercial space industry more robust and resistant to potential catastrophes, and in so doing, advance space exploration forward. Because of the prevalence, historically, of catastrophic medical mishaps related to spaceflight and the impact those mishaps have had on stagnating space exploration, at least for a period of time, the focus of this needs assessment is specific to medical operational needs for commercial spaceflight (especially suborbital flights through the Houston Spaceport) in order to strengthen the resiliency of the commercial space industry to catastrophic contingency scenarios. Because of the newness of the space tourism industry as a whole and the Houston Spaceport specifically, suborbital flights are still many years away. Additionally, there are still many knowledge gaps that remain regarding space physiology and operational space medicine that must be researched and closed. Thus, an established medical infrastructure is unnecessary at this time and is beyond the scope of this needs assessment. As there are currently limited resources available for such a project, the scope of this needs assessment will be limited to developing a hypothetical plan for addressing medical needs for commercial spaceflight.

Step 2: Gathering Data – For this needs assessment, data was collected, utilizing literature reviews, data gathering through online review of news media, and direct communication with spaceport representatives, as well as data gathering from spaceport websites and other online content, to characterize the size and scope of the problem of injury and death associated with spaceflight, as well as to characterize potential measures for mitigating or minimizing these outcomes. Thus, data was collected on the number of mishaps that have occurred over the course of a human presence in space. Data was collected on the number of spaceports that exist in the United States and around the world, what percentage of them have a medical infrastructure already in place, and how many times the medical plan has been used in the facilities that have them. It would also be useful to have data on whether or not the implementation of a medical plan has led to improved outcomes with regards to injury and survival at facilities where a mishap has occurred. Controlled data of this type with evaluations made both before and after implementation of a medical response plan does not exist in the published literature, however, and most likely would have too small a sample size to draw any conclusions even if it did exist. However, we can assume that implementation of some sort of medical infrastructure would yield benefits for the commercial spaceflight industry, as this is the basis for the existence of all emergency medical services that exist around the world and there is plenty of data in the clinical medicine literature that suggests that these services lead to improved outcomes in other environments [95]. Additionally, data was collected on how many more spaceports are planning to be built in the near future. All of this data was collected in the literature review described in the previous chapter.

Step 3: Analyzing Data – Because the literature available on medical emergencies associated with spaceflight (or other mass gathering events) is limited, the data available is insufficiently granular to be able to assess the incidence rates in an attempt to focus efforts on a specific disease process. However, the data were sufficient to assess the overall need for a comprehensive medical response plan for commercial spaceflight operations. As stated previously, there have been 270 fatalities (32 of which were astronauts and cosmonauts) and 67 other accidents associated with spaceflight since the beginning of human spaceflight in 1961 [93, 130]. This amounts to an incidence of 1.47 mishaps per year and 4.9 fatalities per year. It also amounts to a mortality rate of 3.9 per 1,000 person-years for astronauts and cosmonauts and a total mishap incidence rate of 9.9 per 1,000 person-years, assuming a total number of fliers of 547 and an average career length as an astronaut or cosmonaut of 15 years [93, 130]. Again, though these rates are lower than those estimated for other disease processes, the data do suggest that the risk of a medical mishap is great enough during space flight operations to warrant the development of a medical response plan to inoculate against these risks, given the fantastical nature of such events, the fear they can instill in the general public, and the fragile nature of the commercial space industry. How best to do this is not perfectly clear. Implementation of the Basic Priority Rating (BPR) model [92] to analyze the available data was not feasible because, again the data were limited. However, it is possible to glean general recommendations on how a response plan might be structured to ensure its effectiveness based on the previously published spaceflight and mass gathering medical response literature. As stated above, the eight main elements of a comprehensive commercial spaceflight and mass gathering medical response plan are: 1) event planning (based on flight and mission architecture), 2) medical risk assessment, 3) medical personnel, 4) protocols, 5) medical reconnaissance (including evaluation of access points, barriers to entry, identification of local tertiary care facilities, and coordination with those facilities), 6) equipment, 7) communication, and 8) medical documentation [43, 112, 123]. Therefore, organizing these elements into a coordinated medical response plan is the focus of this document.

Step 4: Identifying the Risk Factors Linked to the Health Problem – Identification of the medical events of high-risk during commercial suborbital spaceflight are detailed in Chapter 4 as part of the risk assessment performed, based on the literature described above, in order to determine appropriate medical infrastructure planning. Briefly, the major medical risks inherent to suborbital spaceflight are as follows: 1) ebullism, 2) decompression stress and illness, 3) barotrauma and arterial gas embolism, 4) hypoxia, 5) acceleration injury, 6) trauma, 7) fire, 8) chemical exposures (especially inhaled), and 9) environmental exposures such as cold at altitude, water in the case of a contingency landing, or dangerous flora and fauna [81, 123]. As such, major risk factor determinants for such exposures are: 1) altitude reached during the flight profile, 2) acceleration profiles during the flight, 3) the presence or absence of personal protective equipment, especially thermal, respiratory, hypoxic (oxygen), and hypobaric protection, 4) vehicle design (including emergency abort and recovery capabilities, and 5) the presence or absence of preflight safety protocols, such as a pre-breath protocol for minimizing risk of decompression injury, or wilderness and water survival training.

Step 5: Identifying the Program Focus – Though it is feasible to focus on mitigation strategies for each of the medical risks identified in “Step 4” (and indeed, varying amounts of work have been done in these areas already, depending the risk), this would not eliminate the need for a comprehensive medical response plan in case of an emergency during operations. Response plans are activated in the event of catastrophe and it is therefore reasonable to assume that such a catastrophe could damage or eliminate any mitigation strategies developed for each of the individual hazards previously described. A back up medical response system must be in place for redundancy to manage illness and injury in the event that these primary mitigation strategies have been compromised or overwhelmed. Though limited, there is some evidence that having such an infrastructure in place can lead to a better medical response and that not having it can be detrimental. It has been shown that having a comprehensive and coordinated medical response in place can reduce the burden on local-area emergency response services [95], thus preventing any overwhelming of the system in the event of a mass casualty event. Conversely, the mishap of SpaceShipTwo in the fall of 2014 is example of an event that may have benefited from a more robust and coordinated medical response plan. At the time of the mishap, there was no medical team in place at Mojave Airport to support the flight [19]. Though there is no good evidence to determine whether having a medical operations plan in place for these test flights by Scaled Composites would have changed the outcomes for the two pilots involved in the mishap, it is safe to say that having a well structured and executed response system would have given them the best chance for a positive outcome medically. Therefore, this is the focus of this particular document.

Step 6: Validating the Prioritized Needs – Validating the above outlined needs assessment was done through a three-part process. First and foremost, the needs assessment was conducted utilizing a formal, structured, and standardized approach that has been previously validated in the literature, as described previously [122]. Following the implementation of the needs assessment, this process was checked by reevaluating each individual step in the assessment process to ensure that logic was sound and followed a structured and well-thought-out approach. Finally, to minimize any bias in the process, the needs assessment was addressed and confirmed with outside technical experts to ensure that the process followed was sound and that the conclusions drawn were appropriate.

Program Description –

As no human subjects or animal specimens were used for the implementation of this proposal, no Institutional Review Board or Institutional Animal Care and Use Committee approval was necessary in order to carry out the work outlined in this proposal.

Initial outlines for a medical response plan were determined by conducting a thorough review of the literature (as described above). This was done by searching medical databases such as Pubmed and Medline, NASA and other government internal documents (as allowed), and other Emergency Medical Plans developed for previous spaceports and other crowd events such as air shows, air races, and motor sports events [33, 44, 52, 80, 112, 149]. These literature sources were evaluated for information regarding mass gathering medical care and mass casualty response planning, as well as information regarding spaceflight mission specific medical planning when possible. Specifically, this literature was evaluated for information explicit to the areas of identifying and organizing the appropriate area medical response resources (eg. local EMS and Fire Departments), identifying appropriate local tertiary care facilities, identifying geographical constraints to delivering field care if needed and transport to definitive care when necessary, defining the appropriate medical team makeup and structure, indentifying the major medical risks associated with planned spaceport activities [55], developing the necessary medical response protocols for potential medical events of high risk, identifying and organizing the necessary medical facilities, equipment and supplies to have available on site during mission operations, developing the plans for appropriate communication during a medical response, and identifying the necessary resources for appropriately documenting any medical care that may be administered, as well as any other areas that are discovered and deemed relevant for the development of a complete medical infrastructure for spaceport operations. Results of this literature search were touched on in Chapter 2 of this document and are elaborated upon further in Chapter 4.

Subsequent to a thorough literature search and outlining of an initial medical response plan, each individual component of the plan was then elaborated upon with details specific to the Houston Spaceport and in collaboration with subject area experts and collaborators responsible for local area resources. This includes a thorough evaluation of the air field and potential flight profiles to determine most likely potential medical threats and the best routes into and out of the air field for EMS services to ensure timely delivery of care in the field and rapid transport out to appropriate tertiary care facilities. Local EMS, Fire Department, and Law Enforcement groups were evaluated for their availability if needed, the infrastructure they have in place, and their relative proximity to the airfield. Similarly, area hospitals and other medical facilities were evaluated for the nature and quality of the infrastructure they have in place (especially available trauma, burn, and decompression management services). Based on this, a medical response matrix was developed incorporating the appropriate teams, services and facilities that will be needed in order to transport and manage various medical contingency scenarios. Based on the most likely medical risks and the proper field management of these risks, an index of appropriate medical equipment to have on site, as well as treatment protocols for these high risk medical contingencies (including communication equipment and protocols), was developed. This was done in collaboration with subject matter experts in the area of field medical kit development and field medical management protocol development at UTMB, Baylor College of Medicine, and NASA. A significant part of developing these field medical protocols was identifying the appropriate on-site medical team size and makeup to efficiently carry out these treatment algorithms. This depends on the various expertise that will be required to manage the high-risk medical contingencies identified during the literature review and data gathering phase of the project. Appropriate medical documentation was developed based on pertinent medical information and documentation. This, in turn, is determined based on currently used emergency medicine, disaster medicine, mass gathering medicine, and aerospace medicine documentation.

The information gathered during the initial literature search and the follow on elaboration of this information with the help of field experts have been compiled into this final document for publication and submission for approval as a capstone thesis.

Logic Model –

See **Figure 3.1** for overview of the logic model for the development of a medical response plan for the Houston Spaceport.

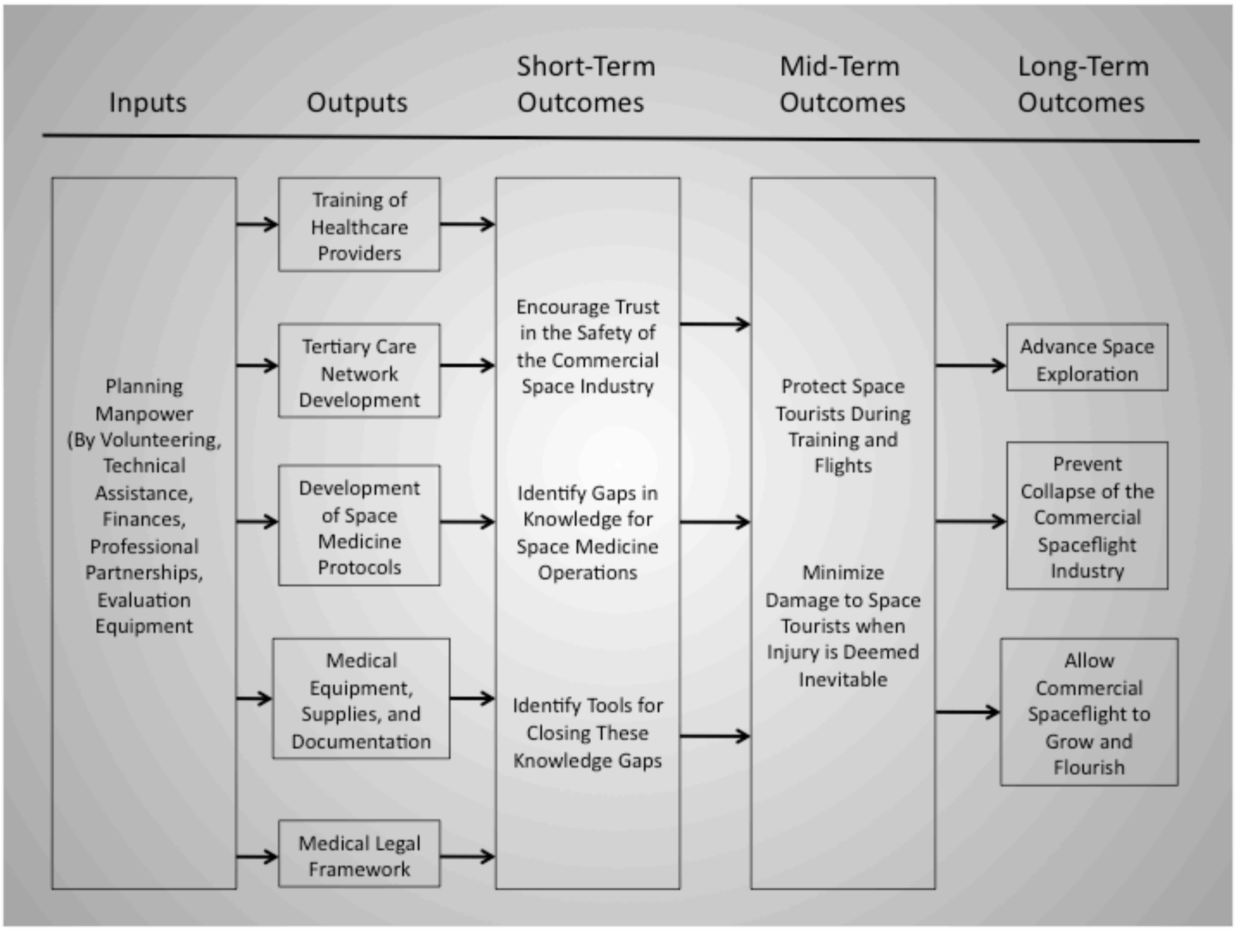


Figure 3.1: Logic Model for a Space Medicine Operations Plan for the Houston Spaceport.

The following is the logic model that was developed for the creation and implementation of a medical response program for spaceflight operations at the Houston Spaceport.

The long-term outcomes desired from the development of a medical response infrastructure are, first and foremost, the advancement of space exploration, especially commercial space exploration. Along these lines (but more immediate) are the desired outcomes to prevent the collapse of the commercial space industry and to foster an environment where the industry can grow and flourish. As such, more mid-term goals for the medical response plan are to create the infrastructure in order to protect space tourists from harm during their training and flights. A related but secondary goal is to minimize damage to tourists and surrounding lay-bystanders if at all possible, in the event that harm is inevitable. Short-term desired outcomes include encouraging trust by the lay-public, especially potential space tourism customers, that the commercial spaceflight industry is safe by demonstrating to the public that there is the appropriate infrastructure in place at the spaceport, including and especially an appropriate medical response program. Additional short-term desired outcomes include identifying, through the process of detailing a comprehensive medical response program, the gaps in knowledge regarding space physiology and space medicine operations necessary to optimize the program from a health, safety and performance standpoint, as well as identifying what research tools are needed to help close out those gaps.

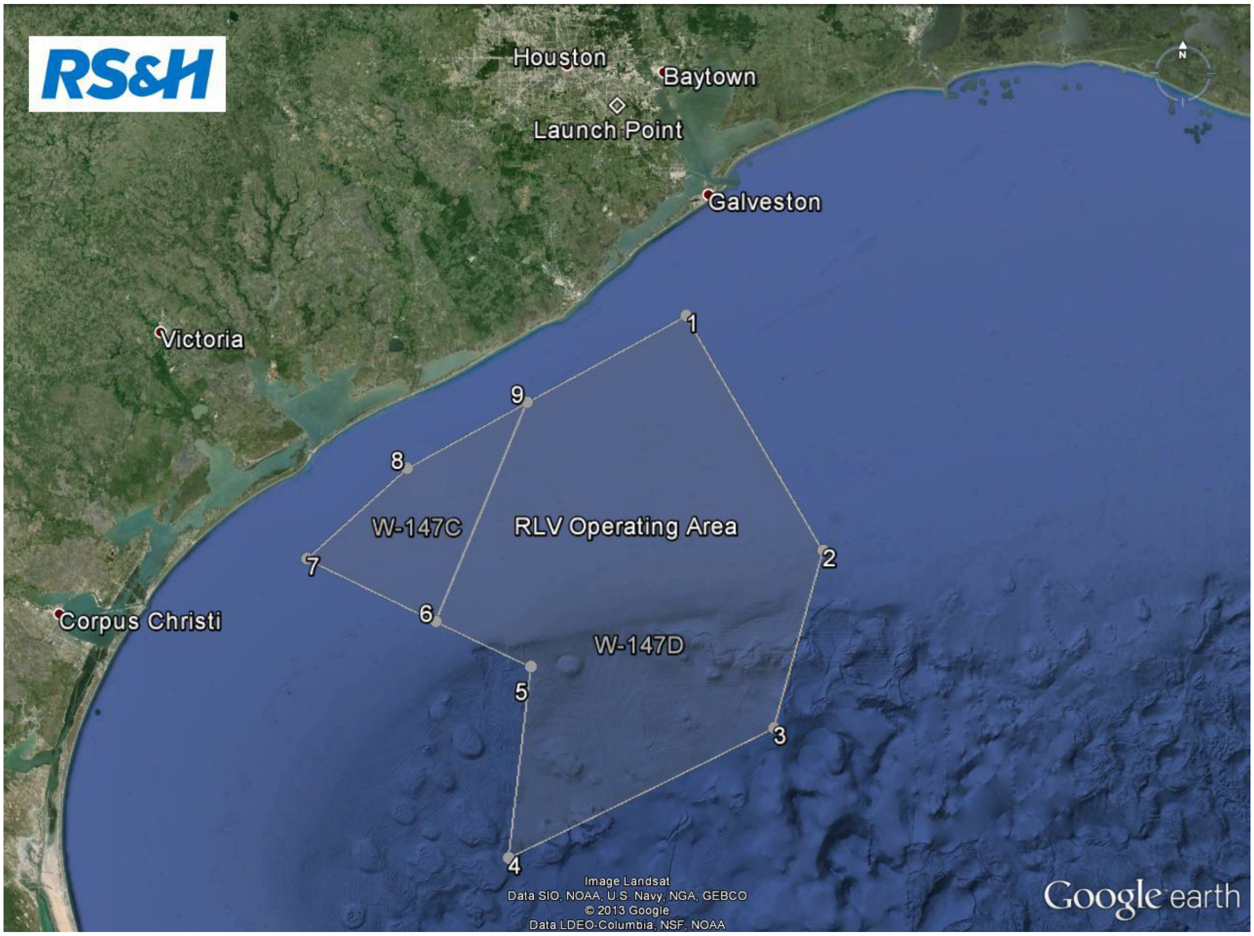
As such, the logic model inputs for appropriate planning, implementation, and evaluation of this type of program include: 1) manpower for developing the initial plan (which initially will operate on a volunteering basis), 2) technical assistance from area experts in space law and spaceflight operations to help with detailing the space medicine operations protocols, 3) finances for medical supplies and ongoing training (when the time comes for implementing the medical plan), and 4) partnerships with outside entities such as local area EMS services and tertiary care facilities for purposes of transferring any injuries to definitive care. In addition, the evaluation phase will also require the input of equipment to document and evaluate the effectiveness of the implementation of the program (eg. video documentation equipment, debrief space, etc.). Logic model outputs for this program are: 1) the development of a medical care network for managing patients in the event of a medical contingency, 2) the development of medical protocols for the management of high-risk space medicine injuries, 3) medical equipment and supplies for implementing the medical response plan, 4) documentation, either electronic or hard copy, for documenting medical care if needed, and 5) training for medical practitioners on the medical plan procedures in place at the Houston Spaceport and practice with carrying out these procedures.

Chapter 4: Results

Implementation Plan –

Planned Flight Profiles - The major medical risks associated with spaceflight depend, in large part, on the particular specifications of the vehicle or vehicles involved (including size of the vehicle, number of passengers, nature of personal protective equipment, and type of fuel used), the flight profiles utilized (especially acceleration profiles and altitudes reached), the procedures carried out pre-, during-, and post-flight, and the nature of the surrounding environment that is included in the flight operating area. This includes whether or not there are highly populated residential areas near by, as well as whether or not there is rapid access to definitive medical care if needed.

The Houston Spaceport will occupy 2,590 acres of land within Ellington Field of the Houston Airport System, and flights are anticipated to operate from runway 17R/35L (one of three runways in operation at Ellington Field) when traffic in the pattern allows. At this time, only suborbital, horizontal takeoff/horizontal landing flights are anticipated for the Houston Spaceport. Flights are anticipated to takeoff from runway 17R and head south towards the designated spacecraft operating area. The spacecraft operating area consists of two off-shore warning areas (W-147C and W-147D, **see Figure 4.1**) [14, 15]. The Houston Spaceport is planning to operate spacecrafts of two different design profiles. The first (termed Model X) will be a one-stage rocket plane, which will take off and land horizontally. Model X spacecraft design will most likely consist of a combination of two jet engines and two rocket engines with a total mass of roughly 75,000 lbs of propellant. The jet engines will most likely be fueled with Jet-A kerosene fuel and the rocket engines will be fueled with a combination of kerosene and liquid oxygen. Model X is designed to initially take off as an aircraft, powered by jet engines, until clear of populated airspace. Subsequent to this, once the spacecraft has entered the desired operating airspace over the Gulf of Mexico, at an altitude of approximately 40,000 feet, the spacecraft will accelerate under rocket power to an altitude of 150,000 feet and coast up to an apogee of 330,000 feet above sea level. Following rocket-powered flight up to altitude, the spacecraft will descend in a ballistic reentry profile and return to spaceport runway 17R/35L either utilizing jet engines or while executing a coordinated, unpowered glide. The maximum speed for this flight profile will be approximately Mach 3.5 and the entire flight will last approximately 1 hour. The prototypical example of a Model X design spacecraft is Rocketplane Kistler's Rocketplane XP (**see Figure 4.2**) [14, 15].



<u>Figure 4.1:</u> Diagram of the two off-shore warning areas (W-147C and W-147D) in the Gulf of Mexico off the coast of Southeast Texas where the rocket-powered limb of commercial spaceflight operations out of the Houston Spaceport will take place (Reproduced with permission from the Houston Spaceport, [14, 15]. RLV = Reusable Launch Vehicle.

Figure 4.2: Artist's rendition of a one-stage rocket plane "Model X"-type commercial spaceflight vehicle that could potentially operate out of the Houston Spaceport. The prototypical example of this type of vehicle is Rocketplane Kistler's Rocketplane XP (Reproduced with permission from the Houston Spaceport, [14, 15].

The second spacecraft model (termed Model Y) is designed as a two-article, aircraft/spacecraft combination. Model Y spacecraft design will most likely consist of four jet engines propelling the carrier aircraft article and a single hybrid solid/liquid rocket engine propelling the suborbital spacecraft article. The total two-article vehicle system will carry a mass of roughly 100,000 lbs of propellant. This will include Jet-A kerosene fuel for the jet engines. Rocket engine propellant will depend on the design of the hybrid rocket [14, 15]. SpaceShipTwo (the prototypical Model Y design) uses a solid state rubber fuel with a nitrous oxide oxidizer [125]. Model Y operations will involve initial takeoff and climb under jet-powered flight by the aircraft portion of the vehicle, while carrying the suborbital rocket plane, until the vehicle is clear of populated airspace. Similar to Model X, Model Y will not operate under rocket power until out over the Gulf in designated spacecraft operating airspace. At this point, at roughly an altitude of 50,000 feet, the rocket plane portion of the aircraft will be released from the aircraft carrier plane and once clear from the aircraft, will accelerate under rocket power up to a peak altitude of 330,000 feet. At this point, the carrier plane will return to Ellington for landing on runway 17R/35L. Subsequent to reaching peak altitude, the spacecraft will execute a ballistic descent and return to the spaceport and land on runway 17R/35L under controlled, unpowered glide flight [14, 15]. The prototypical example of spacecraft of Model Y design is Virgin Galactic's WhiteKnightTwo and SpaceShipTwo vehicles (**<u>see Figure 4.3</u>**).

<u>Figure 4.3:</u> Artist's rendition of a two-article, aircraft/spacecraft combined "Model Y"-type commercial spaceflight vehicle that could potentially operate out of the Houston Spaceport. The prototypical example of this type of vehicle is Virgin Galactic's WhiteKnightTwo and SpaceShipTwo (Reproduced with permission from the Houston Spaceport, [14, 15].

<u>Potential Medical Events of High-Risk</u> - Given the above flight profiles, there are a number of potential medical risks that should be considered when developing an

operational plan for any disaster, mass-casualty, or medical contingency that occurs during flight operations. The following are considered the medical incidences of highest risk and should be considered when considering the development of a medical response program for spaceflight at the Houston Spaceport:

Because of the high altitudes planned for in the flight profiles by both Model X and Model Y vehicles, one potential medical exposure of high-risk is the development of ebullism if the cabins of either vehicle develop a rapid decompression for any reason. Ebullism is the medical condition that occurs at altitudes where the atmospheric pressure is at or below the vapor pressure of water at room temperature (37 degrees C). This generally occurs at around 63,000 feet (although it does vary to some extent based on temperature and pressure fluctuations in the body). This altitude is known as "Armstrong's Line" [129]. At or around this altitude, water, including water in human tissues, will begin to boil, leading to trapped gas expansion and mechanical damage to these tissues, vapor-lock, circulatory collapse, hypothermia from evaporative heat loss, and dehydration from evaporative water losses [171]. The most sensitive tissue to these exposures is lung tissue because it is the organ that is exposed to the lowest pressure, both because it operates via negative pressure in the chest and because it is not adequately protected by the skin, which acts as a mechanical pressure garment for other tissues [171]. Additionally, lung tissues are particularly delicate and susceptible to damage from trapped gas expansion [62]. Exposure of the lungs to low enough atmospheric pressures to trigger ebullism leads to an acute respiratory distress syndrome-like picture where inflammation develops and capillary leak occurs, leading to the development of pulmonary edema. There are limited definitive treatment options for exposure to vacuum and ebullism other than to eliminate the exposure by bringing the individual down from altitude, supportive measures (including lung-protective ventilation), and advanced cardiac life support if needed [129]. The mainstay of managing ebullism is prevention through the use of a pressurized vehicle cabin or pressurized suit. Both Model X and Model Y vehicles are designed to be pressurized, but could experience a rapid decompression in a contingency scenario. It is worthy to note that Virgin Galactic, an example of a Model Y spacecraft, is not planning to utilize pressure suits for either their pilots or their passengers during missions, leaving them exposed to altitude in the event of a depressurization. This point became an issue in October of 2014 when a test flight for SpaceShipTwo by Scaled Composites went off nominal and led to a catastrophic breakup of the vehicle at 55,000 feet (within the band surrounding Armstrong's Line), exposing the two pilots to sufficient altitudes to place them at risk for ebullism [19].

Another potential medical risk because of the high altitudes and low atmospheric pressures planned for suborbital spaceflights at the Houston Spaceport is decompression illness. Decompression sickness develops when the partial pressure of a gas over a fluid (in this case the fluids in the body) decreases, leading to a decrease in the concentration of that gas that is dissolved in solution. This phenomenon is characterized by Henry's Law, which states that for a constant temperature the quantity of gas dissolved in a liquid is proportionate to the partial pressure of that gas over (and in equilibrium with) the liquid [96]. The gas of most concern physiologically with regards to decompression injury is nitrogen. Nitrogen makes up 78% of the atmospheric gas we breath and nitrogen is highly fat-soluble. Thus, a significant portion of breathed nitrogen dissolves and is retained within the body. This nitrogen can bubble out of solution if the body is exposed to a decompression event. These nitrogen bubbles can develop in tissues and compress these tissues, causing pain (especially in joint spaces), as well as ischemia (if blood vessels are compressed). They can also develop within blood vessels and embolize, leading to infarction of tissue if they become lodged within a vessel and prevent adequate blood flow down stream of the blockage [73]. There are two main types of decompression illness, depending on what body organs are affected: 1) Type 1 Decompression Sickness, which primarily involves skin, soft tissue, and joints, resulting in joint pain and reticular rash, and 2) Type 2 Decompression Sickness, which primarily involves the central nervous system and sometimes the lungs, resulting in neurologic deficits or shortness of breath/difficulty breathing [88]. The two main risk factors for development of decompression illness are altitude attained and duration of exposure at altitude [94, 175]. However, other risk factors that have been demonstrated include advanced age [174] and obesity [174, 176], highlighting the fact that health issues in the new commercial spaceflight participant population have the potential to place them at greater risk for medical conditions from exposure to the space environment than has been seen in the highly fit individuals that have flown to space previously. The best management of decompression injury is prevention and this is done primarily through oxygen pre-breath protocols [177]. There are many various types of pre-breath protocols (and describing them all is beyond the scope of this document), but they are all geared towards helping an individual off-gas as much nitrogen as possible on the ground so that this nitrogen cannot bubble out of solution at altitude. This is done by having an individual breath 100% oxygen so as to shift the concentration gradient of nitrogen in favor of off-gassing the nitrogen [177]. Treatment for decompression illness, should it occur, involves supportive measures (including hydration), 100% oxygen administration, and hyperbaric oxygen therapy if/when available. These final two measures help to off-gas the nitrogen load by shifting the concentration gradient of nitrogen. Hyperbaric oxygen is also helpful in compressing any bubbles that have formed so that they cannot compress tissues or obstruct blood flow [71]. Again, Model X and Model Y vehicles are designed to be pressurized, but could experience a decompression, in a contingency scenario, sufficient to cause the dissolved nitrogen in tissues to bubble out of solution.

Another medical risk of concern is barotrauma and development of arterial gas emboli. With a cabin depressurization at altitude during a commercial space mission, it is possible for trapped gas in body cavities (eg. middle ear, sinuses, colon, lung, and even teeth with poor dentition) to expand in the setting of decreased barometric pressure. This can lead to pain and damage to surrounding tissues [150]. Even a small amount of gas expansion in a non-compressible body cavity can lead to sufficient pain to completely incapacitate a person. Barotrauma in the middle ear or sinuses can lead to eardrum perforation and hemotypanium or debilitating sinus pain respectively [69]. This is especially true if individuals are sick with upper respiratory symptoms and are having trouble clearing their ears or have sinus blockage. Gas expansion in the colon can be severe enough to cause bowel perforation and even abdominal compartment syndrome leading to bowel ischemia [51]. Finally, gas expansion in the lung can tear the delicate alveolar tissues and lead to the development of a pneumothorax or intravascular air penetration which can then embolize all over the body and obstruct blood flow, causing infarction in downstream tissues [39]. Treatment consists primarily of repressurization to mitigate the gas expansion [89]. If depressurization is necessary, it is recommended that this occur at a slow enough rate to allow for pressure equalization between the offending body cavity and ambient air. Treatment can also consist of decongestant use to reduce upper respiratory inflammation that can lead to blockage of sinus and Eustachian tube openings [49]. Again, barotrauma and arterial gas embolism should not be an issue for vehicles that are pressurized to a sea level-equivalent pressure. However, it may be an issue if vehicles choose to maintain a lower cabin altitude pressure, similar to commercial airline jets. It may also be an issue in the case of a rapid, contingency decompression (as in an accidental breach of the pressurized cabin), regardless of nominal cabin pressure.

Hypoxia is another potential medical risk requiring consideration. There are four main types of hypoxia (hypemic, hypoxic, histotoxic, and stagnant) [66], but one (hypoxic hypoxia) is the primary cause of hypoxia when exposed to altitude [36]. Hypoxic hypoxia occurs when the partial pressure of inhaled oxygen drops sufficiently enough to shift the equilibrium between oxygen-bound and oxygen-unbound hemoglobin toward a dissociated state [36, 66]. This usually occurs around 0.16 ATM, but can be influenced by other factors such as body temperature, blood pH, carbon dioxide levels, and the concentration of 2,3-bisphosphoglycerate [40]. The principal concern with hypoxia is that body tissues lack the oxygen they need to carry out their regular functions and can even begin to die. The most susceptible organ in the body, because of the massive amounts of energy it requires, is the brain. Because of this, common symptoms of hypoxia are often neurologic and can range from mild cognitive performance deficits to complete loss of consciousness and death by anoxic brain injury [36]. This loss of consciousness occurs more and more rapidly when exposed to lower and lower partial pressures of oxygen. This is called the Time of Useful Consciousness [66]. Even mild hypoxia can be potentially devastating, as performance decrements can lead to further problems, especially when they occur in crewmembers that have mission-impacting roles. An example of this would be if a hypoxic pilot has reaction-time deficits causing him/her to crash a spacecraft. In addition to this, mild hypoxia may result in much bigger problems if it occurs in individuals with pre-existing conditions that have the potential to act synergistically with the hypoxia to worsen symptoms. An example of this might be an individual with a history of chronic obstructive pulmonary disease that becomes dramatically hypoxic when exposed to mild altitude elevations because of his pre existing lung disease. There are many examples of disease processes that could compound the effects of hypoxia in individuals. Additionally, it is not fully understood what effect hypoxia may have on many disease processes, even processes that we believe may have nothing to do with decreased tissue oxygenation. More work must be done in this area (and other areas), as suggested below, to better understand an individual's true risk of hypoxia (or complications of hypoxia) based on their chronic medical conditions, the flight profile they intend to fly, and the probability of a medical contingency scenario. The primary treatment for hypoxia is the replacement of higher partial pressures of oxygen, either through increasing the percent oxygen in a gas mixture (up to and including the administration of 100% oxygen) or providing oxygen under increased pressure when operating at a sufficient altitude (around 40,000 feet) where even 100% oxygen is a low enough partial pressure to make an individual hypoxic [66]. The other mainstay of hypoxia treatment includes removing the individual from the hypoxic environment if/when feasible. As stated above, vehicles that maintain sea level cabin pressure will not nominally be exposed to hypoxia, but could in a contingency situation. Vehicles that maintained a reduced pressure cabin do have the potential to expose individuals to mild hypoxia during nominal operations, as well as during a contingency.

Another medical risk to consider is the effect of G-forces on individuals during their flights. Because of the flight profiles planned, participants should experience both +Gx (acceleration forces leading to relative motion of internal tissues toward the back) and +Gz (acceleration forces leading to relative motion of internal tissues longitudinally toward the feet) forces during their commercial space missions. These G-forces have the potential to reach as high as 6 Gs in the X-axis and 4 Gs in the Z-axis during the mission of certain spaceflight carriers [152]. Humans have the ability to tolerate around 15 Gs in the X-axis [60] and 4 Gs in the Z-axis [61] in a sustained way without the use of any G protection measures such as anti-G straining maneuvers or G-protection equipment like G-suits. Exposure to +Gz can be problematic because it can pull blood from the brain toward the feet and lead to brownouts or even blackouts [54, 154]. At best, this can ruin a trip for someone who has paid thousands of dollars to attend. At worst, it can lead to ischemia and permanent damage from a lack of oxygen to the brain. This outcome is an even greater concern if spaceflight participants already have underlying medical conditions, such as cerebrovascular disease and heart failure. It is important to note that with currently planned flight profiles, these problems are unlikely to develop. However, there is still a small risk, especially in the event of a contingency scenario. Fortunately, it is unlikely for passengers to experience negative G forces (especially Gz forces) during a commercial space mission, as these exposures, if severe enough, have the potential to cause hemorrhage in the brain, permanent damage, and even death [147]. +Gx exposure is more tolerable because the acceleration forces experienced are perpendicular to the hydrostatic column of blood being pumped to the brain. However, individuals can still experience issues with high enough Gx forces, which can make deep inhalation difficult, especially with underlying medical conditions such as congestive heart failure or chronic obstructive pulmonary disease, potentially leading to poor tissue ventilation [134]. The best method for mitigating issues with G-force exposure is prevention. Additionally, some companies are incorporating a component of participant training into their operations, using a long-arm centrifuge, to instruct passengers on G-straining maneuvers to prevent brain hypoperfusion, as well as to identify customers that may have a potential issue before they fly. Similarly, research is being done in this area too, selecting populations of people with specific medical conditions and exposing them to G-forces in centrifuge runs to identify which medical conditions may predispose passengers to poorer G-tolerance [45]. This will help to risk-stratify potential customers and estimate their probability of developing issues during a flight before they ever decided to commit money to a ticket. Lastly, certain protective measures, such as partially reclining vehicle seats, can be incorporated into a mission architecture to minimize the probability that an individual will have negative consequences from G-exposure. There is little that can be done for an individual if they poorly tolerate G-exposure during a flight other than to position their body to maximize blood perfusion to the brain and provide supportive measures.

There are also additional risks related to environmental exposures of which it is important to be aware. “Environmental exposures” covers a broad range of issues. Some of these (such as ebullism and hypoxia) are described above. Other exposures of concern are thermal exposures. This includes extreme cold exposures, leading to hypothermia and frostbite. The coldest temperatures are in the tropopause (around 10km) and the mesopause (around 90km) where temperatures can drop to as low as -80 to -120°F with an area of increased temperature in the stratopause around 40 to 50km [66]. All potential flight profiles for the vehicles intended to fly out of the Houston Spaceport will traverse all of these layers and thus have the potential to expose crew and passengers to these varying temperatures. Prevention of cold exposure can include building in a thermal layer to trap heat if mission architecture involves the crew and passengers to wear pressure suits. Additionally, the environmental control system of the vehicle can condition the cabin environment such that the enclosed atmosphere is of a comfortable temperature to its occupants. From a treatment standpoint, hypothermia is managed initially with supportive care, especially airway management in the event of altered mental status. Advanced Cardiac Life Support may also be needed in the event of cardiac arrest [155, 178]. Great care must be taken with these patients, including with movement and transport, as they are prone to the development of arrhythmias (including pulseless arrhythmias). Additionally, cardiac arrest in these patients has the tendency to be refractory to defibrillation because of the extremely cold body temperatures [155, 161, 165]. It is also important to note that because of the neuroprotective effects of hypothermia, patients with low core body temperature can often experience good outcomes despite prolonged resuscitative efforts [87, 99, 169, 170]. Because of these considerations, it is imperative to continue resuscitative measures in patients refractory to defibrillation until the patient is rewarmed, at which time defibrillation should be reattempted [103]. Hypothermic patients can be broken down into three categories: mild (with a range of core body temperatures from 90° to 95°F), moderate (with a range of core body temperatures from 82° to 90°F) and severe (with a range of core body temperatures less than 82°F) [86]. Hypothermia treatment includes rewarming of a patient, with various modalities for doing so utilized, each depending on the severity of hypothermia experienced. Passive external rewarming with blankets is generally sufficient for mildly hypothermic patients. Active external rewarming with heated blankets or hot air directed at the patient is often utilized for moderate hypothermia or mild cases that are refractory to passive warming [65]. Active internal warming measures, such as warmed intravenous fluid administration [111], intraperitoneal or intrapleural lavage with warmed fluids [108, 139], or extracorporeal blood warming [85, 97, 115, 146, 167, 169], can be employed for severe cases of hypothermia or cases refractory to external warming. Hypothermic patients require close monitoring following stabilization and rewarming for the development of bleeding, lactic acidosis, rhabdomyolysis, electrolyte imbalances, hypoglycemia and secondary infections, as well as hypotension which is often associated with hypothermia because of an initial central volume expansion resulting from the peripheral vasoconstriction associated with cold exposure, which leads to decreased antidiuretic hormone production (this is known as “cold diuresis”) [65, 86, 91, 103]. Because of the high complication rate of hypothermia with secondary infections (and the impacts these infections can have on rewarming), administration of empiric antibiotics in hypothermic patients is often beneficial and can be considered [70]. Frostbite occurs when tissues are exposed to below freezing temperatures and ice crystals form inside and outside tissue cells. This leads to changes in the concentrations of proteins and electrolytes responsible for maintaining the cellular osmotic gradient, causing fluid shifts and cellular damage. This can then trigger an inflammatory response which ultimately triggers the coagulation cascade, leading to microvascular infarction and further downstream tissue damage [128]. Frostbite is treated by removing the exposed tissue from the cold environment and rewarming it in a warm water immersion bath [42]. Severe frostbite can also be treated with intraarterial administration of tissue plasminogen activator if the patient presents within 24 hours of exposure and has no excessive bleeding risks, though evidence to support this treatment are limited [50, 163]. Following rewarming, frostbite should be treated with sterile wound care techniques [42]. Tetanus prophylaxis should be administered if the patient is not currently up to date on vaccinations, as this can be a potential complication [56].

Trauma is another risk of which to be aware. The most obvious example of this would be an impact with the ground, which could occur for a variety of reasons. Accidents could occur because of spatial disorientation during takeoff or landing or during complex flight maneuvers leading to incapacitation or a loss of situational awareness. Other human factors errors could occur due to poor judgment or fatigue leading to poor decision-making on the part of the crew. A hardware or software failure could occur which leads to a loss of appropriate control of the vehicle. Other examples of trauma include in-flight damage to the vehicle that have the potential to physically impact the crew. This could be the result of an explosion or loss of aerodynamic stability and structural breakup of the vehicle (as was seen on SpaceShipTwo [19]), as well as secondary to a mid-air collision which always has the potential to occur in busy airspace and on an active runway such as the one that will be utilized at Ellington Airport. Trauma could also occur during ground operations, such as an explosion of compressed inert gas or combustible products during vehicle fueling. It is also important to note that trauma could occur during nominal operations as well from trip hazards surrounding the vehicle, accidental injury during ingress or egress from the vehicle, during microgravity in a confined cabin with a relatively large number of passengers (especially novice fliers who are not used to efficient locomotion in microgravity), and many other potential hazards. Prevention of trauma mainly involves having in place a thorough concept of operations plan with checklists in place to make sure operations are carried out exactly as designed. This will reduce the risk of human factors errors, such as fatigue, poor judgment, missed critical tasks or a breakdown in situational awareness, which could all lead to a traumatic event. Part of a well-developed concept of operations is a detailed assessment of contingency scenarios and plans in place to manage a contingency should it occur. Such plans, along with redundant plans to manage a contingency should it occur will help to minimize the negative impact of a problem if it occurs during a mission, such as an unexplained hardware or software failure. A fully detailed concept of operations for each leg of a commercial space mission is beyond the scope of this document. Treatment for trauma related injuries begins with Advanced Trauma Life Support, both primary and secondary surveys [2]. Special emphasis should be placed on airway protection, as obstruction is a particularly common trauma complication [75, 100]. Bleeding is also common, and careful evaluation should be made to rule out any bleeding, especially in a patient who is hypotensive [47]. Patient's who have been stabilized require continued monitoring to ensure that abdominal or extremity compartment syndrome does not develop [74, 136], nor the development of an infection. Prophylaxis to prevent the development of thromboembolic events or stress ulcers can help reduce the rate of complications in hospitalized trauma patients [135, 157]. Lastly, it is important to note that severe traumas are emergencies that are beyond the capability of many lower acuity care facilities, and that critically ill patients should be transferred to a dedicated trauma center to ensure that appropriate care is administered in a timely fashion [133].

Fire is another potential hazard of concern. Because of the design of these commercial space vehicles, there are many flammable components, such as rocket and jet engine fuel, as well as many ignition sources, such as various electrical components that have the potential to provide a spark. Additionally, the rapid acceleration and dynamic pressure changes associated with a space mission architecture have the potential to put a great deal of stress on a vehicle and place it at even greater risk of damage, heating and potentially even fire. As described above, ground operations are also a fire risk, as these activities often involve the handling and transport of flammable materials when preparing a vehicle for a mission or when servicing a vehicle for future use. As described previously, the main preventive measure for fires and explosions from combustible materials is to have a well-developed concept of operations plan in place with well-elucidated contingency operations including redundancy measures in place for critical operations, especially critical safety operations. Treatment of burns is greatly dependent on the depth of the burn and the size of the surface area affected [38]. Minor burns are primarily treated with cooling of the tissue (with water or saline-soaked gauze) [142], dressing the wound [41], and pain control with medications [164]. If the burn penetrates the superficial layers of the skin, tetanus prophylaxis [105] and antibiotics can be considered [35]. Burns should be monitored to ensure that proper wound healing is occurring and to ensure that the burn is not extending, the tissue is not becoming infected, and that there is no tissue contracture [124]. Superficial burns can be treated in an outpatient setting without hospital admission [124]. Severe burns should be treated at an experienced burn center. The determination of transfer should be made based on the extent of the burn (typically more than 20%) or a history of either electrical burns, smoke inhalation, or trauma [1]. Severe burns are a medical emergency, so care should be initially focused on stabilization of the airway, breathing and circulation. This is especially important because smoke inhalation is often associated with burns, which can lead to laryngeal edema and airway compromise. A patient's airway should be continuously reassessed to ensure that airway obstruction has not developed [126]. Severely burned patients are at high risk of fluid loss through the wounds and can become volume depleted and experience cardiovascular collapse [78, 98]. Patient's should be aggressively hydrated/resuscitated based on one of several formulas that exist in the literature that take into account weight and percentage of the body burned [58, 148]. Finally, carbon monoxide and cyanide exposures can often be associated with burns requiring oxygen (sometimes even hyperbaric oxygen) therapy [90, 104] and hydroxocobalamin therapy [72] respectively.

Nominal operations out of the Houston Spaceport do not include water landings. Indeed, both Model X and Model Y type vehicles are anticipated to be designed for full reusability. Water landings typically preclude full reusability given the level of refurbishment that is needed when vehicle components are exposed to ocean seawater. However, given that spaceflight operations (especially the leg of operations under rocket powered flight) will be conducted out over the Gulf of Mexico, there is always the possibility of a water landing in a contingency scenario, should the vehicle malfunction and be incapable of making it back to land. In the event of a water landing, the two major concerns from a crew and passenger health perspective are cold exposure (described above) and drowning. Vehicle design to prevent ingress of water into the cabin or the wearing of pressure suits (if the decision is made to include these in the mission architecture) can help minimize water exposure, as well as the resulting cold exposure. Additionally, incorporating automatically deployed or rapidly deployable inflatable flotation devices can help to keep crew and passengers afloat without tiring them out, as well as help them minimize their exposure to cold. However, whether or not to include such flotations into the vehicle design or as part of the personal protective equipment for all crew and passengers must be analyzed from a risk/benefit standpoint during overall mission planning for commercial operations. Given the risk of a water landing in a contingency scenario, it may be beneficial to solicit the aid of the United States Coast Guard, which has a base of operations at Ellington Field, to help with search and rescue and medical evacuation capability and have them on standby for commercial space missions (this is discussed further below). Treatment for drowning centers around supportive care including and especially airway management [113].

Cardiopulmonary resuscitation (with a focus on ventilation opposed to chest compressions and circulation as is typical for other resuscitative efforts) is an important component of any drowning rescue effort where cardiac arrest has occurred [118, 151]. This highlights the tradeoff that one must consider when determining whether or not to use pressure suits as a protective measure, which will help with hypobaric exposure, but add complexity during any kind of resuscitative scenario where access to the chest and limbs may be limited [82]. Because of potential cold water exposure and hypothermia associated with drowning, resuscitative efforts related to these incidences can often last for prolonged periods of time with still positive outcomes because of the neuroprotective effects of the hypothermia (as described above) [87, 99, 169, 170]. Following resuscitation, hospital admission for monitoring is often warranted to ensure no subsequent complications such as hypoxia, cerebral vascular ischemia, cerebral edema with herniation, seizures, or electrolyte imbalances, which could potentially lead to further cardiac events. Hypothermia management has been described above.

Another potential group of hazards are toxic chemical exposures. There are many known hazardous substances related to spaceflight to which an individual could be exposed. Hazardous substances are known to be associated with vehicle propellants, with the unintended break down of the insulation for electronics and electrical wiring (leading to pyrolysis and the off-gassing of toxic byproducts), and with the off-gassing of substances associated with various payloads (especially biologic payloads) [106]. The last of these may seem as though it would not be a major issue for commercial spaceflight operations functioning out of the Houston Spaceport. However, it is important to note that companies like Virgin Galactic and XCor Aerospace are interested in incorporating science payloads into their suborbital flights in addition to space tourists as part of their business model. Examples of potential exposures based on previous experiences include tissue fixatives from payload experiments [106], battery components such as thionyl chloride [106], corrosion of metals such as cadmium [143], formaldehyde, benzene and carbon monoxide from fire [53], and nitrogen dioxide from breakdown of nitrogen tetroxide used as an oxidizer in vehicle thrusters [131]. It is important to recognize that these examples are put forth for informational purposes only to provide a flavor for what could occur. The exact chemicals and other toxic substances to which an individual might be exposed at the Houston Spaceport is unclear at this time, as the specifics of vehicle design and payload architecture are not yet established. It is also important to be aware that substances brought on board by crew and passengers have the potential to off-gas substances, which could then affect those on board the flight. These exposures would most likely be minimal given the short duration of the flight and especially of microgravity exposure. However, they are still worthy to note, as people with asthma, COPD or other reactive airway diseases may need only a small exposure in order to trigger a respiratory distress event. It may be worth considering the implementation of restrictions on appropriate attire and personal items allowed on board a flight, so as to avoid these issues. Included in hazards potentially surreptitiously brought on board by crew and passengers are microbial exposures. Because there will most likely be no quarantine or sterilization programs prior to commercial spaceflights, there is the potential for exposures related to biologics brought on board as well as toxic byproducts off-gassed by these microbes [106]. Also, because of the relatively large number of individuals in such close quarters, any infectious processes brought on board by sick individuals (even quiescently infected carriers) have the potential to be spread to others. Though not a contingency event, another exposure to bear in mind is that of carbon dioxide. A large number of individuals in confined spaces (especially with elevated levels of anxiety leading to hyperventilation) has the potential to create a buildup of carbon dioxide, which can lead to headaches, tachycardia, tachypnea, dyspnea, elevated blood pressure, impaired cognitive function, convulsions, loss of consciousness, and even death [110]. Adequate carbon dioxide ventilation or removal must be incorporated into any vehicle design. The mainstay of preventing exposures during the length of a flight are to implement restrictions so that crew and passengers are unable to bring potentially hazardous materials into the cabin environment, as well as to ensure a sound vehicle design to minimize the risk of damage to the vehicle and to ensure toxic substances from the vehicle or payloads have no access to the cabin. Monitoring for specific substances during flight might be worthwhile and could provide potential abort criteria to help reduce risk of a prolonged exposure to those on board a flight. However, this may have minimal value once a vehicle has entered the rocket powered phase of flight, as there may be no easy way to abort a mission at this point and a vehicle may have no choice but to proceed through the entirety of its flight profile. It may therefore be more beneficial to have available personal protective equipment, such as respirator masks, in the event that a potential exposure is identified. Treatment of any exposure will depend on the specific chemical to which an individual is exposed. Coordinating care with the Poison Control Hotline will ensure best practices are implemented. Often, the main treatment modality for toxic exposures is supportive care. The two most likely exposure routes during a commercial spaceflight would be inhalation and skin/eye exposure, though it is possible for ingestion to occur as well. For inhalation exposures, early intubation is often beneficial for protection of the airway in patients that may have oropharyngeal or tracheal inflammation, pulmonary edema, or decreased level of consciousness. Fluids and vasopressive agents can be used in the event of hemodynamic compromise, and Advanced Cardiac Life Support is the primary response modality for cardiac arrhythmias. Benzodiazepines are often beneficial for agitation or seizures [37]. Enhanced elimination may be helpful, in the form of activated charcoal [30], urine alkalinization [84, 141], or hemodialysis [83], depending on the exposure and whether or not it has been shown to be responsive to any of these measures. If antidotes for an exposure are available, these treatments should be considered as early as possible (again this should be done in coordination with Poison Control whenever possible) [114]. For chemical burn exposures, all extra chemical should be removed from the burn site as quickly as possible (especially dry chemical which can be brushed off). Remaining chemicals can be removed by irrigating the burn site with a large amount of water (except for certain chemicals such as lime, phenol and certain metals, which are negatively impacted by water irrigation) [107]. Once the offending substance is removed, chemical burns are then treated in much the manner of thermal burns (as described above). NASA has developed a database of Spacecraft Maximum Allowable Concentrations (SMACs) for a number of hazardous chemicals [18]. These SMACs were developed in coordination with the National Academies of Science, Engineering, and Medicine and reference known physiologically tolerable doses, but incorporate other known physiologic changes associated with spaceflight that have the potential to impact and modify these toxic limits. Examples of these include the lowering of SMACs for ototoxic substances given the noise environment of spaceflight, lowering of SMACs that affect bone marrow and blood cell production because of the risk of radiation exposure, and the lowering of SMACs related to arrhythmogenic agents because of the propensity of individuals to develop cardiac arrhythmias at a higher rate during spaceflight [18]. Given the fact that commercial spaceflight operations will incorporate individuals with disease processes that have never been exposed to the space environment before, it may be prudent to develop new SMACs for commercial spaceflight based on relevant chemical exposure risks, as well as physiologic changes that are associated with common chronic diseases. Chronic diseases were not considered when developing previous SMACs but would be high yield when flying space tourists with chronic medical conditions. These SMAC values could then be incorporated into the Commercial Spaceflight Concept of Operations for the Houston Spaceport.

Finally, a hazard to consider is exposure to the local surrounding area flora and fauna. This can include exposures such as a contact dermatitis or airway hypersensitivity reactions from various plant allergens, trauma from abrasive plant-life or animal bites, and pathophysiologic reactions to venomous animal exposures. A good ground-based, pre-launch brief on potential environmental hazards, specific to the area of operations, will help to prevent these exposures. Treatment is varied and will depend on what specific exposure was sustained.

Additionally, there may be other potential medical events, depending on the pre-existing medical and/or psychosocial conditions of the pilots and crew on board a particular flight, that are of sufficient risk that they merit further proactive risk mitigation strategies as well. Examples of such risks could include flash pulmonary edema and respiratory failure with fluid shifts during microgravity in a patient with congestive heart failure or watershed cerebrovascular infarct secondary to hypoperfusion during positive Gz exposure in a patient with underlying atherosclerotic cardiovascular disease. In addition, claustrophobia, agoraphobia, and other anxiety spectrum disorders could manifest (potentially for the first time) during the high-stress environment of spaceflight. Such events could not only be disruptive to the individual and to other passengers, potentially ruining the experience of all, but could also place the vehicle in danger by disrupting the focus of the pilots from flying the spacecraft. These are just a few examples of underlying conditions that could pose a potential medical risk during flight. However, with the intentionally limited medical restrictions so far adopted by the Federal Aviation Administration for commercial spaceflight participants, as well as the broad age range of ticket holders already planning to fly on suborbital space tourism flights, there will inevitably be a wide variety of medical pathology exposed to the unique environment of spaceflight. We are only now beginning to evaluate the effects of this environment on various medical conditions, and much more work will need to be done in the future to fully characterize the boundaries of acceptable risk related to various disease processes when operating in the space environment. Work in this area could be aided a great deal by the development of a space medicine database, which would serve to store human health and performance, as well as vehicle and flight profile telemetry data for all commercial and governmental spaceflights. This data could then be “mined” for the purposes of better understanding the risk to participants of exposure to various aspects of spaceflight depending on the flight profile planned and an individual's preexisting medical conditions. It is important to note, however, that the merits of a comprehensive database management system for the storage and systematic evaluation of space medical data are beyond the scope of this document. It is mentioned here only for the sake of completion and to emphasize the fact that in order to better understand the full breadth of medical risk associated with future flights at the Houston Spaceport, further work must be done in order to qualify and quantify individual risk in addition to general mission risk.

Medical Prevention and Contingency Protocols – Given the above described medical risks, there are specific medical protocols that would be beneficial to have in place for any commercial space operations, both for prevention and in case of a contingency scenario. The most important protocol to consider from a prevention standpoint is an oxygen pre-breath protocol to protect against the development of decompression illness [43, 44]. Whether or not to implement a pre-breath protocol and what pre-breath protocol to use will depend on the nature of the flight profile and the degree of pressurization of the vehicle. An example pre-breath protocol is shown in **Figure 4.4**. The main protocol to implement from a contingency standpoint is a protocol for management of potential altitude exposure and ebullism. This is because the neurologic symptoms of neuro-decompression injury, ebullism, and cerebrovascular gas embolism can be similar. However, arterial gas embolism and decompression sickness are both treated with hyperbaric oxygen, whereas past research has demonstrated worse outcomes following exposure to vacuum and the development of ebullism when treated with hyperbaric oxygen [129]. Additionally, because ebullism causes an acute respiratory distress syndrome-like picture with capillary leak and pulmonary edema, methods of ventilation that minimizes further barotrauma from large tidal volumes should be utilized, such as high frequency percussion ventilation. Because of these issues, an ebullism treatment protocol should attempt to differentiate between these various disease processes, so as to determine whether or not hyperbaric oxygen is appropriate, as well as to determine whether or not to use high frequency percussive ventilation as a lung protective modality of airway protection, oxygenation, and ventilation [129]. An example ebullism treatment protocol is presented in **Figure 4.5**. It is also worthy to note that any commercial space mission where crewmembers or participants are wearing pressure garments will require the development of an extraction protocol. This is because pressure suits will make the administration of medical care in an emergency scenario difficult because of the limited access to the body caused by the suit itself [82]. This will not be an issue for flight operations where crew and passengers are in a "shirt sleeve" environment. Thus, as was discussed previously, the use of pressure suits for flight operations creates a risk tradeoff by decreasing the risk of hypoxia and ebullism, but reduced mobility for ground evacuation and limiting chest and extremity access for ACLS [43, 44]. Medical operations requiring a suit extraction protocol will need to be individualized based on the type of suit being used, as each suit has different specifications with different access points that will need to be catered to [82]. All the remaining high-risk medical conditions require only standard emergency medical care, so do not require the development of special protocols and procedures in this document other than the protocols that are already in place for Advanced Cardiac Life Support and Advanced Trauma Life Support put out by the American Heart Association and the American College of Surgeons respectively [2, 79].

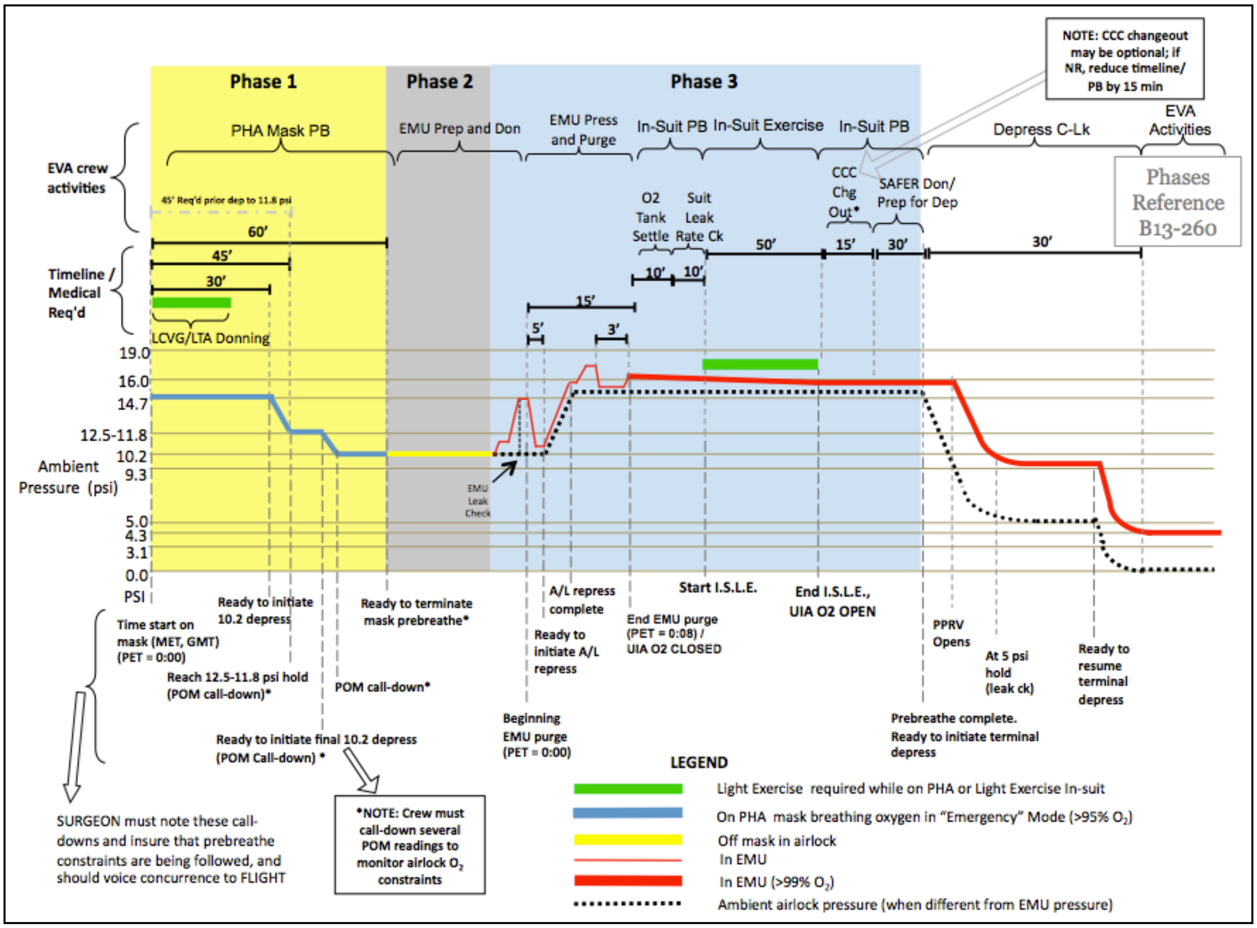


Figure 4.4: Example in-suit oxygen prebreathe protocol for the management of decompression injury risk during pressure-suited operations on the International Space Station. Republished from the NASA Johnson Space Center Flight Operations Division (public domain, permission not needed).

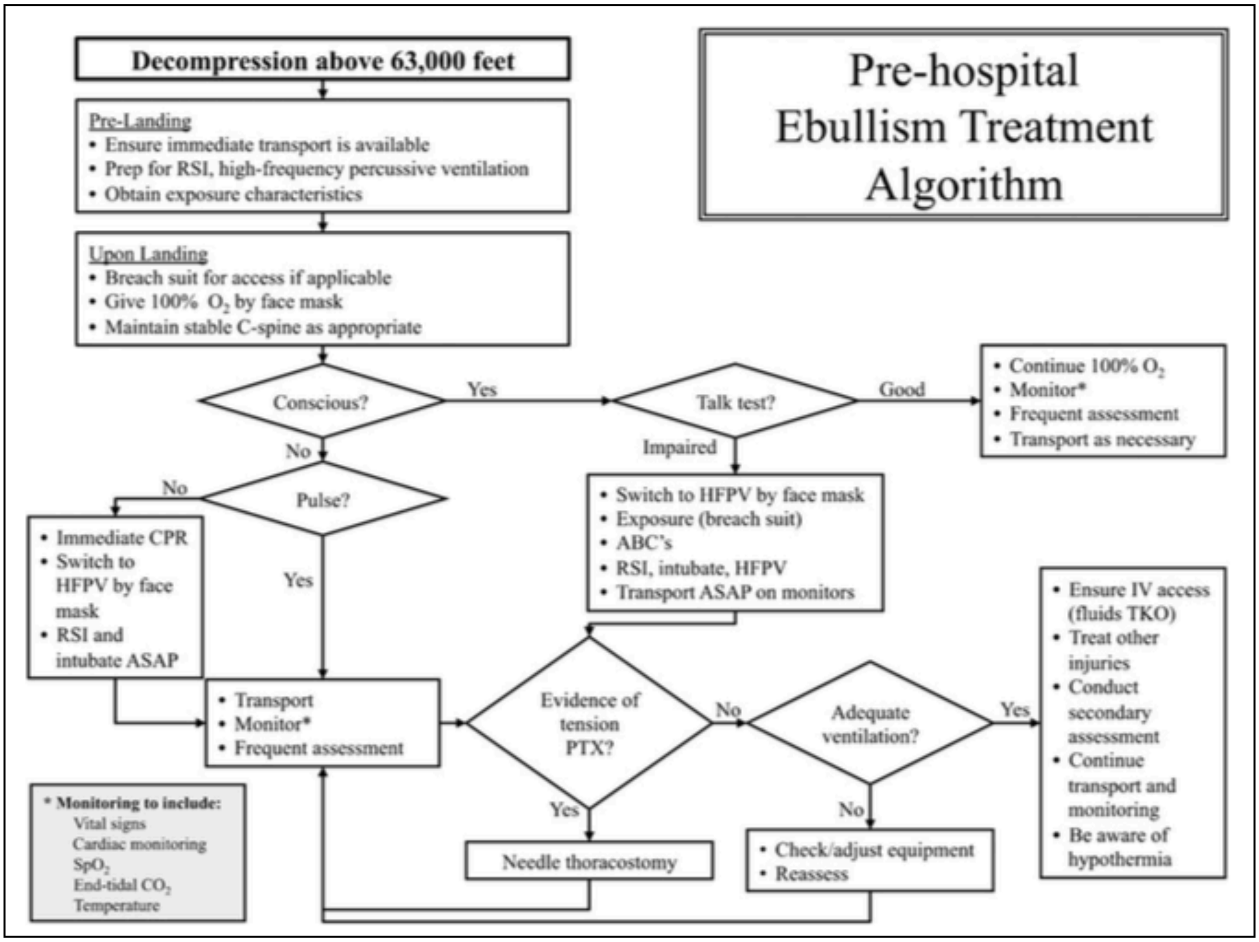


Figure 4.5: Example protocol for the pre-hospital management of a high altitude decompression event where injury has occurred and the development of ebullism is suspected (Reproduced with permission from the Aerospace Medical Association, [129]).

Medical Team Makeup – When developing a medical team for commercial space operations, it is first and foremost important to consider incorporating a multi-disciplinary group of both medical and non-medical personnel into a medical response team. The reason for this is because when dealing with medical contingencies in a complicated environment such as space, there are multiple variables that need to be addressed other than simply the practice of medicine. Complicated equipment, such as pressure suit and vehicle design, are a part of mission operations as well, and it is valuable to have experts in these areas incorporated into any medical response team. For example, in the event of cardiac arrest within a pressure suit, it is necessary to remove that individual from his or her suit because of the limited access medical practitioners have to administer care while the patient is inside. It is neither easy nor intuitive to rapidly remove an individual from a pressure suit to provide medical care and it is helpful to have a suit expert as part of the medical team in order to aid in expediting suit doffing. Studies have shown that this type of multi-disciplinary approach to a medical response in unique and extreme environments leads to better team dynamics and ultimately better outcomes [81, 123]. From the perspective of medical personnel, it is unclear the ideal training level required for the medical response team. It has been shown by some studies that much of the medical care provided for mass-gathering events is for minor injuries and that it may be unnecessary to require physician-level providers as part of medical response team during commercial spaceflight operations [121, 162, 179]. However, it is worthy to note that other studies have demonstrated that employing doctors on a medical response team improves costs, reduces hospital burden, improves the efficiency of the response to a catastrophe, increases patient care approval, and improves the image of the program from a public relations perspective [34, 119, 162]. Regardless of what level providers are involved, an appropriately sized medical response team appears to be around four people [81, 123]. This four-person team would include at least two medical personnel with potentially one or two specialized, non-medical personnel depending on the architecture of the spaceflight mission (eg. having a suit expert if crew and/or passengers are wearing pressure suits). A team of four can be appropriately fast and efficient during a response, but is still large enough to cover all of the major roles needed to administer effective Advanced Cardiac

Life Support or Advanced Trauma Life Support. Non-medical personnel can help with the less complicated aspects of cardiopulmonary resuscitation, such as chest compressions, while the medical personnel are responsible for more complex tasks such as line placement and drug administration [81, 123]. Once teams are established, it is important to incorporate adequate training exercises into all major spaceflight operations in order for the team to familiarize themselves with each other and become comfortable with their respective emergency response roles and procedures [81, 123]. Finally, in addition to the field medical team just described, any medical operations team should have a medical director associated who is a physician with aerospace medicine experience. It is that individual's role to sit in "command center" during spaceflight missions and make operational decisions to ensure the health of the crew and participants during their flight. He or she will coordinate these decisions with the field medical support team and they will help with implementation [43, 44, 112].

Medical Supplies and Area Medical Resources – Given the above potential medical risks, a list of the appropriate medical equipment to have available for commercial space missions can be seen in Appendix C. The purpose of having available the listed equipment is to be able to cover a broad array of medical conditions. The bulk of the medical kit is made up of the resources necessary to manage minor injuries and illnesses, as studies have shown that these make up the majority of medical presentations during mass-gathering events [34, 119, 121, 137, 153, 156, 162, 166, 172, 179]. Though minor issues are the main rationale for seeking medical attention at such events, it is nevertheless essential to have resources and personnel available to manage a major medical event should it occur. Thus, it is important to have the resources necessary to appropriately administer Advanced Life Support care, as well as Disaster Response Medicine (including medical responders appropriately trained in these areas to carry out the necessary medical [34, 149, 166, 172]). Given this, equipment and medications to conduct Advanced Cardiac Life Support and Advanced Trauma Life Support are also listed in the medical kit. This includes equipment for intubation and ventilation (including lung-protecting, high-frequency percussive ventilation), and medical grade oxygen sufficient to bridge to medical evacuation. Lastly, because operations may be conducted in remote locations (or could end up in remote locations in a contingency scenario), it is beneficial to have additional equipment in the medical kit that is geared towards responding to medical concerns more commonly experienced in the wilderness setting, such as traumas, lack of food, water, and shelter, exposure to the elements (including extreme heat and cold), communication and location devices, and exposure to area flora and fauna (especially bites). A perfect example of a scenario where this would be relevant is the potential for missions out of the Houston Spaceport to end up in the Gulf of Mexico or in unpopulated areas along the coast in the event that a catastrophic disaster were to take place. Though it is important to have access, either at the Spaceport directly or in the surrounding area, to a chamber for hyperbaric treatment in the event of a decompression injury or barotrauma, it may also be prudent to have portable equipment (such as the SOS Hyperlite 1™ portable hyperbaric chamber) to administer hyperbaric treatments in the field. Such a capability will be contingent upon available resources.

In addition to the above described equipment, it might be beneficial to have on-site, spaceport medical facilities for the management of medical issues should they occur. With mass-gathering events, there is always the possibility for spectators to become injured or ill, not just those participating in the event. Family and friends of the commercial spaceflight participants who have come to observe the mission may end up needing care, perhaps more so than the crew or passengers of the mission. Having a clinic on-site to provide basic care for these individuals and to appropriately triage them to a higher-level care, if needed, would be of great benefit to manage the medical risks surrounding the spaceport and its activities. This clinic would also prove useful as an occupational health clinic to care for spaceport workers who may develop medical issues as a result of exposures they may receive on the job. A spaceport clinic could include a hyperbaric treatment facility so that individuals exposed to altitude can be rapidly treated without delay. Beyond the medical capabilities located at the spaceport, it is also important to have a wider network of identified and available capabilities for definitive, higher-level care if needed. A list of the relevant facilities surrounding Ellington Field and the Houston Spaceport is provided in Appendices A and B. Important capabilities to have available are area Emergency Medical Services teams for medical evacuation and transport, short distance, easy access emergency facilities for lower acuity emergency care (of note, it is important to have several lower acuity facilities on standby during a mission in case there is a mass-casualty event that has the potential to overwhelm the resources of any one facility), and access to higher acuity facilities that have specific capabilities to manage particular medical emergencies, such as burns, Level 1 trauma, neuro-trauma, and hyperbarics for altitude exposures and decompression injuries. It is worthy to note that these higher acuity facilities may not be quickly or easily accessible from Ellington Field, depending on what specific capability is required, because of their location, which is mostly in the Texas Medical Center. Because of this, it may be prudent to have available for missions air medical transport for more rapid evacuation to the Medical Center for specialized care. This has the added benefit of providing capability to support an off nominal water (from the Gulf) or remote area rescue and medical evacuation in the event that a disaster occurs during the middle of a mission when the vehicle is away from the spaceport and there is no other rapid recovery available. Petroleum Helicopters International (PHI) has a medical helicopter support arm that can provide medical evacuation services for the Southeast Texas area. Their contact information is again listed in Appendix A. Additionally, the United States Coast Guard has a base of operation at Ellington Field and may be able to provide air medical support services for mission operations as well. Ellington Field also has a fire department on site, and this is an important capability to have during mission operations. It may be valuable to consider having additional fire response facilities on standby to help in the event that a fire hazard occurs, which overwhelms the Ellington Fire Department, or if a particular disaster occurs, which renders the Ellington Fire Department inoperable (eg. a vehicle impact with the Fire Department itself). Additional Fire Response assets are listed below.

Medical Reconnaissance/Geographical Constraints to Care – Relatively easy access to areas of spaceport operations is essential for emergency medical providers in case there is a medical event and field medical treatment is needed on site, as well as in the event that escalation of field medical care is prudent and therefore, transportation to a tertiary care facility is needed. Current plans call for the spaceport to be built so that it abuts Runway 4/22 with the main access to the spaceport campus coming via a northwest access point off of Space Center Boulevard. This may ultimately be the only entrance, however, there is also talk of another access point with the addition of another connector road to Highway 3 [14, 15]. This redundancy would be beneficial to have. The way the spaceport is currently laid out, there will be three different North-South corridors (running longitudinally along the spaceport) and three different East-West corridors (running perpendicular to the North-South corridors), creating a grid-like pattern (see **Figure 2.4** for an overview on the current spaceport design) [14, 15]. This is noteworthy, because there will be limited access between the flight line and any potential on-site medical treatment facility, which will have the potential to slow emergency response times. It may be beneficial to consider incorporating a direct access to the flight line from one of the access roads (either Space Center Boulevard or Highway 3) to expedite a medical response and evacuation if necessary. It is also important to remember to build in direct access points to the flight line from the spaceport corridors (not solely access via company hangers) so that an on-site medical team can efficiently respond to a contingency. It is important to note that these are only considerations based on the current outline of the spaceport layout. These medical reconnaissance considerations should be subject to change based on any layout changes that occur in the future, once companies begin to sign on to be a part of the spaceport system and once construction begins. Further considerations can also be elaborated upon once it is better understood what capabilities will be available at the spaceport (such as the presence of potential hazards such as compressed gas, flammables, and toxic materials) and where they will be located.

Emergency Response Communication Plans – Appropriate and coordinated communication amongst all parties involved is an essential component to a fully developed and well-executed medical response infrastructure.

Communications begin, first and foremost, with effective communication among members of the core medical response team. As described above, the optimal core medical response team is a team of four individuals, which is designed specifically to carry out the functions of Advanced Cardiac Life Support and Advanced Trauma Life Support if needed [82, 123]. The team format and individual roles were described in more detail previously. In order to achieve effective communication within this team, it is the responsibility of the team leader to coordinate all communication efforts. The team leader is in charge of directing all resuscitative efforts, and this is his only responsibility with regards to executing life support protocols. All medical team members take their orders from the team leader and do not act in any way not expressly indicated by the team leader [82, 123]. The team will operate utilizing standardized Voice Procedure techniques [28], including the utilization of a closed loop communication system, such as the Pilot-Controller Communication Loop, to minimize communication errors, as well as minimizing non-essential chatter during emergency procedures. A color-coded notification system can be used in order to clearly communicate whether operations are functioning nominally or off-nominally. These color codes can represent different potential contingency scenarios and can have built-in, preplanned actions associated with each one so that all parties involved are synchronized with regards to how to respond. These codes can also be effectively and efficiently communicated to non-medical operators so that everyone involved with mission operations has sound situational awareness regarding what is happening with the flight. The coding system should be memorized by team members, but can also be printed on reference cards to ensure it isn't forgotten when needed. A similar coding scheme was utilized with great success during the Paragon StratEx High Altitude Bailout and Freefall Test Program (**see Figure 4.6**, [82, 123]). Communication between different operational teams (eg. between the medical response team and flight operations, etc.) should be controlled and restricted to one point of contact within each team so as to prevent multiple open lines of communication and the resulting potential for mixed messaging. Communication may flow freely within a team. However, when communicating to other teams, such chatter should be consolidated and flow out of one designated point person as a single, unified message. Experienced radio operators can be incorporated into each team and be responsible for conducting appropriate messaging across teams to ensure good communication [145]. Lastly, an important component of proper communication includes communication with the vehicle (and its contents) pre-, during-, and post-flight. This ensures good situational awareness on what is happening with the vehicle for all operational teams, and enables rapid response in the event that a contingency scenario was to occur. At the very least, such data from the vehicle should include GPS (to be able to track location, altitude, heading, and velocity) and 2-way audio communication (to be able to discuss what is happening with the crew and ensure they are okay). Audio communication is especially important as it can serve as an additional "vital sign" for the medical team, as an appropriately communicating individual can be assumed to have an adequate blood pressure, a (relatively) stable heart rhythm, a protected airway, and (relatively) adequate oxygenation [81]. If possible, additional telemetry data from the vehicle for improved situational awareness could include video data from the cabin and physiologic data from the crew and passengers, including pulse oximetry, 2-lead EKG (including heart rate), respirations, accelerations, and core body temperature. This would give you added situational awareness on the state of the crew during launch operations, as well as valuable data to piece together causal factors related to a mishap in the event of a crash [82, 159]. Though the specifics of a robust vehicle to ground communications system are beyond the scope of this proposal, communication with the vehicle is an essential component of any good medical support plan, and the infrastructure to do so must be built in to any mission operations architecture. Because of the extreme altitudes achieved during suborbital spaceflight, there is a concern that a breakdown in communication with the vehicle could occur. To combat against this, radio frequency boosters could be built into the vehicle to ensure that communications signals will be capable of reaching the ground when the vehicle is at apogee (or capable of relaying with a satellite if appropriate). Likewise, repeaters could be deployed on strategically spaced hilltops between the spaceport and the flight operations airspace in the Gulf of Mexico to ensure that any communications signals have good line of sight between the vehicle and the spaceport’s mission control. Fortunately, the area surrounding Houston is relatively flat, making the deployment of a communications infrastructure more straightforward [43, 44, 123].

Color	Definition	Leadership	Actions
Green	Nominal Extraction	Suit Engineers	Protect Suit and Pilot
Yellow	Minor Injury	Physician	Prioritize Pilot, Minimize Suit Damage
Orange	Spinal Concern	Physician	Immobilize as possible, Pre-notify Trauma/HBO centers, PHI Transfer
Red	Severe Injury	Physician	Field Stabilization, Pre-notify Trauma/HBO Centers, PHI Transfer

Figure 4.6: Example of a color-coded medical communication plan. The color codes for various nominal and off-nominal situations are listed on the left. The column to the right of the code column is what scenario the code stands for. The next two columns describe who is in charge in the event of each of the different codes and what actions must be taken. (Reproduced with permission from ADE Aerospace, LLC, [82, 123].

Medical Documentation – Lastly, an important aspect of both medical care and medical legal considerations is the appropriate documentation of all medical care performed. Such a medical report should include a history of the medical event being addressed as it unfolded, an appropriate physical examination of the patient, a differential diagnosis based on the above information, a well thought out action plan based on likely and/or serious potential diagnoses under consideration from the differential, and appropriate updates and addendums to the report based on the evolving condition of the patient, refinements to the differential based on new, incoming data, what treatments were administered to the patient and what effect (if any, good or bad) these treatments had on the status of the patient, and what tests had been performed on the patient and what the results showed. **See Figure 4.7** for an example template for appropriate medical documentation [101]. This documentation serves as a record for when care is transferred from one medical practitioner to another, so that the new practitioner(s) know what care was provided so as not to repeat any actions unnecessarily, as well as to ensure appropriate follow up on pending actions that were previously executed. At the end of an event, medical documents can also serve as a record for a “lessons learned” debrief. The medical record also serves as documentation for legal purposes of what care was given, and the process by which the decision was made to provide that care which was provided. For this reason, it is also important to document when care was refused by a patient. With current technologies, medical records can be implemented in either a paper or a hard copy paper form. An electronic medical record is the ideal form for documenting medical care because of the many advantages it offers. However, it is unlikely that commercial spaceports will have the resources to devote to the development of such a system, at least initially, so the more likely format for documentation will be paper records. That being said, if a particular company (commercial space or otherwise), organization, or spaceport decided to move forward with the implementation of an electronic space medicine and physiology database management system (more on this in Chapter 5), a logic extension of this endeavor would be the development of an electronic medical record. This medical record could be used at each of the different spaceport locations and all data could then feed into the database management system for storage and data mining to answer research and operational questions. Regardless of the format by which medical data is stored, considerations will need to be made to ensure that the data is stored properly in a secure location with limited access in compliance with Health Insurance

Portability and Accountability Act regulations. For an electronic medical record, this means proper password protection of the software and encrypted transmission of the data. For paper documentation, this means storage of all hard copies in appropriately locked facilities with access to those facilities limited to appropriately designated individuals [27].

Encounter Form

Patient Identification	Treatment Category	Arrival Time:	Date:
Name: Age: Phone:	□ Emergent □ Urgent □ Non-Urgent	Current Meds:	

Time	Temp	HR	BP	RR	PO2

Allergies:

PMH:

PSH:

FHx:

Social Hx: □ EtOH □ Tobacco

Chief Complaint:

HPI:

Check if applicable:

□ Allergic rxn	□ Heat
□ AMS	□ Intoxication
□ BG check	□ Seizure
□ Chest pain	□ SOB
□ Head injury	□ ST injury

Physical Exam:

Last Tetanus:

□ Monitor
□ EKG
□ Continuous PO2
□ IV

BG (Initial):
BG (Second):

Progress Note / Plan:

Disposition: □ Time: ____________
□ Back to Show □ Home
□ Transport to: ____________
□ Unit:

Condition: (on D/C) □ Fair □ Stable □ Critical □ Improved □ AMA

Discharge Instructions:

Provider Name:

Provider Signature: □ MD □ DO □ NP □ PA □ RN □ EMT/PM

(TURN OVER)

Figure 4.7: Example layout of a medical encounter form for medical documentation. (Reproduced with permission from the Section of Aerospace Medicine, Department of Preventive Medicine and Community Health, University of Texas Medical Branch, [101].

Evaluation Plan –

Because this document describes the initial design and development of a medical response architecture for suborbital spaceflight at the Houston Spaceport, the medical plan will need to go through several more revisions prior to implementation, which will probably not happen for several more years. As such, the most appropriate category of evaluation for this phase of the program would be a formative evaluation, and more specifically the component of formative evaluation focused on the quality of a program's content. To do this, the CDC's Framework for Program Evaluation [12] will be utilized. The primary focus of initial evaluations will be on the first 3 steps of the CDC's framework, "Engaging Stakeholders", "Describing the Program", and "Focusing the Evaluation Design". Because this is a new program being developed by individuals outside of the Houston Airport and Houston Spaceport Systems, it will be important to have ongoing discussions with key players within these systems to ensure that their needs are understood and that they understand the program and that the program meets these needs. This will most likely take several months and will result in further iterations to the medical support program design. The initial formative evaluation will most likely be qualitative in nature. The data collected could include focus groups, surveys, interviews, and reviews by panels of experts in the area of medical support for extreme environments, disasters, and mass casualty events. Such data would evaluate the quality of the program with regards to whether or not the program achieves the goals laid out beforehand (in this case, advancing commercial spaceflight, protecting spaceflight participants, and identifying knowledge gaps to improve space safety), whether or not the goals of the program are in line with the priorities of the important stakeholders, whether or not the program is evidence-based and is founded on data that supports the efficacy of such a program, and whether or not the Houston Spaceport has the resources to implement the plan as it has been laid out.

From there, especially as the Houston Spaceport moves closer to actual flights and a finalized medical support plan is implemented, the remaining steps in the CDC's framework can be executed to collect and interpret data on the appropriateness and effectiveness of this program. This can be done with an initial pilot program, potentially with testing of the system, utilizing drills and mock-emergencies to evaluate the protocols that are in place. This can then be followed by role-out of a "full-up", "live" program, once corrections are made based on lessons learned from the pilot program. While it would be nice to develop quantitative measures from the initial qualitative data collected during the pilot phase of program implementation, as has been described by Steckler and colleagues in 1992 [158] with their "Model 1", it will most likely be very difficult to collect quantitative data for this program, as such data, like pretest-posttest and time series study designs involving an experimental group and a control group, will be too logistically difficult, the number of subjects will be too small to reach any kind of statistical conclusions, and it would most likely be infeasible to carry out the study in an ethical way. Thus, the continued evaluation of the program will be carried out in much the same way as the initial formative evaluation, by collecting qualitative data utilizing focus groups, surveys, interviews, and expert review panels. However, now this will be done with a "live", implemented program, so the data will be more valuable, as there will be actual lessons learned from implementing the program, as opposed to dealing only with a hypothetical program. Because it will be difficult to collect data on the efficacy of the program on saving lives, the data will still be focused on whether or not the program is successfully fulfilling the needs of the important priority groups. The one exception to this would be in the event of an actual catastrophe, where the medical response plan is executed for real. This real-world scenario will most assuredly identify gaps in the program not otherwise seen and provide data and lessons learned on the efficacy of the program that could then be used to improve upon the plan for the future.

Chapter 5: Discussion

Elon Musk has been quoted saying that “there is a strong humanitarian argument for making life multi-planetary…in order to safeguard the existence of humanity in the event that something catastrophic were to happen” [31]. Over the history of life on the planet Earth, there have been five known mass extinctions that have occurred [5]. It is arguably inevitable that given enough time, another event will occur on Earth that has the potential to lead to the extinction of the human race. Examples of potential mass extinction level events that could occur include a nuclear holocaust, climate change leading to food shortages, pandemic spread of infection (especially viral infections), or a large asteroid impact. Though admittedly speculation, most estimates place the probability of another mass extinction event that would eliminate the human race to be somewhere between 10% and 30% [120]. The only guaranteed insurance against a mass extinction event is to extend the habitat of the human race beyond Earth. Thus, it is essential to not only continue to explore our solar system with manned flights, but to develop a permanent presence beyond our planet. This must be looked at as an existential necessity on par with curing disease and poverty. Eliminating disease and poverty will improve our civilization now, but space exploration has the potential to continue to improve and secure our civilization for the future.

Just as NASA’s human space program is the face of the agency and helps to keep the general public engaged in space travel and interested in NASA’s missions, so too can space tourism excite the public and act as the face of commercial spaceflight, keeping people interested and invested and propelling the industry forward. However, the commercial spaceflight industry, especially space tourism, is still in its relative infancy and as such, is still fragile and vulnerable to consumer confidence swings. Catastrophic events within the industry, especially coupled with injuries or even death, can shake the confidence of customers and investors and make them skeptical of the value of commercial spaceflight as an industry. This scenario is not hypothetical. In October of 2014, just such an event occurred during a test flight of Virgin Galactic's SpaceShipTwo by Scaled Composites when a catastrophic break up of the vehicle lead to the death of the co-pilot and serious injury of the pilot [19]. While this event did not lead to the complete collapse of the commercial spaceflight industry, it did create concern amongst ticket holders, requests for refunds, and may have contributed to a stall in Virgin Galactic's progress toward flights for paying customers [48]. Spaceflight is inherently dangerous and will remain so, at least until technology progresses beyond the routine use of chemical propulsion as the mainstay for providing access to Low Earth Orbit. Mishaps are going to continue to occur. The only way to minimize the damage of these mishaps, especially to human life, is to have a sound medical response plan in place to execute if needed. This also has the added benefit of helping to ensure consumers' confidence, which as already stated, is so important in the commercial spaceflight industry. A strong, well thought out infrastructure, including a sound medical response protocol, will help ensure stability and confidence in the commercial space market so that it continues to grow and prosper, providing the inspiration by which our civilization can become multi-planetary.

Expected Outcomes, Strengths and Limitations –

This document provides an initial architecture for a medical response plan to address potential catastrophic contingency scenarios that could occur during commercial spaceflight operations at the Houston Spaceport. The benefit of this plan is that it outlines the known risks associated with spaceflight, and specifically the expected flight profiles to be executed at the Houston Spaceport. It identifies, through a comprehensive literature search, the necessary infrastructure components that have been proven effective for successful medical response to a catastrophic contingency scenario during commercial spaceflight operations and/or a potential mass casualty event. Specifically this literature search addressed appropriate area medical response resources (eg. local EMS and Fire Departments), identifying appropriate local tertiary care facilities, identifying geographical constraints to delivering field care if needed and transport to definitive care when necessary, defining the appropriate medical team makeup and structure, indentifying the major medical risks associated with planned spaceport activities, developing the necessary medical response protocols for potential medical events of high risk, identifying and organizing the necessary medical facilities, equipment and supplies to have available on site during mission operations, developing the plans for appropriate communication during a medical response, and identifying the necessary resources for appropriately documenting any medical care that may be administered. Finally, it concretely identifies the assets surrounding the Houston Spaceport that could be deployed and utilized for a medical contingency event specific to one of its flights.

It is important to note, however, that this plan is not, nor does it aspire to be, comprehensive. There are too many unknowns currently, within the industry, within the spaceport itself, and within the field of aerospace medicine and our understanding of the effects of the space environment on human physiology and more specifically human pathophysiology, that need to be addressed in order to make this plan complete. It is unclear, currently, what level of medical restrictions should be placed on potential passengers who want to fly to space. The Federal Aviation Administration (FAA) has to balance making sure the industry is safe with avoiding the urge to overregulate the industry in a way that could potentially stifle growth [132]. Additionally, it is unclear whose responsibility medical support for commercial space operations should be. Should the onus be placed on the spaceports or the commercial spaceflight companies themselves. It is unclear who is going to pay for medical operations when the industry is currently limited and money is tight. In such an environment, there can be pressure to cut corners in order to save money by relying on local EMS to provide a medical response instead of having a well-developed plan ahead of time. The suborbital flight plan for the Houston Spaceport is itself still evolving and not fully detailed. As such, it will remain unclear what final medical infrastructure will be needed until such time when the details of flight operations are finalized and an assessment can be made as to what medical response will be needed given the final mission architecture. Lastly, the field of space medicine is continuing to evolve and has the potential to do so at an even greater rate moving forward with the advent of commercial spaceflight and space tourism because of the shift in philosophy from one of “engineering out” any potential medical risks for space missions by selecting astronauts without any (or at least limited) medical problems to a philosophy of “anyone who can pay for a flight should have the opportunity to go”. This shift in mindset raises new and interesting questions regarding what degree of human fitness is required for human spaceflight and how well individuals with chronic disease will cope in the space environment. These questions remain unanswered and research is needed in this area in order to better clarify the appropriate medical infrastructure to have in place when flying space missions involving individuals with chronic medical conditions.

However despite these unknowns, this document can serve as a framework upon which to build over time as further space medicine research is performed, as the legal aspects of suborbital flights out of the Houston Spaceport are addressed, as the spaceport moves towards detailing their plans for future flights, and as they ultimately executing those flights. With regards to better understanding the effects of the flight environment on human physiology and disease, future research directions that would be of high yield could include: 1) the development of a comprehensive space medicine and physiology research facility, and 2) the development of a space medicine focused database management system for simultaneous storage and mining of medical and operational data associated with spaceflight. These recommendations are elaborated upon below.

Sustainability Plan –

Sustainability is not an issue of particular concern at this time. Though it is important to begin early when developing such things, a medical response infrastructure for the Houston Spaceport is not immediately necessary, as the spaceport is still in its beginning stages and is still many years away from having the commercial space company lease partners or the launch infrastructure for suborbital flights, not to mention having the legal authority to do so. That being said, authorities at the Houston Spaceport are taking the necessary actions to ensure sustainability of a sound medical response plan. They are already planning to incorporate this document into their spaceport “concept of operations” documents. There is little fear that medical operations will not be a sustained component of spaceport operations, given how tightly space tourism is tied to the “appearance of safety” and the high public relations pressures to do so. Additionally, there may ultimately be FAA regulations requiring a certain degree of medical response planning and infrastructure before clearing the spaceport for flight, although currently the FAA has limited such regulations in an effort to avoid stifling growth until the industry has secured a foothold and is more stable [132].

A bigger concern than sustainability for spaceport medical operations is the need to maintain a level of clinical and operational currency for medical contingency events that are unlikely to happen with a high frequency. Thus, regular practice sessions and mock contingency scenarios will be needed in order to make sure the medical response plan is understood by all responsible parties and that the response plan can be implemented in a smooth and coordinated fashion. Another concern, given the remaining unknowns described above regarding the effects of spaceflight on disease, is a need to have a mechanism in place to continuously evaluate the current state of the art in medical care for spaceflight and mass casualty events and update the medical response plan accordingly so that it remains current and optimized.

Recommendations –

Over the course of the last 50 years, the United States, through NASA, has collected a large body of good physiologic data on both short and long duration spaceflight. While this data goes a long way toward filling in gaps in our understanding of the acute, sub-acute, and chronic effects of spaceflight on the human body, it is important to note, (as has been stated previously) this data has been collected on the astronaut corps, which is selected, in part, based on their favorable health and fitness. Thus to date, little work has been done to evaluate the effect of spaceflight on various disease processes. This data, too, will be necessary to fully characterize human health and performance in the space environment and to better understand what, from a medical operations perspective, is needed to support commercial spaceflight. This will be initially limited to suborbital flights. However, as the industry progresses, there will be a growing need to better understand the effects of longer and longer missions to further and further destinations, as industry leaders push towards increasingly ambitious missions. There may even come a point when we will need data in areas we never before anticipated, such as the effects of spaceflight on pregnancy or children. Fortunately, we are entering into a new age of commercial spaceflight where we will have the opportunity to begin to answer these questions because of the shift in those who will be flying to space from a population of highly fit astronauts to one of generally older individuals with pre-existing chronic medical conditions. Because commercial spaceflight is still in its early phases, there is a unique opportunity to establish cutting edge tools to rapidly expand our understanding of space physiology and do so in a way that is seamlessly integrated with the commercial spaceflight industry.

One such tool is a space medicine and space physiology database management system. This database could be developed in a similar way to already existing cancer data and tissue repositories that house data and are able to be quarried and mined to answer clinically relevant questions. This database could be developed now and the infrastructure could be in place with sufficient time to capture all commercial spaceflight data, even from the very first customer. A space medicine database management system could be used to marry the data from both NASA's short and long duration missions with the forthcoming data from the commercial sector to start to clarify the picture of what happens to the human body, with and without disease, during the acute, sub-acute and chronic phases of spaceflight.

It may be that commercial space companies will be hesitant to collect human health and performance data. First off, they may be hesitant to have this type of "permanent record" if and when things go wrong. A similar situation has been observed with the collection of physiological data in professional motor sports (personal correspondence with Jed Drake, 2014). Teams are nervous about the potential for that data to be used against them. Additionally, there may be a concern that some of the data collected and shared could provide insight for competing companies into proprietary aspects of a company's flight hardware or launch profile. There is also some concern over who is going to house such an endeavor. Commercial space companies are somewhat distrustful of government agencies, so whomever houses the database will need to be a non-governmental entity, as well as an entity that cannot be interpreted as another potential competitor. An academic institution is one such entity that has been proposed as a potential home for a space medicine database because of its non-profit and non-governmental status. Lastly, there may be a lack of desire by some companies to compel their customers to participate in scientific data collection. Space tourists are paying customers and are not purchasing suborbital flights in order to participate in research. They are purchasing flights for their own enjoyment and don't want to sacrifice that enjoyment en lieu of data collection. Additionally, some of these paying customers may be high net worth individuals that are in high-level positions in wealthy companies where shareholder prices could fluctuate if the medical data for these individuals made it into the public domain.

However, despite these hesitations, there might be a viable pathway forward to collect the necessary data for a space medicine database. There is an obvious benefit to commercial spaceflight companies for collecting, compiling, and analyzing this type of data. Medical data on the tolerance of individuals with different disease processes to short duration suborbital space missions will help to better characterize future risk of experiencing problems during flight for potential customers. This can be used to better inform customers of their risks during the informed consent process (to date, this process is riddled with unknowns and it is difficult to estimate any level of probability that an individual will experience medical or human performance issues during their mission). This also has the potential to clarify what diseases are (and what diseases are not) of concern with respect to suborbital space missions, which in turn allows companies to streamline their medical testing prior to flight and focus their medical infrastructure for flight operations, cutting out anything that is deemed unnecessary and thus saving time and money. As for the willingness of space tourists to lend their medical data to a space medicine database, experience so far suggests that most customers would be willing to participate. People who care about space enough to purchase a flight tend to be altruistic about advancing spaceflight and are, for the most part, more than willing to help in any way they can to support such a cause.

Data for a space medicine database could include preflight demographic data, physical exam data, past medical history including chronic medical conditions, medications, physiologic data collected (such as pulse oximetry, heart rate, EKG, respiratory rate, and core body temperature) and flight data (such as velocity, acceleration, altitude, vehicle pressure, ambient temperature, radiation exposure, and video data from the flight). The database could initially be set up as a relational database where output files are linked based on a particular person or vehicle flight. These files could be quarried by using particular search criteria to narrow parameters to data of interest based on a particular question that needs answering. From there, the functionality of the database could be expanded by incorporating data reading software for viewing raw data streams. This would allow the visualization of all (or a selected subset of) data streams simultaneously by time-stamping data streams and syncing them so that researchers can compare what is happening in different data streams over the course of a flight. Eventually, “smart algorithms” could be incorporated into the database to interpret different patterns within data streams automatically. For example, algorithms could be used to find premature ventricular contractions or runs of ventricular tachycardia in different EKG recordings. Algorithms could be used to find different physiologic abnormalities associated with different flight parameters, such as hypoxic episodes during the microgravity phase of flight, or with accelerations greater than 3Gx. It could be possible to search based on these calculated parameters as well. For example, it could be possible to search for all episodes of ventricular tachycardia for a particular vehicle or flight profile if you wanted to evaluate what risk factors place a patient at increased likelihood of having an event during a flight. A database of this design would allow investigators to quarry what will ultimately be a massive data set to answer clinically and operationally relevant questions as they arise with the advancement of commercial spaceflight. Answers to these operational questions can then be published in the peer-reviewed literature for others to see and learn from in an effort to advance the field of space medicine forward and develop a better understanding of human health and performance in space.

Another promising area of development that has the potential to advance the field of space medicine forward and contribute to refining the parameters of appropriate medical support during commercial spaceflight is the development of a dedicated space medicine and space physiology research facility. Such a facility could be designed akin to a core research facility at a university, where a single entity (in the case of a core research facility, this entity is the university) maintains and operates the facility for the shared use of the technologies within the facility by any interested investigator who has an affiliation with that entity. The overhead costs for core facilities are paid mainly by the entity which houses the facility, such that the cost to use the technology within the core facility is dramatically subsidized for the investigators who use it. This enables investigators to incorporate cutting edge technologies into their research investigations by collectively sharing the use of the technologies that would otherwise be impossible if their own individual laboratories were responsible for purchasing the equipment on their own. With a subsidized space medicine and space physiology facility in place, it then raises the possibility of recruiting quality and impactful research scientists from varying disciplines to help contribute to the investigation of space medicine related research questions.

A space medicine core research facility would house equipment specific for the simulation and study of the space environment. Such equipment could include a thermal vacuum chamber (equipped with mixed gas titration capability) for evaluation of hypoxia, hypobaria, decompression injury, and thermal loads, a hyperbaric chamber for evaluation of oxygen toxicity and decompression injury, a long arm centrifuge for evaluation of acceleration and vibrations, and drop testing and sled testing systems for evaluation of acceleration and deceleration. Ideally, a core facility would be designed with research in mind and would include an animal facility in order to conduct basic science animal research and would have animal rated equipment, as well as protocols in place for cleaning and maintenance of equipment after animal use. The facility should have “wet bench” space for carrying out research, the infrastructure needed for tissue sample collection and storage, multiple different imaging modalities including both computed tomography and magnetic resonance imaging, and a full surgical suite for cadaveric and animal survival surgery. These capabilities should be designed such that they are seamlessly integrated with the above outlined spaceflight test bed equipment so that research can be implemented with the introduction of minimal artifact. This would allow the conduct of space medicine research, bridging basic science with operational research, with a level of rigor that has never been attempted before, on par with other well-respected basic science research fields like cancer research or genetics. This facility can then be integrated with other analog environments and commercial spaceflight testbeds, such as the Aquarius Underwater Laboratory, the Hawaii Space Exploration Analog and Simulation Research Facility, NASA's Human Exploration Research Analog, SpaceX's DragonLab, and suborbital research flights. This enables investigators to rapidly advance new spaceflight technologies or research experiments from low Technology and Countermeasure Readiness Levels to high Readiness Levels that are ready for integration into the flight environment.

Lastly, in addition to an overall improvement in understanding of the effects of spaceflight on human physiology and pathophysiology, requiring new research tools such as a comprehensive space medicine database management system and a space medicine core research facility, there are other risks unique to the Houston Spaceport that must be evaluated before commercial spaceflights can be implemented because of its proximity to populated areas. This is different from other spaceports like Spaceport America, which are in the middle of deserted and unpopulated areas. As stated previously, this provides the Houston Spaceport with some advantages. Remote locations, like the Jornada del Muerto desert basin for Spaceport America, create logistical issues with medical support because of a lack of nearby tertiary care facilities that are less of an issue for the Houston Spaceport because of the variety of resources and tertiary care facilities in the area surrounding Ellington Field. Additionally, the ease of access to Houston and the Houston Spaceport, makes this locale a much more attractive destination for space tourism than more remote locations and makes suborbital point to point transport much more economical. However, the proximity of the Houston Spaceport to populated, residential areas also creates additional risks that need to be evaluated. Studies must be done to look at hazards such as potential noise pollution, vibrational damage to surrounding structures, toxic exposures to gas pollutants and other noxious stimuli, as well as environmental hazards related to the construction that will be carried out in order to reinforce the current infrastructure at the airfield so that it can tolerate and adequately support space flights. Risk analyses of these various risks are planned for the near future and will be required prior to implementation of any development efforts at the Houston Spaceport and before any approval is granted to carry out commercial space flights [14, 15]. In addition, similar to what has been described in this document, a large part of the risk analysis to surrounding bystanders will be evaluation of the risk of bystander injury associated with catastrophic contingencies during spaceflight operations and whether or not there is an appropriate medical infrastructure in place to mitigate and minimize the negative consequences associated with in-flight emergencies affecting the lay-public. All of these questions will need to be resolved before a fully detailed medical response plan can be implemented for the Houston Spaceport, and will be needed to ensure that the commercial space industry is robust and has the best possible chance to thrive, grow, and be successful.

Appendix A: Medical Facility Telephone Numbers [101]

Fire Chief, Ellington Field TXANG, MSgt Chris Hopkins	281-929-2695
EMS Contacts	
Clear Lake EMC (Chief Roy Hunter)	281-488-3078
Friendswood EMS (Chief Camp)	281-554-1200
Memorial Hermann Life Flight Dispatch	713-704-3590
MH Life Flight Contact – Eric Van Wenckstern	713-704-2788
Texas Guard – Texas Medical Brigade	
LTC James Hays	832-721-5505
MAJ Robert Taylor	713-858-4942
HAM Radio Operators Group	
George Levandoski	832-723-4760
PHI Air Medical Dispatch	877-435-9744
Houston Area Medical Dispatch	713-884-3143
Houston Police Airport Division	713-845-6800
Memorial Hermann Emergency Department	713-704-4060
Ben Taub Emergency Department	713-873-2658/2675/2644
UTMB Emergency Department	409-772-9505
Clear Lake Medical Center Emergency Department	281-338-3708
Memorial Hermann SE Contact Emergency Department	281-929-6282
CHRISTUS St. John Hospital Emergency Department	281-333-8822
Harris County Homeland Security and Emergency Management	713-881-3300
Clear Lake Red Cross Disaster Response – Brady Warner	409-766-0039
Harris County Department of Public Health	713-439-6000

Appendix B: List of Regional Medical Facilities [101]

<u>Level I Trauma Centers</u>

Ben Taub General Hospital (19.1 miles)
1504 Taub Loop
Houston, TX 77030
Emergency Department 713-873-2658 or 2675 (Nurse Manager -2644)

Memorial Hermann-Texas Medical Center (20.3 miles)
6411 Fannin
Houston, Texas 77030
Emergency Department 713-704-4060

University of Texas Medical Branch (36.8 miles)
Galveston, TX 77550
Emergency Department 409-772-1521

<u>Primary Hospitals with Emergency Medical Care Capability</u>

Memorial Hermann Southeast Hospital (3.8 miles)
11800 Astoria Blvd.
Houston, Texas 77089
Emergency Department 281-484-5888

Clear Lake Regional Medical Center (5.8 miles)
500 Medical Center Blvd
Webster, TX 77598
Emergency Department 281-338-3708

Bay Area Regional Medical Center (6 miles)
200 Blossom St
Webster, TX 77598
Emergency Department 281-525-7000

Methodist St John Hospital-Nassau Bay (8.4 miles)
18300 Saint John Dr,
Houston, TX 77058
Emergency Department 281-333-8822

<u>Alternate Facilities with Emergency Medical Care Capability</u>

Neighbors Emergency Center (free-standing) (5 miles)
7215 Fairmont Pkwy
Pasadena, TX 77505
281-487-0339

Emergicare (free-standing) (5 miles)
2409 Falcon Pass, Suite 100

Houston, TX 77062
281-461-1111

First Choice ER (free-standing) (8 miles)
3016 Marina Bay Drive
League City, TX 77573
281-549-9400

St Joseph Hospital (16.0 miles)
1401 St Joseph Pkwy
Houston, TX 77002
Emergency Department 713-757-7557

St. Luke's Episcopal Hospital (19.3 miles)
6720 Bertner Ave.
Houston, TX 77030
Emergency Department 832-355-2121

San Jacinto Methodist Hospital (23.7 miles)
4401 Garth Road
Baytown, Texas 77521
Emergency Department 281-420-8888

<u>Pediatric Emergency Medical Care</u>
Texas Children's Hospital: Texas Medical Center (19.4 miles)
6621 Fannin St # Fc330.01
Houston, TX 77030
Emergency Department 832-824-5454

<u>Burn Care</u>
Memorial Hermann Burn Center (20.3 miles)
6411 Fannin St., Houston, TX 77030
(713) 704-4350

UTMB – Galveston
301 University Blvd., Galveston, TX 77554
(409) 772-2023

<u>Hyperbarics Facilities</u>
Hermann Center for Hyperbaric Oxygen (24.5 miles)
Texas Medical Center
6411 Fannin
Houston, TX 77030
Chamber Contact (713) 704-4268

Bayou City Wound Healing Center (26.2 miles)

4200 Portsmouth
Houston, TX 77027
Chamber Contact (713) 960-7999

Memorial Hermann Southeast Wound Care Center (7.8 miles)
11800 Astoria Blvd., Wing 1-A
Houston, TX 77089
Chamber Contact (281) 929-6494

Columbia Rosewood Medical Center Hyperbaric Medicine (31.8 miles)
9200 Westheimer
Houston, TX 77063
Chamber Contact (713) 260-6764

NASA Neutral Buoyancy Laboratory (0.1 miles)
13000 Space Center Boulevard
Houston, TX 77058
Chamber Contact (713) 483-6735

Select Specialty Hospital (28.4 miles)
1917 Ashland Street
Houston, TX 77008
Chamber Contact (713) 802-8270

Spring Branch Medical Center (33.1 miles)
8850 Long Point
Houston, TX 77055
Chamber Contact (713) 722-3387

Memorial Hermann Wound Care Southwest (33.2 miles)
Medical Plaza 1 First Floor
7600 Beechnut St
Houston, TX 77074
Chamber Contact (713) 456-6100

Gulf Pointe Specialty Hospital Wound Care (22.3 miles)
610 East Loop
Houston, TX 77087
Chamber Contact (713) 640-2400

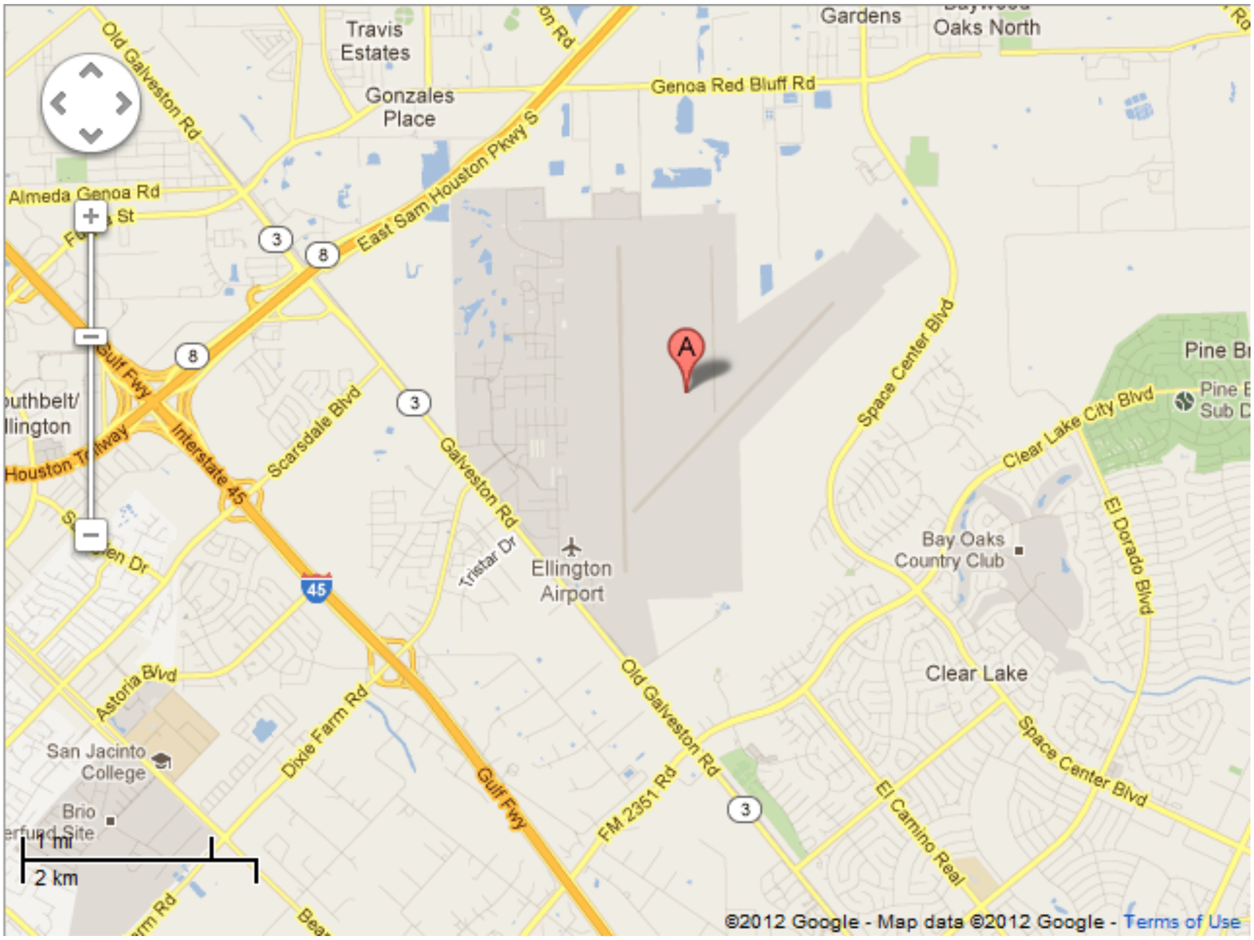
Appendix C: Sample Medical Equipment List

	Base Kit	Trauma Add on	Medical Add On	Airway/IV	Rx	
Small	Bandaids x10	kerlex x2	Bendaryl 25mg x2	CPR mask		
	Ibuprofen 200 x25	ace wrap2", 4"				
	Acetaminophen 500 x25	gauze sterile x10	Gatorade powder			
	1" silk tape	Alcohol wipes x 10	Plastic bag			
	Sunblock & lip balm		Water bottle/protein bar			
	3 pairs gloves/hand sanitizerx1		Flashlight/leatherman			
	Epipen					
	Glucose bar/drink					
	Notepad/sharpie/forms					
Medium	Box of Gloves	Band aids x20	Ibuprofen 200 x50	NPA 24 28F	Ondansetron ODT 15 pills	
BACKPACK	Stethoscope	Olaes/Israeli/Quickclot x3	Acetaminophen 500 x50	Lube x2	Ondansetron IV	
x4	BP Cuff	ACE Wrap, 2"x2, 4"x2	Hydrocortisone cream 1% 1 tube	Suction	Tylenol #3 x20	midazolam 2ml jan 2015
	Thermometer	Sterile 4x4 sterile gauze x20	Diphenhydramine 25mg x8 PO	ett HOLDER x1	Loperamide x10mg x10	midazolam 10ml aug 2014
	Pen light	abd pads x3	Loratadine 10mg x10	Nasal cannula x1	Phenergan 25mgx4	coban?
	Trauma shears	Kerlix x3	Pseudoephedrine 60mg x10	NRBx1	Morphine IV/IM 20mg smallest vial	Benadryl (exp: 112014)
	Tweezers	Xerform 1" x5, 4"x2	ASA 81mg x 50	O2 tank + tool x regulator	Dexamethasone 4mg IV x3	Eye wash (exP 052016)
	PulseOX	Tourniquet x2	Calamine lotion 1 tube	ETT Tubes 7.5 x2	Prednisone 20mg x8 PO	xeroform, small (exp: 062014)
	Notepad/sharpie/forms	Dermabond x2		ETT Tubes 6.0 x1	Narcan 0.4mg x2	xeroform, large (exp: 042015)
	tongue depressorsx5	Steri strip x5 1/8" x 1 pack	Glucometer + strips	DL / MAC4 Miller 4	Atropine 1mg/10ml luerjet x2	Burn sheet (exp: 032018)
	hand sanitizerx1	60cc leur syringe + igloo		BVM x1	Epi 1:10000 1mg/10ml Luerjet x2	CO2 Monitors (exp: 032016)
	Alcohol wipes x 20	Biomed wash (wash spray bottle)		OPA x8 sizes	Lidocaine 2% 100mg/5ml Luerjet x2	lidocaine, 10mL (exp: 082914)
	Ice pack/Hot pack			EzIO	Calcium Cl 1g/10ml Luerjet x2	dexamethasone IV (exp: 092014)
	Epipen x2	scalpels 11x2		500cc NSx2	Amiodarone 150mg/3ml vial x4	atropine (exp: 112014)
	Eye glasses (PPE)	Lidocaine 1% w/o 30cc x1 vial		18/20/22G x2, IV start kit x2, IV tubing	Magnesium 1g/2ml vial x4	narcan (exp: 062015)
	Margicel	10 cc syringe x5		Chlorhex sticks x2	Bicarb leurjet x2	epi (exp: 112014)
	1" silktape x2, 3" silk	18G, 22G needles x4		Sharps container x1	Adenosine 6mg x3	lido leur (exp: 042015)
	Glucose bar/drink	SAM splint x2	Water purification tabs	biohazard/waste bags x1		ca cl (exp: 062015)
	Mylar sheet	finger splints x2	heavy duty gloves	Bougies		bicarb (exp: 0315)
		rat teeth pickups, scissors	**smoke/flare**	Cric kit (10 blade, gauze, hook, skin spreader, cric attachment)	Diltiazem 20mg vial x2	amio (exp: 072014)
		Needle driver, hemostat x1	Headlamp	**etco2 color change**	Diltiazem PO 30mg	mag (exp: 11/14)
		Sutures - x2 3-0 prolene, x2 4-0 prolene, 5-0 prolene, 5-0/4-0 fast absorbing	batteries	D50 luerjet x2	Etomidate 40mg x2vial	adenosine (exp: 12/14)
		10G PTX cath + valve x2	ear plugs	Benadryl 50mg IV	Succ 200mg x2	etomidate (exp: 09/14)
		C-collar	sunscreen		Ketamine 500mg x1vial	roc (exp: 12/14)
		tegaderms	bug spray	Gam Sterile Burn sheet	Rocuronium100+mg x1vial	succ (exp: 05/14)
		Eye patchx1	sunglasses	Albuterol MDI x1 w/spacer	Versed 10mg/2ml x2	dilt (exp: 06/14)
		tetracaine	emesis bags		Versed 10mg/10ml vial x2	zofran ODT 4/2016
		Bacitracin/neosporin x1 tube	USB charger		Fentanyl 0.05mg/ml 2ml vial x10	
Large	**Medium PLUS:**			**Special Materials:**		Things still need:
	Backboard					laryngoscope batteries (x2 C-batteries for each)
	NS 1L x3			Black light		pill boxes (small)
	IV Start Kits			Panoptic x1		sharpies
	IV tubing kits			***Bird Ventilator***		pens
	IV Pressure Bag x2			LOX		
	More Gauze			satellite phone		
	More Kerlix			Defibrillator + Pads x2		
	More ACE Wrap			**Air-Ground Radios**		
	More Olaes/Israeli					
	More tape					
	xeroform					
	Staplers x1					
	Abd pads					

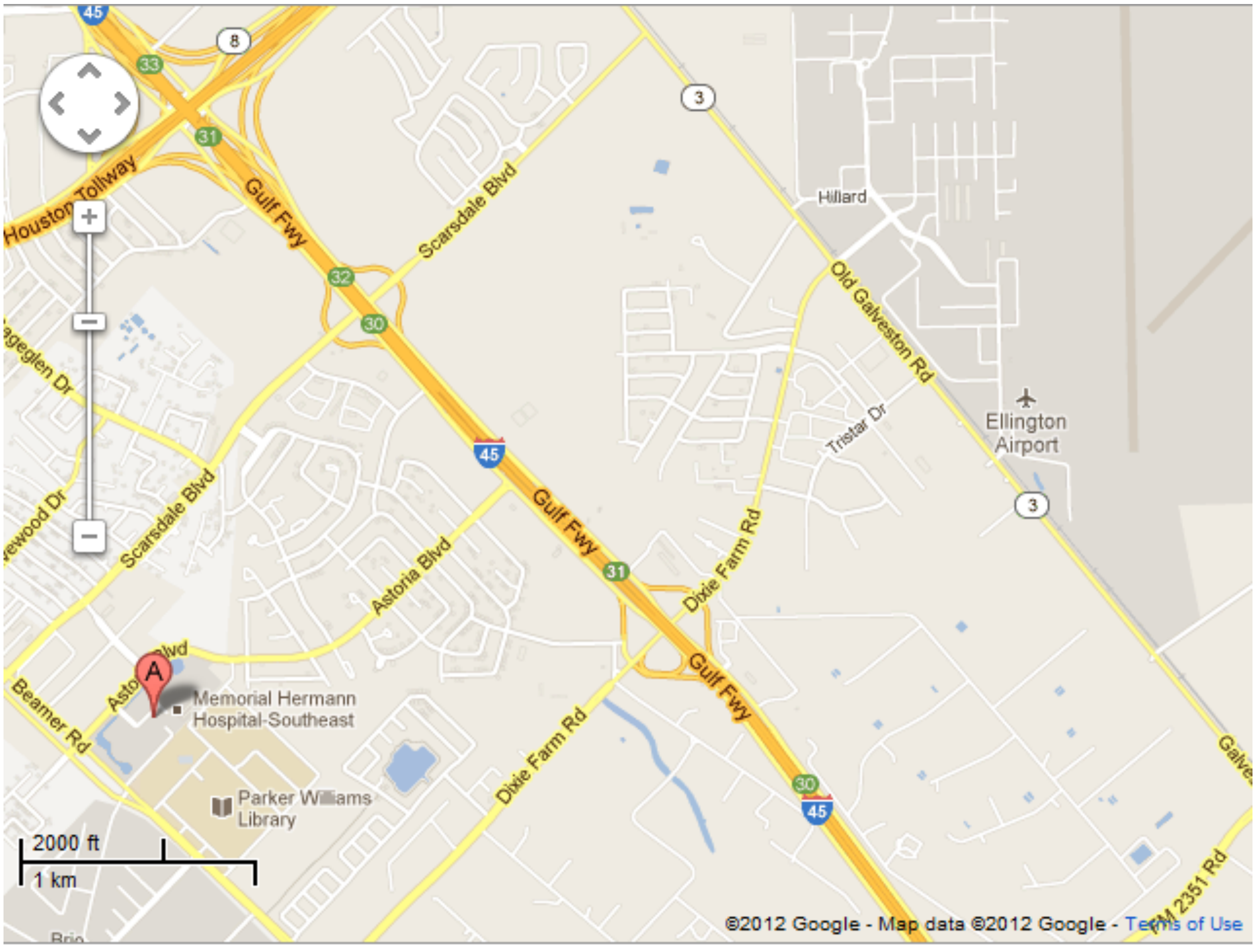
Clinic Supplies	Stethoscope	Pelican cases & organization boxes	Question:
	Blood pressure cuff	duct tape and trash bags	BVM valve
	Thermometer	work gloves	Backboard scoop
	Ophthalmoscope/otoscope	snacks	Suction splint
	box gloves x2	crate of water	LMA?
	Book derm, bites, toxins	gatorade powder	Shears x2
	UPTx2	Mosquito spray	
Analgesics		Big hand sanitizer	
	Acetaminophen	Big sunscreen	
	Aspirin	Ear plug box	
	Ibuprofen	Blanket	RADIOS ORDERED NOV 5
Antihistamines		Cot x2	
	Diphenhydramine	Nalgene x4	
	Loratadine		
Cold remedies			
	Pseudoephedrine		
	Dextromethorphan/guaifenesin		
	Cough drops		
GI	Peptobismol		
	Loperamide		
	Tums		
	Meclizine 25mg x100tabs		
Skin			
	Hydrocortisone 1%		
	Triple antibiotic ointment		
	Sunblock		
Basic wound care			
	Bandaids		
	Bandages		
	Gauze		
	Arm sling		
	Wrist splint		
	Ankle splint		
Eye			
	Fluorescein		
	Tetradoxine		
	Cipro drops		

Appendix D: Ellington Field Map

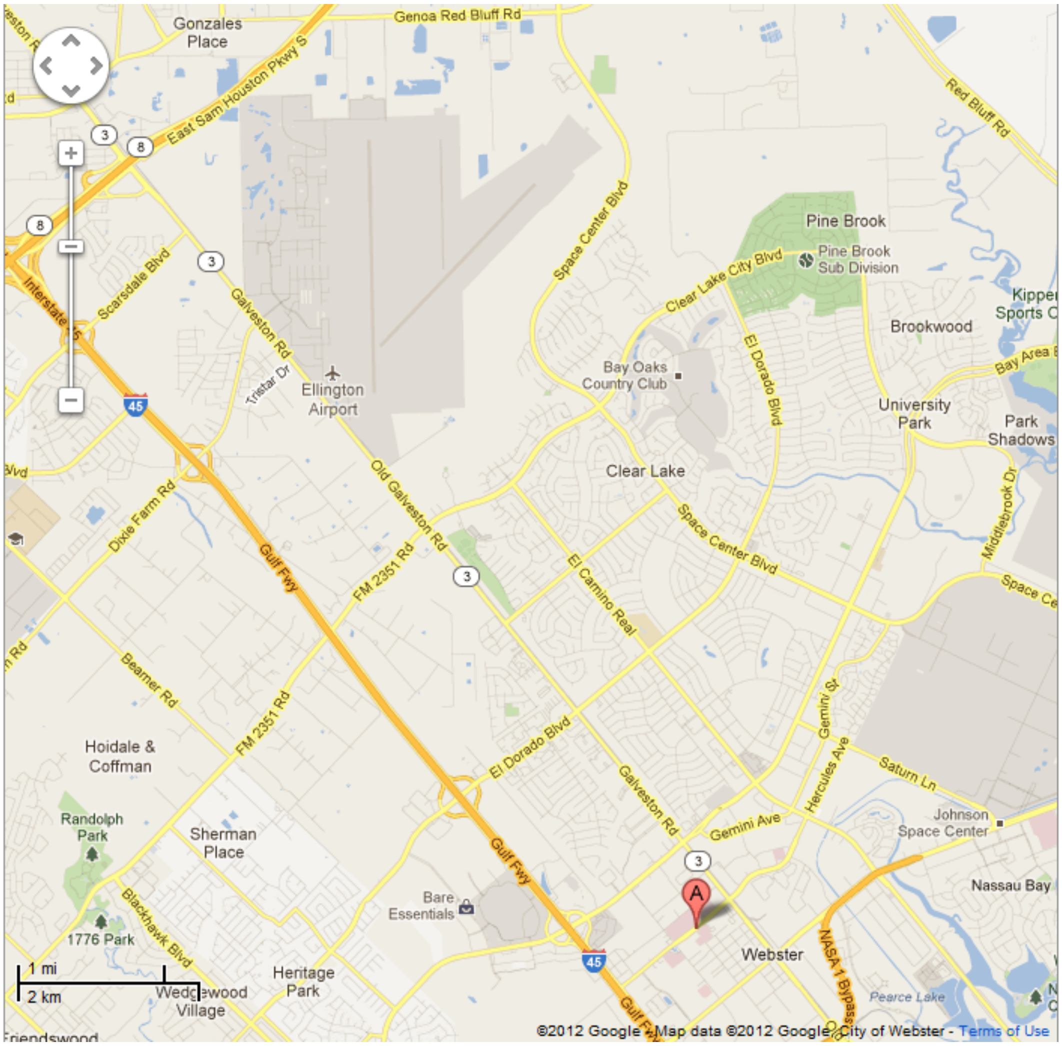
Appendix E: Local Area Map

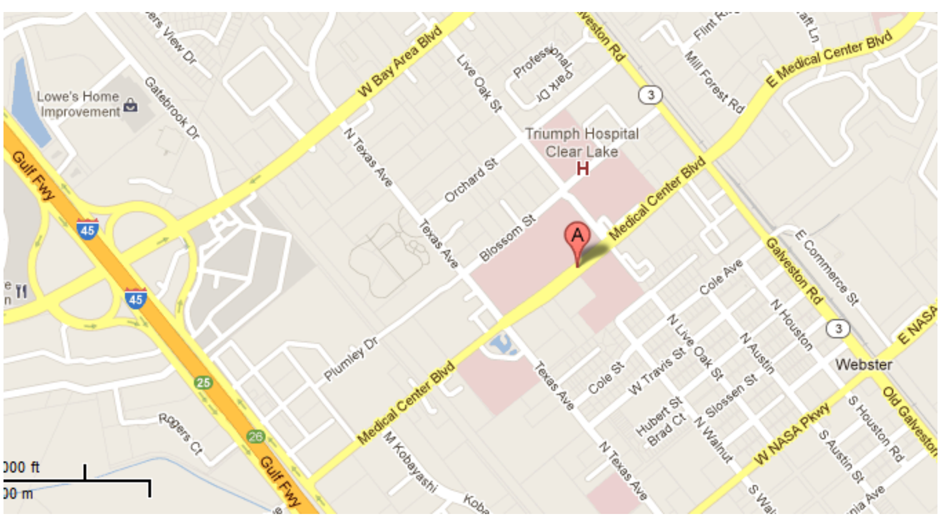


Appendix F: Map of Memorial Hermann Southeast Hospital

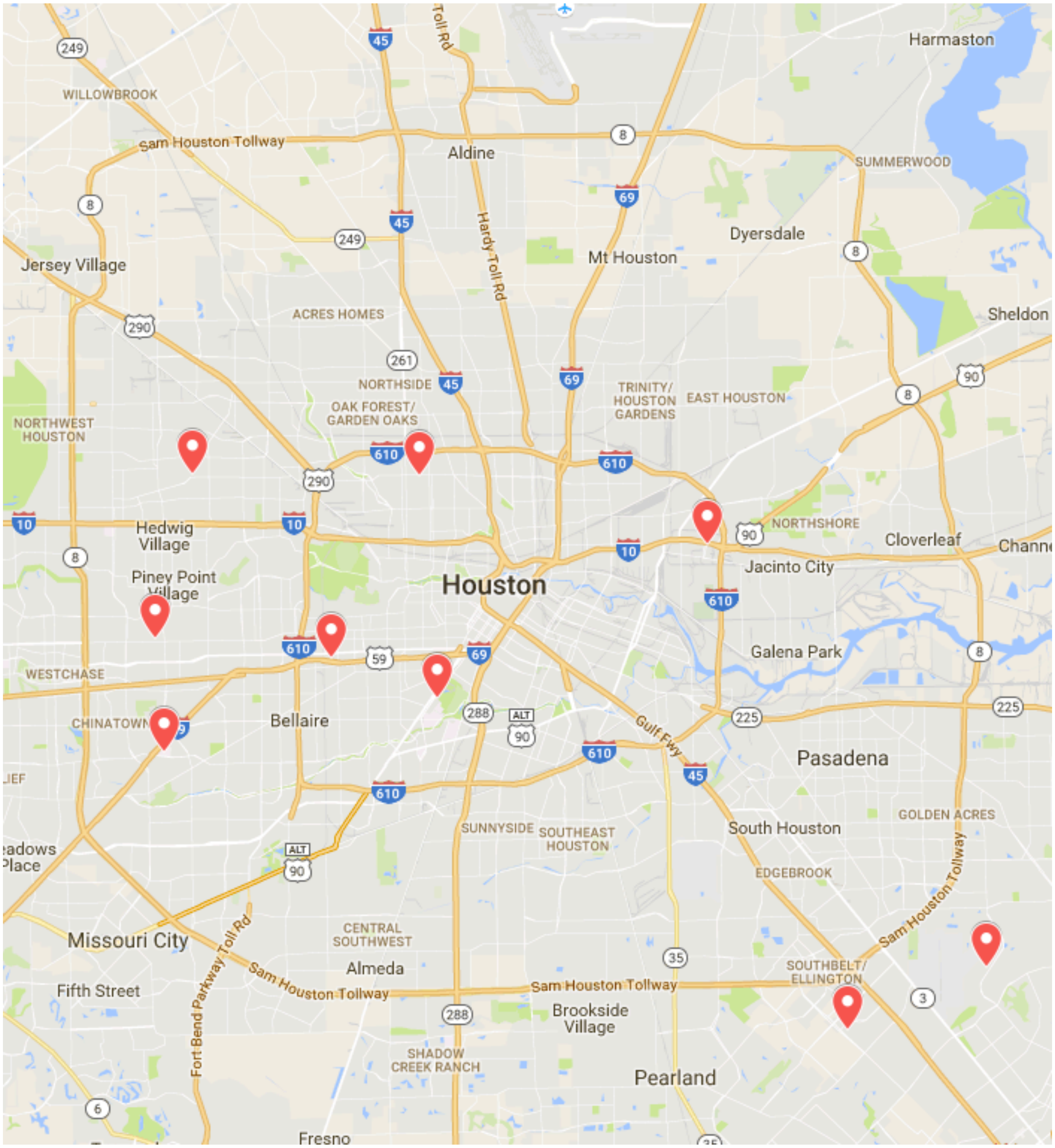


Appendix G: Map Showing Clear Lake Regional Medical Center





Appendix H: Map of Hyperbarics Facilities



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Vita

Derek Matthew Nusbaum was born on July 18th, 1982 in Sturgis, Michigan to Barbara Lee and Ronnie Wayne Nusbaum. He attended Northwestern University where he received a Bachelor of Arts degree in 2005 in Biology with a concentration in Neurobiology. He attended Michigan State University College of Human Medicine for medical school, graduating in 2009 and did an Internal Medicine Residency at the Baylor College of Medicine from 2009 to 2014. While there, he did a Doctorate of Philosophy program in Neuroscience where his research focused on developing animal models of elevated intracranial pressure and visual dysfunction to mimic and study the visual impairment seen in astronauts during long-duration spaceflight. He has also worked internationally providing medical care to underserved populations in Nepal, Tanzania, Zambia, Botswana, and Costa Rica. For his efforts, he has received multiple grants and scholarships, including the Christus Foundation for Healthcare, Hitoshi Nikaidoh, M.D. Memorial Endowed Scholarship, the Space Medicine Association Wyle Scholarship in honor of Robert Ellis, the Jeffrey R. Davis, M.D., Aerospace Medicine Endowed Scholarship, the International Association of Military Flight Surgeon Pilots Scholarship, the Space Medicine Association Jeffrey R. Davis Scholarship, and the Aerospace Medical Association/Aerospace Medicine Student and Resident Organization Scholarship.

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