IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES

By

JAMES D. POLK

Master of Medical Management
University of Southern California
Los Angeles, California
2010

Doctor of Osteopathic Medicine
A.T. Still University
Kirksville, Missouri
1993

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF EDUCATION
December, 2022

IDENTIFYING ENVIRONMENTAL AND FORENSICS

ASPECTS OF HUMAN SPACEFLIGHT MISHAPS

THROUGH EXTREME CASE STUDY ANALYSIS:

LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP

INVESTIGATORS AND TECHNICAL AUTHORITIES

Dissertation Approved:

Dr. Kat Gardner-Vandy
Dissertation Adviser

Dr.Timm Bliss

Dr. Jon Loffi

Dr. John Frucci

ACKNOWLEDGEMENTS

I would like to acknowledge the National Aeronautics and Space Administration, which has allowed me the opportunity to pursue this additional education with the intent of becoming a more informed technical authority for the agency, and perhaps with greater insight, preventing future spacecraft mishaps. I'd also like to thank the faculty and my fellow students at Oklahoma State University, who have been outstanding mentors and colleagues throughout this journey. Lastly, I would be remiss if I did not thank the families of the astronauts and cosmonauts who gave their lives in pursuit of exploration. It is my hope that this body of work honors their sacrifice. Ad Astra

Name: JAMES D. POLK

Date of Degree: DECEMBER, 2022

Title of Study: IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES

Major Field: APPLIED EDUCATIONAL STUDIES

Abstract: This study is an in-depth analysis and case study of human spaceflight fatalities, studying the forensic data, engineering data, and spaceflight environment that separates spaceflight mishaps when compared to other mishaps, but most especially to aviation mishaps. Because the Federal Aviation Administration will be charged with certifying commercial private spaceflights, and the National Transportation Safety Board will be charged with the investigation of private spaceflight mishaps, this information will be critical to future investigators as well as future spacecraft technical developers and engineers. The study will use the qualitative method of Case Study using extreme cases in which fatalities occurred. Cross-case comparison will be undertaken for identification of trends in human spaceflight mishaps, and then comparison of the spaceflight findings to the known literature of aviation mishaps will allow for identification of commonality or disparity between the two populations.

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CHAPTER I

INTRODUCTION

"Life, forever dying to be born afresh, forever young and eager, will presently stand upon this Earth as upon a footstool, and stretch out its realm amidst the stars."

- ***H.G. Wells***

Introduction

It may seem intuitive that investigation of spacecraft and aircraft mishaps are inherently different, yet there is a scarcity of data or publications in the literature that address these differences, be they the physics and mechanistic forces that are imposed on the vehicle, the environmental factors, or the forensic evidence that is available as a result of the mishap. Many of the books and publications that are written about spaceflight mishaps focus on the decision making and the organizational and cultural events that led up to the mishap or the decision to fly, but few if any detail the specific investigative differences between aviation and human spaceflight mishaps. Further, human spaceflight is rapidly expanding beyond the typical government model, to include commercial spaceflight companies and non-government sponsored flights into space. The rise of this commercial spaceflight market not only increases the opportunity for human beings to access space beyond the previous government astronaut paradigm, but also creates the possibility of a higher number and greater likelihood of human spaceflight mishaps. The National Transportation Safety Board (NTSB) investigates civilian aviation mishaps and space mishaps alike, but has far greater depth and experience in the former than the latter. State and county medical examiner offices have experience in car accidents and aircraft mishaps, but with exception of the Virgin Galactic mishap, they have never been a part of or been mentored on human spaceflight mishaps. Yet the county and state forensics teams and medical examiner offices will be the prime forensic investigators for private commercial spacecraft mishaps, unless they cross state lines or involve federal property, in which case the Federal Bureau of Investigation (FBI) would take the lead.

Likewise, the NTSB may have mishap investigators that have never been a part of or mentored on a human spaceflight mishap or possess deep knowledge of space physics or spacecraft engineering. This could lead to difficulty in the investigation, with false assumptions and errors in analysis; the physiologic impacts of microgravity and the physics of the forces of spaceflight add injury patterns and engineering and physical force patterns that are distinctly different from aviation mishaps, and that would be unfamiliar to the typical forensic medical investigator or aviation mishap investigator. The purpose of this study is: (1) to identify and research unique case studies of human spaceflight mishaps, and (2) to identify areas that have significant differences from their aviation mishap counterparts, in order to educate those who may be involved in future spacecraft mishaps and to apply lessons learned to future vehicle development.

Problem Statement

This dissertation and study aim to identify those unique characteristics found in human spaceflight mishaps and detail those findings to further inform future human spaceflight mishap investigation, and more importantly, inform future human spacecraft design. Recognizing those differences is paramount to forming accurate causality and assumptions about the mishap, and may help prevent such mishaps in the future.

Statement of Purpose

Historically, human spaceflight has been the domain of governments. When spaceflight mishaps have occurred, there have typically been commissions and political ad hoc committees formed, and multi-agency boards used to investigate and explore the mishap and its cause. But the deep portions of the investigation, such as the forensics, physics, environment, or engineering that give clues to the root cause analysis and final causality, typically are not shared, or are reduced to sound bites for the masses. The public is aware of “O-rings”, “tile damage”, and other such items implicated in a disaster, as well as the leadership failures in decision making that lead up to the mishap. But the actual details of the mishap and how to investigate a human spaceflight mishap are typically not shared in full. This omission of the nuances and differences in human spaceflight mishap investigation, especially in relation to aviation mishaps, becomes critical as we move to commercial spaceflight ventures.

All of the human spaceflight mishaps that have occurred using National Aeronautics and Space Administration (NASA) assets or vehicles had the appointment of a Presidential Commission by the President of the United States, in order to oversee the investigation and ensure objectivity. The Federal Bureau of Investigation (FBI) performed or was involved with the forensic analysis and recovery, and the Armed Forces Medical Examiner performed the autopsies. But in a private commercial human spaceflight mission, this will not be the case. Typically, the county law enforcement (or state law enforcement if multi-county) performs the initial investigation and scene forensics. The bodies are sent to the local medical examiner or coroner's office for exam. The National Transportation and Safety Board (NTSB) and Federal Aviation Administration (FAA) are involved in the investigation. These entities have an abundance of aviation experience, but not a vast amount of human spaceflight experience, which may inject errors in the assumptions about root cause, identifying forensic evidence, or establishing causality. There is currently no treatise on how to investigate a spaceflight mishap, no articles, or textbooks on what the essential or unique findings are in spaceflight, and no method of training for these individuals. The purpose of this study is to identify those unique characteristics for human spaceflight mishaps to better inform future mishap investigators.

Research Questions

The main questions to be asked in this study are the following:

1) Are there physical or environmental differences between a spaceflight mishap and other mishaps that stand out in your mind that would be important to highlight for future investigators or tech authorities?

2) Are there forensic differences that are unique to spaceflight mishaps? If so, what are those forensic differences or unique aspects in spaceflight mishaps that stand out in your mind from the mishap/mishaps you were involved with?
3) For future human spaceflight mishaps, be it commercial, NASA, or military- what are some of the most critical lessons learned that should be relayed to future mishap investigators?
4) For a technical authority charged with aiding in human systems design of new spacecraft, are there lessons that stand out in your mind that they should consider based on the mishap that you were involved in?
5) What skills should the mishap investigator possess when dealing with a human spaceflight mishap?

Overview of Research Design

The design of this study will be qualitative in nature due in part to the limited sample quantity or “n” number (Bloomberg 2018). The method will be a case study analysis using only those extreme or unique cases which align with the method proposed by Patton et al. (Patton 2014) under Purposeful Sampling or, more appropriately, Unique Case Orientation. The extreme or unique cases will be those in which death occurred as a consequence of the mishap. This will eliminate many close-call cases, such as Apollo 13, Apollo-Soyuz, and several emergency aborts where death did not occur. It is thought that by doing a deep exploratory case analysis of the extremes of human spaceflight mishaps, a richer substrate of the differences and unique characteristics can be found and highlighted (Seawright 2016). This follows the examples by Yin et al. (2011) when using exploratory case studies to evaluate trends more deeply than quantitative analysis will allow.

The historical and contemporary documents that will be evaluated and studied in-depth include the accident reports, commission findings, investigator notes, autopsy reports, and previous published and unpublished materials in the NASA and Armed Forces Medical Examiner archives. These documents will comprise the initial case analysis. This will be followed by interviews with individuals involved in the mishap investigation of each of the accidents to gather personal insights that may or may not have made it into the final reports, or in which the insights were sanitized or shortened for brevity or deemed insignificant at the time. Findings will be grouped by their characteristics, such as “environmental”, “engineering anomaly”, or “forensic findings” using NVivo qualitative analysis software to group the domains accordingly. These groups should underlie common themes or traits that infer commonality, association, or patterns (Gerring, 2006). A cross-case analysis will be undertaken to identify any commonality across the extreme cases of human spaceflight mishaps (Aberdeen, Yin 2009). It is doubtful, based on the low volume of cases, that a regression or Bayesian analysis will be possible or meaningful when applied to the human spaceflight mishap data. However, the findings will then be compared and contrasted against the literature on aviation mishaps (where large sample sizes have made quantitative analysis possible) by identifying whether the findings in spaceflight are congruent with the known aviation literature and databases or differ significantly. Commonalities or departures from the aviation literature will be highlighted, and unique characteristics of human spaceflight mishaps will be detailed.

Rationale and Significance

There is a paucity of literature on the details of human spaceflight mishap investigation to date. Most of the articles and books focus on the decision making and culture of the organization, such as when NASA pressed ahead with the Challenger mishap despite concerns over the solid rocket booster O-rings. The unique physical forces, environment, life support, accelerations, radiation, engineering, and forensics of these mishaps remain virtually uncatalogued. Indeed, the United States government itself was not forthcoming on early spaceflight mishaps, perhaps in part to prevent negative public sentiment toward spaceflight and exploration. The Challenger spacecraft debris is currently buried in concrete in an old, decommissioned missile and ammunition silo at Cape Canaveral Air Force Station. Although much has been published in regard to the fateful launch decision, there is virtually no discussion found on the forensics or kinematics of the orbiter mishap. The advent of commercial spaceflight negates any previous concerns for sharing such information, as it is paramount to educate the next generation of potential mishap investigators. Indeed, the Virgin Galactic fatal mishap is a good example. The pilot’s body was recovered by county medical examiners and the autopsy performed by the local coroner, who had no spaceflight physiology background or knowledge, nor experience in spacecraft mishaps. This can create errors when confronted with features or evidence without the context of the physics or environment the human body was subjected to. Such errors may propagate and lead to incorrect assumptions regarding root cause, and in so doing, mislead investigators as to what occurred. This further propagates in that faulty root cause or error analysis does not allow engineers or designers to address the appropriate problems or issues with the spacecraft, which may in turn cause repetition of the variables that allowed for the mishap to occur.

This research is significant as it will outline those unique features that a human spaceflight naïve or novice mishap investigator would otherwise not be aware of, exposed to, or have experience in. This research will explore in depth the detailed clues as to the order of events and the forces that the astronauts (private or government) were subjected to. This will greatly enhance the knowledge and expertise of those investigating future human spaceflight mishaps but may also inform the technical authorities and engineers tasked with writing the standards and requirements and building the actual spacecraft to make the necessary changes to avoid the fatal flaws or enhance the likelihood of survival.

Role of the Researcher

The researcher in this case has experience with a previous human spaceflight mishap in that the researcher was the flight surgeon for the Expedition 6 crew for the International Space Station and was on console in Mission Control during the Columbia mishap. The researcher also had a personal relationship with the members of the astronaut crew. Because of this, great care will be undertaken to formulate open-ended questions and follow up questions when interviewing the subjects for the study to prevent leading or steering the conversation or outcome in any particular direction.

The experience of the researcher with the technical aspects and human physiologic changes that occur as a result of microgravity and the environmental effects of spaceflight may help the researcher identify minute and unique clues that a novice researcher would not uncover. NASA is filled with acronyms and operational jargon, and the researcher's knowledge of the subject matter may help with the context of any comments or findings. The researcher's knowledge of engineering as a technical authority, knowledge of physiology, knowledge of life support systems, knowledge of forensics, and knowledge of the physics of spaceflight would prove to be an advantage to amalgamate the findings and their relationship to one another. However, the researcher's close proximity to the subject matter could also lead to an incorrect leap in logic based on past personal experience. For this reason, the interviews with those involved with past spaceflight mishap investigations is paramount. If themes begin to arise or unique aspects are identified by multiple participants, it begins to add credibility and power to the inclusion and identification of those areas.

Researcher Assumptions

Because spacecraft operate at much higher speeds than aircraft, require complex engineering systems and undergo higher accelerations and thermal loads than aircraft, and are subjected to forces that are not seen by aircraft, it is assumed that there will be significant differences in the findings between fatal human spaceflight mishaps and aircraft mishaps. The radiation environment and hazards, plasma upon entry into the atmosphere, closed environment and toxicologic hazards, forces of launch and acceleration, and unique aspects of flight in spacecraft are sufficiently different to suggest that there will be unique findings. Yet, we currently have the FAA and NTSB, who are well versed in aircraft mishap investigation, at the helm of a private commercial spacecraft investigation and to large extent, also involved in a government spacecraft mishap investigation. Private commercial spaceflight mishaps will have the local law enforcement and county medical examiner and coroner to deal with the remains and autopsy of a fatal mishap, despite no previous experience in the subject matter or its potential impact on the findings. The researcher postulates that there will be unique findings worth pointing out in human spaceflight fatal mishaps, and that key investigative findings will be identified.

Definition of Key Terminology

Key terms used in this dissertation that will be important for context and understanding of spaceflight mishaps include the following:

1) Accident- In general, the terms “accident” and “mishap” are interchangeable. However, government entities tend to refer to them as “mishaps” because we have a scale depicting the type and severity of a mishap. This is usually differentiated based on cost, severity of damage to property, or escalation of injury or death. Example- a Type A mishap has a total direct cost of mission failure and property damage of $2,000,000 or more, loss of vehicle, or loss of life or permanent disability. Civilian publications typically use the word “accident”. Where a civilian report or agency has called the event an accident, that verbiage will be used.
2) AFIP/AFME- Armed Forces Institute of Pathology, now called the Armed Forces Medical Examiner. The organization charged with performance of autopsies of military personnel killed in the line of duty. NASA has a Memorandum of Understanding (MOU) with the AFME that requests their performance of autopsies for astronauts killed in the line of duty.

3) Algo Mortis- Second stage of death, when the body cools and reaches equivalent ambient temperature.
4) Armstrong's Line- the altitude above sea level in which water boils due to a lack of pressure.
5) ATCO- Ambient Temperature Catalyst Oxidizer, used to scrub carbon monoxide from the atmosphere of a spacecraft after a fire.
6) Barotrauma- injury or trauma to tissues secondary to a rapid change in pressure or pressure wave.
7) Bends- decompression sickness or Caisson's disease where nitrogen forms bubbles in the blood, vessels, or tissues as a result of a decrease in pressure.
8) CAIB- Columbia Accident Investigation Board. The Presidential Commission formed to investigate the cause of the Space Shuttle Columbia Disaster.
9) CapCom- Capsule Communicator. The astronaut who relays commands from Mission Control to the astronauts in the spacecraft.
10) Capsule- The crew compartment of a spacecraft that is designed to have a ballistic coefficient to allow the rocket to more easily pass through the atmosphere, and typically the portion of the spacecraft that returns to Earth by parachute in non-glider spacecraft.
11) CHI- Closed Head Injury
12) CO- Carbon Monoxide
13) DDMS/Det 3- Department of Defense Manned Spaceflight Support Office, now called Detachment 3 of the U.S. Space Command, charged with search and rescue of U.S. astronauts.

14) Decompression- The act of a sudden loss of pressure in an aircraft or spacecraft.
15) Ebullism- the act of the blood boiling above Armstrong's line due to the nitrogen and other constituents of blood boiling due to a lack of pressure to hold them in solution in the blood.
16) ECLSS- Environmental Control and Life Support Systems
17) EMS- Emergency Medicine Services
18) External Tank- The tank that holds liquid oxygen and liquid hydrogen for the Space Shuttle Systems.
19) FBI- Federal Bureau of Investigation
20) Flail- the act of having the arms and legs violently moving due to excessive and rapid motion.
21) Flight Altimeter- instrument used to assess the altitude of a spacecraft or aircraft.
22) Flight Deck- The portion of a glider spacecraft or aircraft where the cockpit and pilots reside.
23) Forensic Pathology- The specialty of pathology that examines the remains in order to determine the cause of death.
24) Gehman Report – The report from the Presidential Commission on the cause of the Columbia Accident lead by Admiral Gehman.
25) Hatch- the portal of entry and exit of a spacecraft.

26) Hydrazine- Monomethylhydrazine, a hypergolic rocket propellant used in thrusters and fuels for spacecraft that is typically activated or combined with an oxidizer such as nitrogen tetroxide.

27) Intracranial Hypertension/SANS

28) Livor Mortis- the gravitational settling of blood into dependent spaces of the body, usually beginning within 30 minutes and continuing for a period of up to 12 or more hours.

29) Max Q- the point of which a spacecraft traversing the atmosphere reaches maximum dynamic pressure.

30) MCC- Mission Control Center.

31) MECO- Main Engine Cut Off, typically after the boost and atmospheric phase of flight of a spacecraft when orbital velocity has been achieved.

32) MIB- Mishap Investigation Board

33) Mid Deck- the portion on a Space Shuttle where the payload specialists and mission specialist reside, below the flight deck.

34) Mishap- As noted previously, the words “accident” and “mishap” are generally interchangeable. However, government entities tend to refer to them as “mishaps” because we have a scale depicting the type and severity of a mishap. This is usually differentiated based on cost, severity of damage to property, or escalation of injury or death. Example- a Type A mishap has a total direct cost of mission failure and property damage of $2,000,000 or more, loss of vehicle, or loss of life or permanent disability. Civilian publications typically use the word “accident”. Where a civilian report or

agency has called the event an accident, that verbiage will be used. Otherwise, the term mishap will be used throughout this document.

35) Nitrogen Tetroxide- The oxidizer used in combination with hypergolic fuels like monomethylhydrazine for thrusters and propellant for spacecraft.
36) NTSB- National Transportation and Safety Board.
37) Osteopenia/Osteoporosis- Loss of bone that occurs with microgravity of spaceflight.
38) Parachute- the material used to slow the atmospheric speed of a spacecraft upon re-entry.
39) PSI versus PSIA- PSI is Pounds per square inch, a unit of pressure or force, whereas PSIA is Pounds per square inch absolute, which refers to the absolute pressure above vacuum in the atmosphere.
40) Rigor Mortis- the third stage of death characterized by muscle rigidity due to actin and myosin cross bridges in muscle being depleted of Adenosine Triphosphate.
41) Rule of 9's- Method to estimate burns of the extremities and torso.
42) Salyut- The first Russian Space Station program.
43) Service Module- the module next to the crew capsule that supplies the ECLSS, houses volatile fuels, and provides power.
44) Shock-Shock Interaction- the intersection of heat, pressure, and vibration build up upon a spacecraft at leading edge surfaces in hypersonic flight.
45) Solid Rocket Booster- boosters encompassed by solid fuels used to aid in the booster of rockets.

46) Soyuz- A Russian Crewed Spacecraft.

47) TAEM- Terminal Area Energy Management

48) Technical Authority- The three main NASA Subject Matter Experts responsible for safety of flight consisting of the Chief Engineer, Chief Safety Officer, and Chief Health and Medical Officer.

49) TPS- Thermal Protection System

50) TsUP- Russian Mission Control Center

51) Two-Chute Pendulum- the act of a spacecraft swinging in a pendulum motion under the canopy of two parachutes, typically when one of the chutes does not deploy.

Organization of the Dissertation

This dissertation is laid out with the following chapters: Introduction, Literature Review, Methodology and Research Approach, Findings/Analysis/Interpretation/Synthesis, and Conclusions and Recommendations.

The case studies will focus on the fatal human spaceflight cases. Specifically, these include Apollo 1, Soyuz 1, Soyuz 11, Challenger, Columbia, and Virgin Galactic. One could argue that Apollo 1 was not a human spaceflight mishap but rather a tragic pad accident. However, the environment of the plugs-out test which set up the substrate for the fatal Apollo 1 fire is unique to spaceflight, and therefore it has been included in the analysis. Cases where near-miss incidents did not result in a fatal accident, such as the loss of control of the thrusters and Agena docking module attitude on Gemini VIII, the explosion and loss of mission in Apollo 13, the toxicologic exposure on Apollo-Soyuz re-entry, the collision of the Russian Progress with the Mir, the Mir fire, and numerous other incidents are not included in this analysis. These represent potential future mining of additional information for future studies.

CHAPTER II

REVIEW OF LITERATURE

"I don't think the human race will survive the next thousand years, unless we spread into space. There are too many accidents that can befall life on a single planet. But I'm an optimist. We will reach out to the stars."

\- ***Stephen Hawking***

Introduction

The sudden rise of private commercial human-rated spaceflight in the summer of 2021 has captured the public's imagination. In the span of just four months, two companies sent private astronauts above the fifty-mile mark into suborbital space, one company sent four private astronauts on a three-day orbital mission, and the Russian Federation launched two private astronauts along with a professional cosmonaut to the International Space Station for a fourteen-day mission.

With so many companies engaging in the private astronaut enterprise, one might begin to believe that flying to space is now common or routine. But spaceflight is still an inherently risky business. Systems engineering is not a common or easily acquired trait for the commercial vendors that are new to human spaceflight, as they have not had sufficient experience in human system design and integration. A loss of a satellite payload due to explosion of a rocket body might be an acceptable risk at 1 in 30 (Cao, 2019), but this is not acceptable for loss of a human crew on a human-rated spacecraft. The tempo at which the commercial human-rated spacecraft are coming online, and flying has outpaced all previous human spacecraft development.

The inexperience in human systems design and the speed at which the companies are moving makes the likelihood of a future mishap involving a commercial or private vendor high, if not certain. Investigating such a spaceflight mishap will fall to the National Transportation Safety Board and the Federal Aviation Administration, neither of which has a large amount of experience with spaceflight hardware, certification, or systems. Both entities lack human-rating engineering expertise for spacecraft and expertise in space physiology and spaceflight human factors. Although each entity has a vast amount of experience in aviation human factors and physiology, there are distinct differences between those found in aviation versus spaceflight. Recognizing the differences when investigating a spaceflight mishap will be paramount. A significantly limited amount of published knowledge exists on the forensic findings and differences between human spaceflight and aviation mishaps.

The purpose of this literature review is to identify what is currently written on the most common causes of death and forensic findings in aviation mishaps and compare them to the known or published findings and research on human spaceflight mishaps. Additionally, the literature will be examined regarding suitable analogs for spaceflight, such as Antarctic missions and submarine missions, to see if there is any cross commonality between those missions, aviation mishaps, and spaceflight mishaps and if there are other suitable areas from which to glean human spaceflight mishap expertise.

Because of the breadth of data that may be encompassed, the conceptual framework for comparison will focus mainly on the data of aviation fatalities and space mishap fatalities. Those two types of fatalities will mirror the currently outlined process for investigation of private commercial spaceflight mishaps, where two government bodies with great experience in aviation mishaps will be called upon to investigate a spacecraft mishap. To date, there has been no body of literature or research study that has looked at the critical cases, performed a comparative analysis between spaceflight mishaps and aviation mishaps, or performed a comparative cross case analysis between spaceflight fatal mishaps to look for commonality.

Search Strategy

The literature and databases were searched using the following key search parameters: *Aviation Mishap Investigation, Aviation Mishap Forensics, Cause of Death + Aviation Mishaps, Human Spaceflight Mishaps, Apollo 1 Mishap, Space Shuttle Challenger Mishap, Space Shuttle Columbia Mishap, Soyuz 11 Mishap, Soyuz 1 Mishap, and Virgin Galactic Mishap.* Additionally, searches were conducted using *Fatalities in Spaceflight, Analog Fatal Mishaps, Antarctic Fatal Mishaps, Austere Mishaps, Submarine Fatal Mishaps, and Forensics of Mishaps.* The search databases used included Google Scholar, PubMed, OVID, SCOPUS, IEEE Explore, JSTOR, and Science Direct. The search parameters were not initially limited in order to acquire data on early submarine and analog mishaps. However, focus was placed on those mishaps that have occurred in the last twenty years, with exception of the Soyuz 1, Soyuz 11, Apollo 1, and Space Shuttle Challenger mishaps. The sources included peer-reviewed journal articles, government mishap reports, government investigations and Presidential Committee investigation reports, book chapters, theses, internal government reports, and review articles. In all, over 688 sources were identified. Scanning this material for relevance narrowed this selection to 172 sources. Further refinement occurred after building a conceptual framework, and that subset is available in the references section of this dissertation.

Conceptual Framework and Review of the Literature

The Conceptual Framework of this review was to begin reviewing the literature in reference to fatalities. Fatalities were specifically used as the research will focus on the extreme cases in human spaceflight, which will be those cases that ended in astronaut fatality. Aviation fatalities, since these are the most familiar to the NTSB and FAA, were reviewed first. Submarine fatalities, because of their having an enclosed environment akin to spacecraft, toxicology and radiation issues, and fire risk were also reviewed for later comparison to spaceflight mishaps. Analogs, due to their extreme environments, similar medical screening exams, and austere medical care were examined next.

Occupational deaths, although most likely work-related due to the hazards of machinery, rocket fuel, and explosion possibility, were also briefly reviewed but found to be widely divergent and thus not included in the review or comparison due to lack of relevance outside a 1-g, 1-atmosphere environment. Non-fatal spaceflight mishaps and close calls are numerous in the space program, and each have their lessons learned. However, it was deemed that extreme cases should be limited to fatality for this study. A brief review of the general forensic findings and scene investigation findings common in most mishaps were also reviewed. Finally, the fatal human spaceflight mishap literature was reviewed in more depth because of the relatively small case number.

Aviation Fatal Mishaps

In Wiegmann's book on human error in aviation accidents (2017), he recounts the very first aviation fatality. Lt. Thomas Selfridge of the Army Signal Corps was a passenger with Orville Wright in the Wright Flyer in 1908, when on their fourth pass around the airfield, the propeller struck the guywire running to the rudder, fracturing the propeller, and disabling the rudder. The aircraft rapidly descended from 175 feet to 75 feet, then went nose down into the ground. Selfridge died of a head injury and skull fracture later that evening. Selfridge's head injury became a hallmark for the cause of death in aviation mishaps and would become a repetitive theme in the review of the literature.

The treatise on aircraft mishap investigation by the North Atlantic Treaty Organization (NATO) is an official manual by the organization (EN-HFM-113) with multiple authors writing about specific aspects of aircraft mishap investigation, including human factors and biodynamics (Tejada, 2005). In this review by the NATO members, multiple authors from multiple countries added chapters based on data and evidence shared among the partners where the authors felt there was consensus. In essence, their collaboration was akin to a kind of miniature Delphi study, wherein consensus was required in order to bring agreed upon principals to light. The report from NATO cites that 70-80% of all deaths and injuries in aviation mishaps arise from abrupt decelerations, causing fatality from face and head injuries caused by the head striking surrounding structures in the aircraft. The next most common cause of death or factor is post-crash fire. Baker's (2009) review of aviation accidents from 2000-2005 revealed that the vast majority were private non-commercial pilots and passengers, with head injury accounting for 38% of the major causes of death and lower limb fractures being the most common injury among both fatalities and survivors.

In Vidoli's study (2012) of the American Airlines flight 587 crash, she examines the position of commercial passengers in the aircraft and the fragmentation and injury patterns of the bodies to help try and establish the point of impact and roll direction of the aircraft. In that mishap, multiple blunt force trauma was the major cause of death, followed by post impact fire. Her study shows that those passengers closest to the impact (on the side of the aircraft that first impacts the terrain) take a substantial portion of the kinetic energy and are more likely to fragment than those on the other side of the aircraft. Li and Baker (1997) studied aviation crashes between 1980 and 1990 and found that the multiple blunt force trauma followed by head injuries were the most common immediate causes of death. In fact, nearly a third of the fatalities were secondary to head trauma. Multiple extremity injuries were also common, although usually not contributing to the immediate fatality.

Wiegmann and Taneja's study (2003) of general aviation accidents between 1996 and 1999 revealed that blunt force trauma, with a predominance of fractures to the skull and ribs, was the most common cause of death, followed by post-crash fire. Li (2008) goes on to further describe the FIA (Fatality in Aviation) score as a means of using a four-point risk index to predict the likelihood of death in an aviation crash after reviewing over 44,000 general aviation crashes in the National Transportation Safety Board database from 1983 to 2005. The score is based on three risk factors: fire, instrument meteorological conditions, and distance from the airport. Whereas Li focused on the potential reasons and factors that would lend themselves to fatal general aviation crashes, Schuliar et al. (2014) developed a tool called the Crash Injury Pattern Assessment Tool (CIPAT) to code and analyze injuries in order to determine where they were seated in an aircraft and what the injury patterns might suggest in terms of forces, direction, and vectors. The coding system for CIPAT is derived from the Abbreviated Injury Score (AIS), which is associated with the amount of force required to cause a specific injury. Head injuries and multiple blunt force trauma again top the major findings in the fatalities.

Levy et al. (2007) used Computerized Tomography (CT) scanning on postmortem victims to analyze injury patterns. The most common findings were musculoskeletal fractures, most of which would not have been fatal, followed by fractures of the ribs, skull, and facial bones, the latter of which would lend themselves to organ and brain trauma and a high likelihood for fatal injury. Levy also found that physical autopsy was superior to finding the extent of injury as opposed to postmortem CT scanning.

Alaska is known for having the highest per capita number of pilots. Air transport and private piloting is a major means of transportation in Alaska. Not surprisingly, Bensyl and colleagues (2001) found that aviation related crashes were the number one cause of occupationally related death in Alaska (greater than 410 per 100,000 per annum). Head and chest injuries were higher in those fatal mishaps where the pilot was without shoulder restraint, but the highest determining factor for fatality in their study was post-crash fire. Wolf and Harding (2008) found head and chest injuries to be the predominant cause of death upon autopsy in their investigation of sport-aircraft related deaths in Southwest Florida. Ruatji et al. (2001) evaluated an Indian corporate jet mishap and found that liver, heart, and spleen laceration with associated rib fractures and cerebral hemorrhage predominated as the cause of death. What was interesting in this study was the lack of specific mention of head injury, which predominates most other large studies, but it can be assumed with the finding of cerebral hemorrhage that blunt force trauma to the head was present.

Likewise, Chalmers and colleagues (2000) noted in their review of 104 aviation crashes in New Zealand ~~that~~ the presence of multiple blunt force trauma to the chest and abdomen, but they also noted a large percentage of head injuries accounted for the most common causes of death. Only Makhadi and colleagues (2021) differed in their findings from the bulk of the literature. They reviewed aviation mishap victims that were brought to a Level One Trauma Center in South Africa between 2011 and 2019. In their study, spinal injury was the most common following by thoracic and rib fractures and organ injury. However, it should be noted that their patients were alive when they presented to the trauma center, and this may account for the difference versus those cases in which victims were found dead of their injuries at the scene. Interestingly, Shkrum et al. (1996) were the only researchers to find drowning as their second most common cause of death after blunt force trauma, but they studied ultra-light aircraft crashes in Ontario, and many of these mishaps involved engine failure over water.

Air Commodore Stephen Anthony (Tony) Cullen is well known in aviation circles for having described injury patterns in detail from aviation mishaps (Cullen, 1980). He is the foremost authority in the United Kingdom on aviation mishaps and specializes in *aviation pathology*. His work on aviation mishaps is often cited by the International Civil Aviation Organization (ICAO) and he has authored numerous chapters on aviation pathology from accidents, toxicology, burns, and the like (Cullen, 2011). It is important to note that he was the first author to characterize "aviation suicide" (Cullen, 1998) by reviewing thousands of aviation mishaps in the United Kingdom and classifying those where the pilot purposefully crashed their plane into terrain. This is especially interesting in that Cullen characterized this prior to the events of 2001. Prior to that, hijackings typically did not end in terrorist pilots flying their aircraft into buildings in aviation suicide/homicide.

Ast et al. (2001) reviewed aircraft mishaps from 1979 to 1996 in Lower Saxony (Northwest Germany) and found that autopsies were enlightening on the cause of death, but often also shed light on the initial cause for the aircraft mishap itself, with findings ranging from gunshot wounds, alcohol, carbon monoxide poisoning, to medical ailments that precipitated incapacitation of the pilot. Thus, not all aviation mishaps are attributable to mechanical failures, weather conditions, or human factors. Thus far, spaceflight mishaps do not mirror this behavior or potential causation for mishaps.

Military aviation mishaps, despite the high energy in jet aircraft, appear to have similar patterns of pathology. Cogswell, in both his chapter and his lecture series (1998), states that head injuries are the most common cause of death. This is both surprising and interesting in that this is despite pilots wearing helmets in jet aircraft. However, their data show head strikes appear to be common, including head strikes on the canopy, at ejection. Multiple blunt force trauma followed by post-crash fire account for the remaining top causes of mortality in military aviation crashes in the majority of the study.

In an attempt to have autopsy and pathology data feed into aircraft design and safety prevention systems, the Federal Aviation Administration (FAA) created the Aerospace Accident-Injury and Autopsy Database System. The autopsy findings are fed into this system to categorize the injuries based on type of aircraft, energies (speed, mass, velocity upon impact), and investigation findings. Ricarte and Gallimore (2006) reviewed the data on 4,000 aviation crash autopsies from the database from 1985 to 2005. Their findings and analysis of the NTSB and FAA data are enlightening in that a large percentage of passengers on commercial airliners who had survivable injuries, succumbed to post-crash fire or smoke inhalation.

Fire was a higher cause of death in commercial aviation than military aviation (47% versus 32% respectively- Ricarte and Gallimore, 2006). Analyzing and separating the post-crash factors only, fire was the leading cause of death. Essentially, their findings show that if the impact in a commercial airliner crash with associated head injury or chest injury did not kill you, then the post-crash fire most likely would. What was also interesting in their findings was that if you had survived the initial impact, you had a 90% chance of survival as long as there was no post-crash fire. Thus, fire suppression and containment of fuel would be areas that would have a major impact on post-crash survival. Berner (1971) likewise showed that if you survived the impact, there was a high likelihood that you would survive in total, unless there was a post-crash fire. Fire therefore represents a significant risk to aviation mishap survival and is a high cause of death.

Hill (1989) described how the preponderance of injuries found by most researchers can be grouped by the types of aviation mishap and their relation to force and velocity. In general, Hill states that they can be classified as: 1) decelerative, 2) impact, 3) intrusive, and 4) thermal. Decelerative injuries disrupt the aorta, heart, spleen, or liver because the weight of those organs continues forward, despite the body having a sudden deceleration, and they are found in a large percentage of high velocity impact autopsies in commercial airline mishap victims found by Pezzella's research (1996). Impact injuries to the chest, abdomen, and head are well characterized. Intrusive injuries are where a portion of the aircraft or fuselage or seat penetrates the body. Thermal refers to the post-crash fire. Based on previous research, Hill and Pezzella would do well to add head injury to their analysis and category of impact. It is clear that head injury and post-crash fire account for the bulk of mortality, but higher energy crashes give rise to multiple blunt force trauma and very high energies give rise to fragmentation of the body.

Submarine Mishaps

Although military submarine mishaps are not investigated by the FAA or NTSB and are not in the aerospace domain, they do nevertheless have some attributes that mirror spaceflight in that they are both enclosed environments, use radiation sources, scrub the carbon dioxide, and balance their oxygen, and require changing pressures.. These attributes make it worthwhile to explore the causes of submarine mishaps and the associated forensic findings on fatalities, to see if they are perhaps an analog for spaceflight given their common environmental challenges.

Probably one of the best works in this area was a sixty-year statistical review of submarine mishaps, their causes, and their cause of death by Tingle (2009) and a previous historical review by Romig (1966). Romig's (1966) work was part of a RAND

Corporation assessment of risks and cataloged submarine fatalities and their causes from 1900 to 1965, but Tingle's work is more recent and includes the advent of the nuclear submarine and the complex technologies for long submergence. Tingle performs a robust analysis comparing the types of mishaps and fatalities throughout submarine history that builds on Romig's work.

The causal factors are sometimes shrouded in mystery or are locked in the deep blue ocean due to the vessel being unrecoverable, which leads to speculation based on radio reports, witness testimony, or known engineering flaws at the time. According to Tingle (2009), the height of submarine usage was in the early 1990's when over 900 submarines were deployed throughout the world. Currently, fewer than 540 submarines are in use, levels lower than at the end of World War II. Perhaps not surprisingly, drowning accounts for the largest number of fatalities, usually due to flooding of compartments or compromise of integrity or disruption of the vessel. Related to flooding is the process of "snorting".

Snorting is the exchange of air either by sucking air in through an induction valve on an intake snorkel or by expelling carbon dioxide and carbon monoxide from the diesel engines through an exhaust snorkel. Although submarines can produce oxygen through electrolysis of water and scrub carbon dioxide with Lithium Hydroxide (much like a spacecraft) they try to limit these procedures due to the consumables required unless submerged. Otherwise, they attempt to circulate the air with the snorkel masts. The difficulty with snorting is that the masts must extend beyond the surface of the water to reach air, which could make the submarine visible to their enemies.

Tingle (2009) outlines several mishaps in which a snorkel failure, presumably a failure of the ball valve that keeps water out and allows air in, caused a catastrophic situation. A failure of an exhaust snorkel can likewise be catastrophic. In these circumstances, carbon monoxide from the engines may accumulate or the engines may overheat and seize, both of which could either cause toxic situations or the submarine to begin taking on water and sinking to a depth that could cause implosion due to pressure.

The second leading cause of submarine mishaps, which in turn leads to flooding of compartments and thus demise of the crew, is collisions (Tingle, 2009, Romig, 1966). Collisions with other submarines, with geological features, or with surface ships can cause catastrophic damage and weaken bulkheads or damage masts or rudders, all of which can lead to potentially catastrophic circumstances. Explosions and fire are the third most common cause of submarine catastrophe after collisions (Tingle, 2009). When the batteries come in contact with salt water, they can explode. Weapon systems, torpedoes, overheated engines, and other engineering devices upon the submarine are subject to faults, fire, or combustion with catastrophic consequences. Surprisingly, radiation anomalies are not at all common and radiation exposure is likewise not a common consequence for submarine mishaps, perhaps owing to the number of safeguards put into place to protect the crew.

Whybourn (2019) argues that a disabled submarine occurs about once every 10 years, and that augmentation with emergency supplies to allow the submarine crew to survive until a potential rescue might help prevent fatalities as the vast majority of events occur in rescuable water depths. He also argues that many of the incidents in his review were a result of operator crew error, causing collisions and groundings as well as flooding. In his review of 64 disabled and 148 near miss events for submarines, he argues that only 20% of those were non-survivable, and with the proper stores and procedures, many could avoid catastrophe and fatalities. Surface abandonment, the ability of a submarine to surface and evacuate all personnel to rescue rafts or the topside of the submarine, was seen as having the highest potential for survival.

Chen (2019) likewise reviewed submarine mishaps from 1900 to 2009 using analytical software (SSPS 17.0) to group the mishaps by cause. As with Tingle, Roberg, and Whybourn's analyses, Chen found that flooding and sinking were the most common factors, followed by explosion and fire. Unlike Tingle, Chen did not extrapolate whether collisions were responsible for a portion of the flooding, sinking, or explosions. However, much like Whybourn, Chen found that human error in the form of operator crew error accounted for the bulk of issues that left the submarine stranded, including collisions, flooding, and fire.

Deptro et al. (2021) outline how they believe the fire risk has increased with time, rather than decreased. Diesel-electric submarines are quieter and smaller than their nuclear submarine counterparts and therefore stealthier. Whereas a nuclear reactor must run constantly, the diesel electric engines can be shut down and the submarine can run on batteries for a time, offering a strategic advantage over their nuclear submarine counterparts. This has caused an increase in use and installation of large rechargeable lithium-ion batteries to be included on such submarines, and combined with new Air Independent Propulsion systems, has allowed the submarines to stay submerged without the need for snorting or snorkel. Although this has increased the stealth and submersion run time of smaller submarines, it has also substantially increased their potential fire risk as lithium-ion batteries are known to have both fire and combustion risk with runaway thermal overheating.

The depths with which submarines become disabled also complicates the potential survival of submariners (Roberg, 1966). Deep Sea Submersible Rescue Vehicles have been invented to allow for dry escape of submarine crews by diving and docking with the hatch of a submarine. Typically, these vehicles are much smaller, such that they would require repeated trips to evacuate a crew. Prior to Deep Sea Submersible Rescue Vehicles, the predominant method of trying to escape a disabled submarine was by having the crew attempt an ascent individually. Moses (1964) reviewed the free ascent (swimmer ascends under own power) and buoyant ascent (device such as life vest or air-filled membrane helps the swimmer ascend) fatalities during submarine emergency escape training from 1928 to 1957. The training included an escape and ascent from 18, 50, and 100 feet respectively. Over 62 casualties occurred during that time period for the underwater escape training. Of those 62 casualties, 44 of them showed signs of air embolism. The remaining crew drowned or ran out of air before reaching the surface. Thus, free ascent or buoyant ascent of a submarine crew at a depth below 100 feet would be fraught with casualties.

White (2000) went further by explaining that a submarine crew submerged at 1.7 bar (24.6 psi or around 90 feet of sea water depth) for more than 24 hours will have a higher nitrogen saturation in the blood, such that if the occupants are not pressurized on their ascent, they will undoubtedly have severe decompression sickness. This complicates the rescue in that the operators in a deep-sea submersible rescue type vehicle would be at less risk than the crew they are rescuing for severe decompression sickness. They would have to slowly come to the surface with multiple decompression stops, with high oxygen concentration in the breathing air at high enough pressure to avoid severe decompression sickness (Bennet et al., 1993) in any crew they rescued, which would further increase the amount of time before they could return to rescue more crew.

Elliot in his treatise on submarine escape (Elliot, 1999) discusses the first known submarine escape in 1851 by Wilhelm Bauer, as well as the history of devices intended for breathing and submarine escape. Differing types of bladders, rubber air lungs, and devices were contrived, including escape suits that weighed over 50 pounds. None of these were practical, and several had fatalities in both training and practical use. The Momsen Lung was one such device. Momsen worked with McCann to devise a more practical method of submarine rescue than relying on a submarine crew to utilize a breathing device, due to the high risk of bends and drowning. The Momsen- McCann bell, devised in 1929, was a wide-shaped metal container that was narrower at the bottom. It had the ability to dock onto a submarines hatch and allow several crewmembers to enter. It was devised as the more practical means of submarine rescue. The bell was slowly adopted by multiple countries over the next decade. Unfortunately, before that decade was out, the world would see the worst year in submarine seafaring history in1939, when there were close to 300 fatalities. Elliot relays the history of the USS Squalus, which was a submarine that set sail off the coast of New Hampshire but mistakenly had an air-induction valve open and sank in 243 feet of water. What is remarkable about the Squalus is not that over 25 men died, but according to Elliot, after sitting on the bottom at 243 feet for 24 hours, 33 men were saved using the Momsen-McCann Bell, taking over 15 hours and four trips.

Gray (1996, 2006) likewise gives an in-depth history of submarine mishaps and rescues. Surprisingly, crew error accounts for a large number of the mishaps, with valves being left open, collisions with other ships, or fires being responsible for a fair number of mishaps according to both Gray (2006) and Glover (2002). The area that submarines and spacecraft appear to have in common is not the mode or method of the mishap (spacecraft mishaps are typically not from crewmember error) but in the enclosed environment and fire risk. Despite the nuclear weapons and nuclear thermal energy and power on many submarines, radiation has not been the immediate cause of death or cause of a submarine mishap, though it does remain a risk if the reactor cooling is compromised in a disabled submarine (Goodenough, 2008).

The causes of death for submariners do not appear to be analogous to spaceflight, but the intricacies of submarine rescue do have parallels. After Columbia, NASA was only allowed to launch the STS-125 Hubble repair mission if they had a second Space Shuttle ready to rescue the crew in the event of a catastrophic injury to the vehicle. The higher altitude of the Hubble mission meant that the orbiter would not be able to seek refuge at the International Space Station if the vehicle were damaged, and consumables would allow the crew to survive only a couple of weeks, such that having another Space Shuttle ready to launch to perform a rescue was the only potential option.

The STS-400 mission was just that mission. It had a crew of four assigned and the Space Shuttle was moved to the pad, ready to launch in case the STS-125 Space Shuttle orbiter was damaged on launch and the crew was stranded in space (Azbell, 2010). This movement and rescue of one crew from a pressurized vehicle to another pressurized vehicle (through Extravehicular Activity (EVA) in order to get from airlock to airlock), is analogous to submarine rescue. Therefore, although there are not great parallels for mishap, there may be lessons learned for future spacecraft rescue.

Analog Fatal Mishaps

For many years, NASA has used the polar regions as analogs for planetary missions. They are remote, they require logistics planning and survival skills, and are dependent on life support systems to some degree to maintain adequate heat, water, and air filtration. Although they may mimic planetary risks, however, they do not appear to be good analogs for the mishaps and fatalities of spaceflight. Wallace (2010) gives accounts of the expeditions that suffered fatalities in the Antarctic, and Xin (2010) discusses the multitudes of mishaps leading to large numbers of fatalities, such as aircraft crashes and shipwrecks. Over 20 aircraft have crashed on Antarctica, killing over 300 people with icing conditions and weather being the culprit in the vast majority. The 1819 shipwreck of the Spanish gunship San Telmo killed over 644 people when it ran into ice on the way through the Southern passage in route to Peru. Handfuls have died from fires, asphyxiation from working on fire suppression equipment in an enclosed space, and a researcher dragged underwater and drowned by a seal (Owen, 2003).

The Arctic likewise has similar characteristics when reviewing fatalities in those areas that are akin to analog missions, with shipwrecks and aircraft crashes accounting for the bulk of fatalities, and a polar bear attack in place of a seal drowning. Brown et al. (2021) have modelled the likelihood of evacuations and illnesses from ships in the Arctic, and without question the medical maladies that might occur on either an Arctic or Antarctic expedition coincide with what might be seen on an exploration mission. In fact, NASA utilizes some of this data in its estimation and Monte Carlo analysis and modeling when devising risk data for exploration missions (Myers et al., 2018).

Despite the smaller numbers in terms of fatalities, the more famous of the expeditionary fatalities was Scott's famous expedition to reach to South Pole before Amundsen. This quest ended in tragedy, with Scott and his fellow explorers getting caught in a blizzard, unable to find their rations and food/water stores, and essentially starving and freezing to death (Solomon, 2002). Shackleton's expedition resulting in a nearly two-year ordeal involving a shipwreck, stranding on the ice, sailing in a lifeboat for weeks to get help, and returning to rescue his stranded crew without a single fatality, was in itself a miracle and noteworthy as well (Shackleton, republished 2004). But none of these parallel the types of injuries, forces, or environment akin to spaceflight missions. They may be more aptly compared to planetary exploration risks in the future, however, which may warrant future study.

Forensics

Hellerich and Pollak (1995) discuss the relationship of mass and acceleration to their forensic findings. Specifically, they detail how bodies can be fragmented by the excessive force upon impact, particularly in large airliners impacting the ground at high speeds. Of interest is that this does not correlate to the majority of spacecraft mishaps. Spacecraft have impacted with high speeds, such as Komarov impacting the ground in Soyuz 1 when no parachute deployed from the spacecraft, and the Challenger crew impacting the ocean after the dynamic breakup of the vehicle at altitude. But the findings were not consistent with what the authors found in aircraft high-speed impacts to terrain.

Payne-James (2019) and McMeekin (1973) both discuss the types of injuries seen in the multiple blunt force trauma of aircraft crashes, with head and torso injuries and extremity flail injuries predominating. Olsen (2014) discusses the types of injuries seen in the person at the controls of the aircraft, with fractures to the thumb and wrist, and fractures to the malleoli (the bones of the lower extremity that compose either end of the ankle mortis) seen in those who had their hands on the stick and feet on the rudder pedals. While these are helpful in aviation mishaps, with exception of the pilot who is flying a spaceplane lifting body-type spacecraft, they may not be helpful in forensics of the remaining crew. This would especially be true in a capsule, where the gravity vectors are more in the Gx direction, and glass cockpits predominate instead of stick and rudder.

Moser (1990) undertook a unique study looking at the nutrient groove of the pelvis in aviation mishap investigation. Moser argues that this area of the pelvis, and particularly its disruption on x-ray, is evidence of high velocity impact trauma. The groove is made by the nutrient artery in the ilium and may take either a parallel, V, or Y shape, and lies a few centimeters lateral to the sacroiliac joint. But one might argue that the disruption of the sacroiliac joint itself is a better marker. Kahana (1997) et al. argue that the unique shape of a patient's nutrient groove may help with identification of the body, particularly if pre-mishap x-rays of the area are available for comparison. Their findings help support the assertion of Lichtenstein (1988) that radiology plays a significant role in the forensics of mishap investigation.

The forensics for aviation and spaceflight in the literature focus almost solely on mishap investigation, while general forensics looks for the cause of death to rule out suspicious deaths in criminal proceedings. Eventually, as humans venture further out into space and commercial entities take more and more passengers to space for longer periods, criminal intent and malfeasance will no doubt follow. In this case, the principles of forensics used on the ground in suspected criminal cases will have to be modified to account for the changes in microgravity or environmental factors.

The Federal Bureau of Investigation oversees forensic evidence gathering of all spaceflight mishaps that have occurred at NASA, secondary to NASA being a government entity. Local law enforcement oversees the forensic evidence gathering at commercial spacecraft mishaps, unless the mishap crossed state lines, involved a government asset, or occurred over/in international waters. Most likely, the FBI will follow maritime law traditions, in that if a spacecraft is chartered, licensed, or approved by the FAA, launches or lands in the United States, or involves government assets, they will assert their jurisdiction over the forensic evidence gathering. In these cases, the forensic evidence gathering is to assure the chain of custody, gather data for the mishap investigation, and to ensure there was no criminal intent. The criminal intent in this case may be from a company who sold inferior or counterfeit parts, that may have subsequently led to a spacecraft mishap and demise of the astronauts. As spaceflight continues to evolve from a mainly government-supported activity to a commercial and private venture, the potential for criminal negligence or other aspects necessitates the need for forensic knowledge and especially knowledge of how spaceflight or its physiologic changes impact basic tenets of forensics.

Traditionally, many of the changes in the deceased occur due to gravity and the remains coming to equilibrium with the surrounding environment. According to both Saferstein (2016) and Spitz (2006), livor mortis is the “bluish-purple discoloration” that occurs when blood settles into the gravity-dependent tissues. The vessels dilate and the blood compresses and eventually serum and blood cells extravasate from the capillary beds. If the capillaries rupture, you can have Tardieu Spots in addition to the blanching discoloration. But what if there is literally no gravity? In microgravity there is no gravity-dependent blood settling. Currently, there is no body of literature that addresses the effects of livor mortis in the microgravity of space or partial gravity environments of the Moon and Mars. Most likely, if someone died in microgravity, the blood would stay central. The typical rouleaux formation and stacking of red cells leading to leakage of capillary blood through loss of vascular integrity and the pressure column would not occur due to a lack of gravity. Bhattacharjee (2013) argues that the density of the fluids and their requisite specific gravity would cause layering with the heavier and more viscus fluids remaining central while others would leach out through the capillaries. But again, this assumes that gravity is present to layer the fluids based on weight and specific gravity. To date, no data on mice or other experiments in microgravity have looked specifically at this phenomenon. It is more likely that Tardieu spots would not occur, and that marbling would be the predominant feature. Thus, livor mortis would not be a good indicator of position of the body or movement of the body if, in fact, that body were in microgravity such as on the International Space Station.

Per Kori (2018) and Spitz (2006), rigor mortis is the post-mortem rigidity of the muscles due to locking chemical bridges between the actin and myosin chains, due to the lack of ATP and continuing glycolysis. The lower extremities of the astronauts undergo a morphologic change on orbit from slow twitch to fast twitch fibers. It is doubtful that this would have much effect on rigor mortis and per Koybiyashi et al. (2001) rigor mortis is unaffected by muscle volume. However, the antigravity posture would most likely become the posture the astronaut would be frozen in**.**

Thorton (2017) outlined the "sleep position" that occurs in microgravity. On the space station in microgravity when sleeping, the astronauts all assume the same posture. This posture is elbows flexed at 90 degrees, wrists flexed between 20-40 degrees, shoulder abduction of between 15-30 degrees, hip flexion of between 15-45 degrees, and knee flexion between 45 and 90 degrees. The lower extremity flexions can be hampered by having the hips and knees restrained with Velcro straps when sleeping. But every astronaut assumes this posture. It can be assumed that an astronaut who dies in microgravity would or should be found in this posture in microgravity.

Per Spatz (2006) and Meshram et al. (2017), algor mortis is the decrease in thermal temperature of the body after death until it comes into equilibrium with its environment. Depending on the study, most calculations show that the heat loss is more rapid in the first hour, between 2-2.5 degrees F and then slower thereafter, for an average of 1-1.5 degrees F. Meshram and his colleagues argue that algor mortis has the benefit of being able to estimate the time since death with more accuracy and less time range, due to less influence of environmental factors, with exception of surrounding surface and air temperature and that the body cools at a predictable rate. This allows an estimate of the time of death. But several things happen on Earth that do not happen in microgravity.

First, the body may come to rest on a cold surface such as a floor or the ground, thereby losing heat via conduction. The body also loses heat via convection and, if moist, via evaporation. However, all of these methods of heat loss are altered in microgravity.

Because of the lack of gravity, a body would not come to rest against a colder surface such as ground or flooring. Therefore, conduction would not occur. Convection is also not as efficient in microgravity as it is on Earth. Although heat loss occurs by convection, it is at a slower rate than on Earth. Lastly, evaporation is also dependent on the humidity on the spacecraft and whether the ventilation system is on and what fan speed is operating. The prime method of heat rejection in microgravity is radiant heat loss.

In fact, as Stahn et al. (2017) has shown, the astronauts have a higher core body temperature in space. Stahn (2017) argues that because of the anomalies in heat transfer as well as the interleukin-1 agonist upregulation in microgravity, the astronauts run a 2-degree F higher temperature than on Earth. Therefore, the calculations used to estimate time of death would not be as useful for determining the time of death on orbit. In all likelihood, the astronauts would average somewhere between 0.7- and 1.0-degrees F loss per hour and would start at a higher thermal temperature of 100 degrees F. Again, no animal experiments or human data has been published on this area as of yet, but thermal properties of space and peculiarities of human spaceflight would most likely impact the assumptions put forward in the earth-bound literature.

Prieto-Bonete et al. (2017) discuss the use of vitreous potassium in the eye as a reliable indicator of the time of death with a predictable regression analysis of the amount of potassium that leaches into the vitreous over unit time. They argue that there is a reliable and predictable rise in potassium in the postmortem vitreous humor that no doubt comes from the deterioration of local cells and the breakdown of the sodium potassium ATPase pump in those cells, thereby increasing the potassium concentration in the vitreous fluid, peaking around the 100-hour mark.

However, studies by numerous authors, including Kramer et al. (2012) has shown that astronauts on long duration microgravity missions such as the International Space Station, have an occurrence of elevated intracranial pressure and choroidal edema that occurs starting about the second month on orbit. This can cause vision changes in the astronauts and impacts male greater than female, with an incidence rate of around 70%. NASA is investigating agents such as Acetazolamide and GLP-1 agonists to treat this elevated intracranial pressure, based on the work of Mitchell, Mollan, and Sinclair (2019). Acetazolamide causes an increase in renal excretion of potassium and can temporarily lower intra-ocular pressure**.** The combination of its diuretic effects and its impact on pressure could change the normal distribution and curve of potassium accumulation in the vitreous humor and the amount of choroidal edema experienced by astronauts may also impact the amount of cellular water and potassium released on cell death. GLP-1 agonists lower intracranial pressure but also have an impact on aquaporins and CSF production via receptors in the choroid plexus (Botfield, Sinclair, 2017), which in turn may theoretically also cause a change in the fluid movement in the aqueous and have an impact of the vitreous potassium measurements. Therefore, vitreous potassium may not be a reliable indicator or predictable means of measuring the time of death.

Both Akin (2005) and Karger (2008) give an excellent overview of blood spatter, the patterns, the trajectory, and the physics that are behind the patterns secondary to velocity of the viscous fluid at crime scenes. But all of those assumptions are based on the 1 G gravity environment. Blood spatter requires an understanding of viscous fluid dynamics, force, velocity, and gravity. A viscous fluid flies through the air at a speed dependent on the force that wielded it, and encounters drag via air resistance against the surface tension of the fluid. It also encounters gravity, which impacts the angular acceleration and exerts a force that eventually causes an arc toward the force of gravity.

Kull (1991) and Sharp (1983) discuss the Rayleigh-Taylor instability in the flow of viscous fluids through the air and help define the interactions based on velocity, turbulence, viscosity, and acceleration. On the ground, the travel and direction of blood is influenced due to air resistance coupled with the angular momentum and gravity constant, which allows one to be able to predict the point of origin of the source of the initial force. However, in the microgravity environment, fluid dynamics behave differently and there is no gravity constant acting on the momentum or causing angular deceleration of a blood droplet. Thus, a droplet of blood could coalesce with other droplets in microgravity increasing the size of the droplet, and the droplet would continue along a straight-line trajectory until it meets a solid surface. It would therefore have a very different pattern than one would expect on the ground. Future work would need to be aimed at refining the Rayleigh-Taylor instability calculations to account for these features. To date, there is no literature on the impacts of microgravity on this area of forensic investigation.

Mallak's article (2018) is basically the only article, outside of NASA's special Columbia reports, that addresses the general forensics of human spaceflight. But even Mallak's description gives a very high-level general overview of what caused the death of the astronauts in Apollo 1, Challenger, and Columbia without going into great forensic detail or extrapolating the differences or unique aspects of spaceflight fatalities.

Both Frieberg (2020) and Staples (2014) give a comparison of the risk of fatality in human spaceflight compared to other risks such as driving in a car. But neither goes into the forensic findings on either a macroscopic or microscopic level or the specific differences seen in human spaceflight, but rather they focus on the amount of energy imparted and the safety factors weighted for the likelihood of a mishap between spaceflight and other modes of transportation. Reynolds et al. (2018) provides an overview of the general mortality of space explorers, but this is addressed more toward the lifetime and longitudinal health factors that might impact all-cause mortality of those flying in space and the causes of death for space explorers in general over their lifetimes. Beyond those articles, there is a paucity of literature or data on the forensics and differences in findings, especially forensic findings, in human spaceflight when compared to their aviation counterparts.

Spaceflight Fatal Mishaps

Despite there being relatively few fatal spaceflight mishaps by comparison to submarine, aviation, or even analog fatalities, there has been a plethora of articles written on them. Many are focused on the decision making, ethics, and politics of NASA for the Challenger and Columbia disasters. Only one or two of the articles in the literature delve into the actual forensics or the human systems aspects of the mishap investigation, with a notable exception being the NASA publications entitled *Columbia Crew Survival and Investigation Report* (2008) and *Loss of Signal: Aeromedical Lessons Learned from the STS-107 Columbia Space Shuttle Mishap* (Davis, 2014), both of which address the forces and findings for the Columbia crew. This was a notable departure for NASA to address these issues with such transparency, as no such report exists for Challenger or Apollo 1.

The Soviets investigated their spacecraft mishaps, but their investigative materials were never made public. Instead, first-hand accounts and witness reports have been pieced together over the years into articles and books that relay the accounts of the mishaps and their findings. Although I reviewed the literature looking at aggregated data for aviation and other analogous mishaps, which speak to more generalities, I will review the articles on the fatal spaceflight mishaps in more depth.

Soyuz 1

The Soyuz 1 mishap was secondary to the Russians suddenly feeling like they were leapfrogged by the United States. Gatland (1967) relays in his article that the Russians were pressing hard to achieve orbital rendezvous in space and had developed a new model of spacecraft to replace the Vostok and Voskhod spacecraft. This new model would be named the “Soyuz”. Neither the Vostok nor Voskhod were capable of docking with another spacecraft. This next mission would be both the checkout of an entirely new spacecraft, the Soyuz, and having these spacecraft dock with one another.

Oberg (1988) describes in his work that the Chief Designer, Vasily Mishin, was against the launch as he felt the verification and validation of systems had not been completed to satisfaction, but he was over-ruled by his superiors. In this mission, Soyuz 1 would launch first, followed a day later by lift-off of Soyuz 2. The two vehicles would rendezvous and dock in space. Soyuz 1 would carry a single cosmonaut to space, whereas Soyuz 2 would launch with a crew of three. Once docked, two of the crewmembers would transfer from Soyuz 2 and land with the command pilot in Soyuz 1. Komarov got the nod to command Soyuz 1 and Gagarin would be his back-up crewmember (Oberg, 1988, Ivanovich, 2008).

Almost immediately upon obtaining orbit, trouble began. The solar array on one side of the vehicle did not deploy properly, decreasing power to the vehicle. Two antennas did not deploy correctly, compromising communications. The navigation system did not give the correct feedback. Komarov fought to maintain guidance and control of the spacecraft. So many issues cropped up that the Soyuz 2 launch scheduled to launch the next morning was cancelled. The best trajectory to have Komarov land in the contingency area was to wait a day and bring him back home over Kazakhstan. Komarov attempted to get the vehicle in the right configuration for landing, but after separating from the service module he had difficulty keeping the right orientation (Ivanovich, 2008, Pesavento, 2003). As he began to enter Earth's atmosphere the spacecraft heated up and the cabin with it. Most likely the spacecraft's orientation was off slightly such that the vehicle was not entering squarely with the heat shield taking the major brunt (Oberg, 1977).

Komarov had poor thruster control and was unable to maintain the appropriate orientation. Frustration filled Komarov's voice as he spoke to the TsuP, the Russian version of Mission Control (Oberg, 1988, Hall, & Shayler, 2003). An audio recording of Komarov arguing with the ground control as he was about to re-enter, knowing he was likely to die, was recorded by a National Security Agency listening station in Istanbul (Oberg, 1988, Grahn, 2008). A 2011 article by National Public Radio (Krulwich, 2011) contains an audio file of the recording and the desperation in Komarov's voice is apparent, in any language.

After entering the atmosphere intact despite the high heat loads, the parachute system failed. The parachute system had been packed too tightly into the containment system, and the abnormal heat loads may have also damaged the compartment. Komarov plummeted in the Soyuz at 144 km/h or 40 meters per second impacting the ground. Per multiple authors (Oberg, Hall, Grahn, Shayler) the cause of death was obviously blunt force trauma from impact with the ground. Komarov's capsule burst into flames upon impact. Thus, blunt trauma and post-secondary fire were the findings for the autopsy. From a forensics standpoint, this mishap is very similar to those findings in high-speed aviation mishaps such as large jet liners.

Soyuz 11

Without question, the most authoritative work on the Soyuz 11 mishap is the Ivanovich (2008) book on the Salyut. Ivanovich relays in great detail how cosmonauts Viktor Patsayev, Georgiy Dobrovolskiy, and Vladislav Volkov launched from the Baikonur Cosmodrome early in the morning of June 1971. The issues and problems from Soyuz 1 had long been fixed, and multiple design changes had been made to the Soyuz vehicle. This mission was the first to rendezvous and dock with the Salyut space station, which had been launched into orbit unmanned by the massive proton rocket. But it was not the first attempt. Soyuz 10 had launched with the same mission and failed to hard dock with the space station. This was the second attempt to successfully attempt docking with the Salyut space station. The space station had a dual purpose: research into the human adaptation to space, and military reconnaissance (Ivanovich, 2008).

Upon a successful docking, the Soyuz 11 crew were to open the hatch between the orbital and docking mechanism, pressurize the tunnel leading to the space station, and then enter the station through a hatch at the end of the small tunnel from the docking port. However, there was an issue with the hatch to the docking port: the expected signal light did not come on. The crew could see air pressurizing in the tunnel, so they proceeded with opening the hatch. It was the first time in history that a crew had entered a space station (Chernyakov, 1975). The air in the space station was stale. Six of the eight ventilation fans in the space station had failed shortly after launch, so the crew began turning on the air scrubbers in order to recirculate the air (Ivanovich, 2008). Patsayev was able to remediate all six fans and reinitialize them, and the atmosphere cleared quickly. The crew carried out their experiments and set multiple records, spending 23 days in space. They ran multiple science research experiments, including on each other. It was the first time people had lived and worked in space for this length of time, and measurements of all bodily functions, electrocardiograms, and lab work were taken. A special telescope was used for observations and evaluating charged particles in space. By all accounts, it was a tremendously successful mission. Per Ivanovich (2008), all of the mission objectives had been completed.

Midway through their mission onboard the Salyut, a fire broke out. The acrid smell of burning electrical wires and smoke was evident behind one panel of the space station, and the crew called down to the TsuP alarmed and ready to retreat to the Soyuz for an emergency undock and de-orbit (Cavallaro, 2018). The ground controllers deactivated the power to that particular panel, and with it, the source of the burning smell and smoke. Smoke remained in the cabin and the crew complained of headaches. The ground controllers advised the crew to switch on the air scrubbers, which cleansed the atmosphere (Ivanovich, 2008).

Ivanovich (2008) describes how the remainder of the space station mission went without much excitement. On landing day, the crew prepared the station to be in “safe mode” to allow operations of fans and power from the solar panels so that the next crew to arrive on station would have power and a safe atmosphere. There were several hatches that the crew would pass through and close: the hatch from the station to the pressurized tunnel between vehicles, the hatch from the pressurized tunnel to docking mechanism, the hatch from the Soyuz service module to the docking mechanism, and finally the hatch between the service module and the descent module. If the hatches to the space station did not seal, the station would be lost. If the hatches in the Soyuz vehicle did not seal, the crew would lose their air to vacuum.

In Ivanovich’s (2008) account, when Dobrovolskiy closed the last hatch, the “Hatch Open” indicator light remained lit. TsuP advised the crew on a procedure to open and close the hatch again, thinking perhaps some small amount of debris was causing the issue. Again, the hatch open light remained (Ivanovich, 2008; Cavallaro, 2018). The crew was advised to use insulating tape to place over the sensor and then reclose the hatch. This time, the light went out.

On any given Soyuz flight, the same pattern occurs. The vehicle aligns itself for re-entry, the braking maneuver occurs to lower the vehicle in orbit to begin the descent, the vehicle then separates the descent and orbital module, and simultaneously separates from the service/propulsion module. This typically occurs about three hours after undocking to align the descent module for re-entry. The cosmonauts feel the braking maneuver occur as the vehicle adopts an orientation such that it is initially perpendicular to the direction of travel, so that when the two modules separate from the descent module, they are carried away from the capsule by atmosphere drag. The descent module then orients itself with the butt or bottom toward the direction of travel and slightly rotated down so as to take the brunt of the plasma and heat onto the heatshield. The other two modules burn up in the atmosphere, whereas the descent module, with its thermal insulation and heat shield, plummets through the atmosphere and plasma of re-entry (Ivanovich, 2008).

After re-entry, the vehicle deploys a drogue chute to slow down the vehicle and pull the main chute out of the parachute containment system. When the parachute is fully deployed, the heat shield is separated so that the gamma altimeter can measure the gamma scatter off of the Earth and determine the altitude. Radio contact is usually made with the crew as they descend. At around 10,000 feet, pressure equalization valves open up to equilibrate the air in the descent module with the outside air, to avoid any pressure differentials across the hatch and prevent barotrauma of the ears of the cosmonauts. Just prior to landing, four solid rocket motors fire to slow the descent of the module even further just prior to impact. In the early Soyuz program, the cosmonauts flew in shirt sleeves, without pressurized spacesuits. The suits were deemed unnecessary due to the pressurized cabin.

On this occasion the landing program worked as expected. The drogue chute opened, and the main parachute deployed without incident. The landing teams radioed the crew, but the crew was silent (Ivanovich, 2008). Multiple attempts were made to call the crew, but again silence**.** The ground team surmised that perhaps an antenna was damaged upon re-entry or parachute deploy. The solid rocket thrusters fired precisely on time, and the capsule landed perfectly in the steppes of Kazakhstan. The capsule came to rest on its side, which is often the case as the chute catches wind and tips it overThe landing team again tried to radio the crew, to no avail. Upon opening the hatch, the landing team found the crew perfectly in their seats, but the crew was dead. According to Ivanovich (2008), all three of the cosmonauts had cyanotic or blue patches about their faces and blood running from their ears and nose. Neither rigor mortis nor livor mortis was noted. In fact, Dobrovolskiy was reported to still be warm (see previous discussion on heat transfer in space and its potential impact on algor mortis), and other than the bluish mark on his face, and the blood from his nostrils and ears, looked as though he should get up and walk away. The Time of Useful Consciousness (TUC) would have been as low as 5-10 seconds for a cosmonaut exposed to vacuum and physically working to close a valve (Parker & West, 1973). That simply was not enough time for the crew to assure their own survival.

The medical teams started cardiopulmonary resuscitation (CPR) immediately on the crew, to no avail. Defibrillation was attempted in addition to CPR. The men could not be resuscitated. What the ground crews did not yet know is that a catastrophic failure had happened upon jettison of the orbital and service/propulsion modules. Somehow the jolt or shock of the jettison had caused the pressure equalization valves to open, venting the cabin air to the vacuum of space. The crew had heard the whistle of air rapidly moving through the vent and knew they were in trouble, but were unable to unstrap, find the valves and crank them closed in time. The crew had spent the better part of 12 minutes at vacuum and without the aid of pressure suits or oxygen, and thus died as a result of the lack of oxygen and ebullism (Ivanovich, 2008; Murray, 2013). Ebullism is the rapid movement of substances like water from a liquid to a gaseous state that occurs due to a lack of pressure. In this case, the dissolved gases in the blood literally boil causing bubblies in the tissues. Ebullism does not occur in aviation or aircraft mishaps, thus this finding and the physics behind it are unique to spaceflight secondary to the craft's exposure to vacuum (Busby, 1968).

Apollo 1

Shayler (2000) describes a scene at the Cape that is strongly reminiscent of a scenario that we are seeing today. The capsule arrived at the Cape from North American Aviation still in need of work. Ordinarily, this work would have taken place and been completed at the factory. But the schedule was pressed, and North American decided in this case to complete that work at the Cape. (Currently, both SpaceX and Boeing have plants at the Cape for their capsule work, in addition to NASA having its own Orion capsule work finished and processed there).

The Saturn 1B booster was at Pad 34 where the three crewmembers were suited and dressed for dress rehearsal known as the "plugs-out test", where the umbilical power cables are disconnected and the spacecraft operates under its own fuel cells and power. Gus Grissom, Ed White, and Roger Chaffee were assigned to the Apollo 1 mission and two of the three were veteran space fliers. The crew had been performing simulations in the main sim building but were due to test and perform this dry run and simulation on the pad. This allows the seals, auxiliary power, and radios to be checked and allows the crew to go through the simulated count-down (Shayler, 2000; Thompson, 1967). NASA does a similar test on the pad in current vehicles.

These simulations can be 5-6 hours but are usually halted at 3-4 hours due to "time on back", meaning the crew can get pretty uncomfortable lying on their backs strapped into the capsule. However, this simulation was going long because there were numerous issues with the vehicle. On this particular day on January 27th, 1967, the biggest concern on the mind of the crew was the communications (Shayler, 2000)**.** This was before the days of cell towers, and radio communications were relied upon between the capsule and launch control, and the block house where technical monitoring of the spacecraft took place. Previous simulations had shown multiple problems with the communications, so much so, that Deke Slayton (who was at the time the Chief of the Astronaut Corps) and Joe Shea (Program Manager) were tempted to sit in the capsule with the crew to listen in to the communications in order to hear what the crew was experiencing. Ultimately, it was deemed too difficult to accommodate both men and to rig up additional communications equipment for them (Thompson, 1967).

The capsule was going to be as flight-like as possible. It would be saturated with 100% oxygen and the capsule would be over-pressurized by 10% over atmospheric so if there were any leaks they would leak from within the capsule to the outside air. That meant that instead of 14.7 psia, the capsule was now going to be at 16.7 psia (Shayler, 2000; Seamans, 1967)**.**

The crew had been on their backs the better part of 5 hours and Grissom was getting increasingly frustrated with the ratty communications. He stated angrily "how are we going to get to the Moon when we can't talk between two or three buildings". Roughly ten minutes later Grissom can be heard stating "Hey…Fire…..we have a fire in the cockpit"….. "we have a bad fire….get us out….we are burning up….." (Shayler, 2000; Thompson, 1967). The transmission ends with the sound of Grissom or Chaffee in a fatal scream (Shayler, 2000; NASA Audiofile, 1967). In total, from the start of the fire until the crew was dead was roughly 17 seconds (Shayler, 2000). All three crewmembers perished in the fire. It would be several minutes before the pad crew could get close to the capsule and open the hatch, but everyone knew what they were going to find. The autopsy was noted in the Presidential Commission Report, and it was determined that the cause of death for the crew was inhalation of hot gases, combined with burns and toxic fumes (Johnston, 1967).

One could argue that this was a pad industrial mishap and not a spaceflight mishap, especially since the vehicle did not leave the ground. But the over-pressurization of the cabin, the 100% oxygen environment, and the vehicle were all unique to spaceflight. it is possible that research will show how these differences affected the outcomes in this mishap as compared with aviation mishaps.

Challenger

In 1986, NASA was struggling to make good on the promise of up to 50 launches per year of the Space Shuttle from Kennedy Space Center and Vandenberg Air Force Base. The original idea of the Space Shuttle was to launch payloads for commercial and science from Kennedy Space Center and launch military payloads from a Vandenberg Air Force Base into a polar orbit. In fact, the size of the payload bay for the vehicle was dictated more heavily by the Air Force requirements than they were from commercial or civilian requirements.

NASA had flown Senator John Glenn and Congressman Bill Nelson as "Congressional Observers", which was a bid to keep interest in the space program going, especially in Congress. NASA had also flown several "payload specialists" from the space and aviation industry and was attempting to get other industries interested in space by soliciting potential payload specialists from pharmaceutical, materials science, and semiconductor industries. There were discussions of how best to engender public support for the space program, which had dwindled sharply after the Apollo missions. NASA was concentrating on the business and political case. Think-tanks discussed sending actors, writers, painters, and others that might somehow translate the emotion of spaceflight to the average person. After a briefing on these options to President Reagan by the NASA Administrator, James Beggs, the President seemed to lack any interest.

Two weeks later, the President asked NASA to send a civilian to space, but not an artist or author, but a teacher. The Teacher in Space Project then launched in full force with a national competition to find a teacher who could spur Science and Math education and perform lesson plans from space (Shayler, 2000, Vaughn, 1996).

Christa McAuliffe, a teacher from Concorde, New Hampshire, ultimately won the selection as the "Teacher in Space". Barbara Morgan, also a teacher, was her back-up They were (or, McAuliffe was) assigned to STS-51L in an effort to increase public support for the space program and science education. The mission was garden variety, with deployment of a Tracking and Data Relay Satellite (TDRS), a handful of science experiments, and no spacewalks scheduled. The main event, aside from the satellite deployment, was to be McAuliffe giving lessons from space to school children across America (Shayler, 2000)**.**

Challenger was originally scheduled to launch in December of 1985. The orbiter was mated to the stack of external tank and solid rocket boosters on December 10th and began its journey to pad 39B from the Vehicle Assembly Building on December 16th. Pad 39 B was an old Apollo Saturn launch site, which had recently finished its refurbishment in preparation to have two launch sites available at Kennedy in addition to the launch site at Vandenberg, so the program could increase its launch rate and operations tempo (Shayler, 2000).

Both Shayler (2000) and Vaughn (1998) briefly touch on the decision chain of NASA and the politics at the time. At the mission Flight Readiness Review (FRR) Morton Thiokol engineers brought up a concern that the O-rings in the solid rocket boosters had not been designed or given adequate performance testing for super low temperatures such as those predicted in this unseasonably cold Florida time period (Shayler, 2000). The contraction of the rubber seals and potential cracking was a concern. Great debate took place both inside Morton Thiokol and at NASA. NASA was concerned about the schedule. President Reagan was scheduled to mention the Teacher in Space Project during his State of the Union address and delaying the launch until warmer temperatures was not something they wanted to do. Morton Thiokol was also non-specific in some of their concerns, with limited data to bound the risk. The O-rings had not been tested adequately at those temperatures, so the risk was seen as theoretical by some in NASA management.

However, Thiokol engineers who worked directly on the booster unanimously opposed launching in those temperatures. Shayler discusses that ultimately, Morton Thiokol's Vice President signed the Certification of Flight Readiness statement at the FRR. It is customary for all of the heads of departments and main contractors to sign the Certification of Flight Readiness statement when they agree that a mission is ready to fly. Shayler does not mention the one oddity about the Flight Readiness Review, perhaps because he was unaware of it: the NASA Administrator was not present. Beggs had been indicted on fraud charges stemming from inflated billing practices at his previous job as a Vice President at General Dynamics (Marshall, 1987). Beggs did not attend the FRR while he was pursuing his defense against the charges, even though technically he was still the NASA Administrator at the time.

Challenger sat on the pad in Florida for 37 days before the crew was loaded into the vehicle and strapped in by the close-out crew, which always has one astronaut on it as a result of the Apollo 1 fire. The astronaut member of the close-out crew assisting the crew and helping them strap in was Dr. Sonny Carter (Shayler, 2000)**.** The close-out crew had trouble sealing the outside orbiter hatch. Another close-out team came to assist, but unfortunately had power tools with them (electrical power tools are not permitted to be used on the vehicle once it is fully fueled; a single spark when vapors are present could be catastrophic). According to Shayler, the hatch issue "delayed the launch by 80 minutes", at which time the launch window was narrowing and the winds had picked up dramatically.

The launch was scrubbed due to weather and winds aloft. The crew returned to crew quarters and would try again the next day. The crew consisted of Christa McAuliffe, veteran astronaut/Commander Dick Scobee (Air Force Major), Pilot Mike Smith (Naval Commander), Mission Specialist and Flight Engineer Judy Resnik (PhD), Mission Specialist Ellison Onizuka (Air Force Captain), Payload Specialist Greg Jarvis (Hughes Aircraft Corporation), and Mission Specialist Ron McNair (PhD in Physics from MIT).

Overnight the temperatures dropped well below freezing into the lower 20's. Ice inspection teams who would go to the pad throughout the night noted large amount of ice forming on the vehicle and tower. Mist from the ocean shore combined with the freezing temperatures allowed a cascade of ice to begin forming throughout major areas of the pad in the night. It did not look likely that the crew would launch at 08:30am that morning. The crew were strapped into the orbiter, and each crewmember noted how cold it was in the white room before entering the vehicle (Shayler, 2000).

The launch window would allow the team to wait until roughly before noon to launch, and it was assumed that the warm Florida sun would melt most the ice and increase the temperatures (Vaughn, 1998). Holds were put into place to allow the vehicle to launch just after 11:30am Eastern. Per Shayler (2000), the ice teams believed enough ice had melted and they had knocked off enough ice to proceed with the launch. At around 10:30am, an hour prior to scheduled launch, the ice teams reported favorable ice, and the launch teams reported the left-hand Solid Rocket Booster (SRB) to be 33 degrees F (in direct sunlight) and the right-hand booster to be 19 degrees F (in shade of the vehicle and tower). The launch team proceeded with the countdown and on 28 January at 11:37am, liftoff commenced.

In photos after the mishap, a small puff of smoke can be seen from the right-hand SRB O-ring joint. A few seconds later, the right solid rocket motor pressure reads slightly higher than normal. After the Space Shuttle main engines are at 104% throttle, there is indication of flame at the right-hand solid rocket motor at the area where smoke was first seen (House Report 99-1016 ,1986). The crew was given a go for throttle up, which occurs after the vehicle passes the boundary layer for maximum dynamic pressure on the vehicle from the atmosphere. Slow motion photography shows a plume from the solid rocket booster to the external tank ring frame. Hydrogen then begins leaking from the external tank. There is a change in pressure in the liquid oxygen fuel tank of the external tank, and then a large bright cloud followed by a flash between the external tank and the orbiter. An explosion ensues and the solid rocket boosters come apart from the structure and begin a winding pattern in the sky, and eventually are destroyed by the range safety officer. The last thing heard on the flight recorders after “roger, go with throttle up” is Smith saying “uh-oh” just before the explosion. The Challenger was seven miles down range from the Cape, at an altitude of 50,000 feet (Roger et al., 1986).

The crew compartment came apart from the vehicle and continued an upward trajectory from 50,000 feet to around 64,000 feet before arching and starting to its journey to the ocean. A trail or streamer of wires and bundles can be seen trailing after the crew compartment of the orbiter, which had separated just before the payload bay (Shayler, 2000). As the pressurized crew compartment begins this arc, the front aspects of the orbiter can be made out in high resolution photos. Shayler states that the crew was unconscious after the explosion and that autopsy results were inconclusive. Certainly, impact trauma as the compartment slammed into the ocean was a contributor to the cause of death. However, no specific autopsy report is included as part of the Rogers Commission Report (Rogers et al., 1986).

Columbia

There is a noticeable change in the Presidential Commission and NASA internal reports regarding Columbia: they are transparent and open. The Gehman Report and NASA's *Columbia Crew Survival Investigation Report* and *Loss of Signal: Aeromedical Lessons Learned From the STS-107 Columbia Space Shuttle Mishap* reveal the engineering analysis of both the crash itself, the aerodynamics, and physics of what occurred, and the forensic analysis of the crew. It is the most comprehensive and forthcoming report on the forensics for this spaceflight mishap in publication. But it does not provide a cross-case analysis or identify those areas that are most unique to spaceflight versus aviation mishaps. It provides an in-depth analysis of Columbia, but does not serve as a primer for spaceflight mishap investigation in general and how the forensics differ between spaceflight and other transportation entities.

NASA had been dealing with foam issues on the external tank for some time. Foam had been shedding from several areas of the external tank on lift off, principally from areas around the bipod ramp, which was part of the structure that mated the external tank to the Space Shuttle orbiter. NASA had looked at different methods for applying the foam, as well as coverings or "stockings" to cover the external tank in case of foam shedding, and all of these were regarded as not adding value to the risk mitigation. The foam shedding had struck an occasional tile on the orbiter, but the risk was considered acceptable, and the foam shedding was "within family." This particular mission was a science mission for the Space Shuttle, and not headed to the International Space Station. It was a brisk morning on February 1st, 2003, when the crew launched from the pad at Kennedy Space Center. Several of the cameras noted what appeared to be foam striking the left wing on the orbiter on ascent.

There was some debate among the Mission Management Team as to whether imaging of the left wing should be done. Because of the science payload on this mission, the Canada remote manipulator arm was not attached to the orbiter, and there also was not a method for repairing the wing on orbit if it had been identified as a problem. In addition, it would require a plane change and orbit change to get to the International Space Station for safe harbor, and Columbia neither had the docking mechanism nor the fuel to achieve such an orbit. NASA had always considered the tiles or insulating blankets as potential areas of concern, but never regarded the leading edge of the reinforced carbon-carbon wings as particularly vulnerable.

NASA engineers asked if perhaps Spy Satellite assets could be used to evaluate the areas where a suspected foam strike took place. But the fact that there was not a good mechanism for repair of any findings, as well as the cost to refocus the satellites, made this an untenable option. It would also telegraph the classified nature of those satellites and their resolution capability to adversaries. With these factors in mind, the mission managers decided against it (Gehman, 2003).

With their 16-day mission completed, the crew of Columbia began their return to Earth. Sadly, they would not make it home. Plasma entered the left wing in the hole created by the foam strike and began superheating struts. Pieces of the wing began to shed. The thrusters began firing to try and maintain attitude control. The tire pressure light and landing gear light in the left wing came on. Rick Husband began trying desperately to maintain control of the spacecraft coming in at Mach 15. The left wing then departed the spacecraft, and the orbiter began a nose up leftward pitch and flat spin, causing aerodynamic instability (Horvath, 2014). Hydraulics had been lost.

The pilot attempted to recover hydraulics with an APU restart. The vehicle became unstable and began to break up with a G load of 3.5 G's and aerodynamic instability between 140,000 and 180,000 feet (Gehman, 2003). Per Barratt and Banks' chapter in *Loss of Signal* (Davis, 2014) the crew module remained intact initially during the catastrophic event but depressurized soon thereafter. Per Barratt and Banks (Davis, 2014) the Crew Module Catastrophic Event (CMCE) occurred roughly 30 seconds after the vehicle began coming apart at an altitude of approximately 60 km.

The loss of pressure at that altitude would have caused the crew to have nitrogen coming out of solution (the bends), pulmonary barotrauma, immediate loss of consciousness, and mechanical injuries from the torsion and forces being exerted (Packham, 2017). Barratt and Banks (Davis, 2014) discuss that the autopsy results revealed that the crew suffered mechanical injuries, such as bracing injuries during the event where the orbiter was losing integrity. Bracing injuries are where a person uses their feet or hands to brace themselves and end up suffering fractures in those areas as the forces overcome their ability to brace. Depressurization injuries and barotrauma as well as thermal injuries from the intrusion of plasma and exposure to the atmosphere at that speed were also encountered (Davis, 2014).

Lastly, injuries due to impact with the ground were also seen. Vascular tissues and pulmonary tissues experienced near vacuum, and ebullism was apparent with deposition of bubbles in the tissues and vasculature, not unlike that experienced by the Soyuz 11 crew. Mechanical injuries were seen, including the above-mentioned bracing injuries but also torsion and tears in the musculature from flail, with ensuing bleeding into the musculature, which indicated the cardiovascular system and heart were still working in order for those tissues to bleed. Thus, many of the injuries were antemortem events (Davis, 2014).

There was no evidence of fire; although the skin had thermal injury, it was not consistent with flame, but rather with plasma. Unlike typical aviation injuries, the mechanical trauma was due to flail and not due to impact trauma. Likewise, although several of the crew experienced depressed skull fractures, those were secondary to a valve located inside the helmet. Atlanto-occipital dislocation, where the weight of the helmeted head causes fracture at the cervical spine and essentially separates the skull and head from the cervical spine, were also seen (Davis, 2014). Again, these are injuries that are not consistent with the typical injuries discussed previously with aviation mishaps.

Virgin Galactic

In October of 2014, two test pilots took the Virgin Galactic Spaceplane for another operations and checkout test flight. Unfortunately, according to the NTSB report (2014), the co-pilot unlocked the commercial spaceplane’s feathering system well before the checklist required them to do so, causing dynamic instability (Witze, 2014). The system is supposed to be activated after hypersonic flight over the speed of sound (greater than Mach 1) to place the spacecraft in appropriate position for atmospheric re-entry (See, 2016). By activating the system too early, it caused instability as the spacecraft attempted to cross the threshold of the sound barrier, causing the twin tail booms to reverberate and begin to break apart.

The vehicle suffered a catastrophic failure and came apart. The pilot had his seat torn clear of the spacecraft, and he unfastened his seat restraint and was able to use his parachute. The co-pilot was unable to exit the spacecraft and was killed upon the spacecraft impact with the terrain. Per the NTSB report the pilot was thrown from the spacecraft at an altitude of 50,000 feet, and per Chappel (2015) he suffered flail injuries including four fractures to his right arm, a dislocated shoulder, fractured right clavicle, and foot fractures. He sustained severe contusions to his face, torso, and legs and had debris injuries to his corneas (eyes).

The pilot did not remember portions of the spacecraft breaking up, most likely due to G loc (loss of consciousness from high G and low blood pressure), (Chappel 2015). The Virgin Galactic mishap represents an almost hybrid between aviation mishaps and spacecraft mishaps in that the forces at atmosphere were those not typically seen in aviation mishaps. The decompression of the cabin and loss of integrity of the vehicle also lends itself more to spacecraft mishaps than aviation mishaps, but the death of the co-pilot due to multiple trauma from terrain impact and human factors errors leading to the mishap are seen more in aviation mishaps than spacecraft mishaps.

Conclusion

There are significant gaps in the research and literature on spacecraft fatal mishaps, especially in terms of the forces, environment, atmosphere, and cause of mortality. There is also a paucity of data or research that extends to an evaluation for commonality across spaceflight mishaps or in comparison to aviation mishaps. This information is incredibly important for those investigating spacecraft mishaps, especially those involving future commercial spacecraft. There are sufficient differences between the trends seen in forensics and investigation of aviation mishaps from spacecraft mishaps such that errors could occur if the investigator is not familiar with the physics for spacecraft. Hazards, both toxic and radiologic, could also be seen at the scene and at autopsy such that knowledge of these is imperative to maintain safety of the investigative team.

Perhaps the most important reason to characterize and group fatal spacecraft mishaps to identify trends and differences is in order to prevent the mishap from occurring in the first place. Engineering, safety, and medical technical authorities who oversee spacecraft development should study and note specific lessons learned from fatal spacecraft mishaps which may impact design and may allow more appropriate risk management and the development of crew survival equipment or countermeasures. This may be especially relevant for the rapidly expanding commercial spaceflight industry, in order to increase passenger safety and survival in off-nominal situations.

Although Arctic and Antarctic missions are often seen or utilized as analogs for spaceflight, the mishaps and fatalities in those areas do not represent or mirror those seen in spacecraft mishaps. They may reflect or be analogous to surface occupational mishaps on the Moon and Mars in future exploration missions, and therefore their lessons learned may be important to future mission planners in order to avoid similar such circumstances. Future studies in this area may be valuable toward that end.

Submarine mishaps and fatalities likewise do not mirror the forensics of spaceflight mishaps. However, the rescue of stranded submariners must take into account the docking and mating of two pressurized vessels, decompression sickness, and potential toxic and radiologic hazards such that lessons learned from submarine rescue could be applicable to future spacecraft rescue. Again, although not analogous to current spacecraft mishaps, the mining of such data and focus on the crew rescue components may be worthwhile for future studies.

CHAPTER III

METHODOLOGY AND RESEARCH APPROACH

"The power of statistics and the clean lines of quantitative research appealed to me, but I fell in love with the richness and depth of qualitative research."

- ***Brené Brown***

Introduction

The purpose of this study is to identify the unique aspects and distinct differences between spaceflight mishaps and how they differ from aviation mishaps in terms of physics, forensics, and environmental details. This will be important both for future mishap investigators and for technical authorities who oversee the construction and development of new human-rated spacecraft. If you know the causes, risks, hazards, physics, and environment that contributed to the lack of crew survivability in previous mishaps, then you are better able to mitigate them when designing or building human-rated spacecraft in the future. It is postulated that this study will show there are significant differences between spacecraft mishaps and aviation mishaps. As the Federal Aviation Administration will be tasked with certifying the flights and the National Transportation Safety Board will be tasked with the investigation of any commercial or private spaceflight mishaps, it is paramount that these differences be identified and highlighted. Otherwise, if an investigator or official treats a spacecraft mishap just as they do an aviation mishap, details will be missed that might lend themselves to causality, and more importantly to lessons learned to prevent future mishaps.

Rationale for Research Design

In exploring the ways in which to research this subject matter, it was clear that a qualitative analysis would be more valuable than a quantitative approach. The reasons for this are that the sample size for human spaceflight mishaps is relatively small, and therefore a quantitative approach would lack sufficient power. But a quantitative approach would also lack sufficient depth. Although it might lend itself to likelihood or incidence rates, it would lack the depth of context required to fully understand why and how a human spaceflight mishap occurred, and the evidence it leaves behind, and what makes that mishap different from others.

Even a regression analysis or simple student T-test would not have enough sample size to make assumptions about causality nor get to the deeper questions of why or how human spaceflight mishaps are unique. In the preceding chapter where the literature on mishaps was reviewed, it was clear that there was a lack of detailed depth on the human spaceflight mishaps, and that previous authors had spoken mostly to the political decisions and faulty logic when coming to a launch decision and had missed some of the greater engineering and forensic data that would be valuable to future investigators or to those charged with future spacecraft development. Therefore, a qualitative approach with a deep dive into the findings and data would be more valuable in this instance.

When deciding on the type of qualitative approach, the logic in selecting which design to use is important, especially when taking the type of data into account. Since the study is targeting human spacecraft mishaps, which in itself is a purposeful sampling, this type of qualitative approach begins to rise to the top in terms of methodology.

However, the phenomenology and epistemology of the study should be aimed at diving deeper into the context of the spaceflight mishap cases, and specifically at the data surrounding the environment, physics and forensics of the human body and what caused the failure of human tolerance to the stress or environment of the mishap and what evidence of this fact remains for the investigator to find. Patton's (2014) text explores multiple different strategies, but Suri (2011) breaks these down into sixteen such strategies specifically when employing purposeful sampling. While the research question is focused on the unique aspects of human spaceflight mishap cases, Patton's Unique Case Orientation methodology is only partially viable to that end. The Case Study Method begins to rise to the top in that it allows for the review of the extreme cases (fatal spaceflight mishaps) in depth, a cross comparison between those cases, and a comparison to known findings in aviation mishaps.

As shown in the literature review in chapter two, there were several papers that used qualitative methods to evaluate mishaps, and at times they were used to augment the quantitative research. In a paper by O'Connor (2007) the consensual qualitative research (CQR) method was used to explore diving mishaps in the Navy because of the relatively low sample size. Quantitative measures were used, but interviews with the divers used open ended questions and an emergent strategy of purposeful sampling. Miranda et al. (2018) used a mixed method to explore Navy aviation mishaps with both quantitative and qualitative data and using Bayes Theorem to calculate the probability of an incidence occurring, but also explored the qualitative data using purposeful sampling and criterion sampling. Of specific note is Miller's (2005) treatment of the NASA knowledge management system and passing down lessons learned, where qualitative data and multiple mixed sampling was used to explore the depth of the engineering lessons learned.

The Delphi and modified Delphi were briefly entertained, but the purpose of the Delphi is to use subject matter experts to gain consensus on an issue or probability of a future state occurrence. This study will instead be retrospective, not prospective, and it could be argued that there are no true subject matter experts on spaceflight forensics. Delphi may be valuable in discussing consensus on areas of focus or future policy but is not sufficient for the deep, rich context required for this analysis.

In Sandelowski's paper (1996), she argues that the epistemological basis and main impact of qualitative research is built around the case study. Likewise, Malterud et al. (2016) suggest the term "information power" for qualitative studies, suggesting that the more information and context that a particular sample holds, especially in a rich case study, the less quantitative number of samples are needed. This would not hold true for something like proving causality or certainty, but it would certainly show context for deeper trends and thorough investigation. A good example of this is the Challenger disaster. The "n" number of Space Shuttles that have met their untimely end due solely to an O-ring is only one. But deeper lessons from the deep dive of this case extend to the political, cultural, and engineering rationale for the decision to fly that day. Books have been written about this single case, and NASA changed its culture and organization as much as it could after that case. The forensic and mishap lessons learned from that case are unique. Malterud et al. (2016) would argue that the power in that information gained from the Presidential Commission on the Challenger Accident and specific lessons from that mishap changed entire organizations and space policy, despite having been a singular case. Thus, in Malterud's treatise, it is argued that "power" has less to do with statistics and more to do with the potency of the information gained. This lends itself to case study again being the best methodology.

Despite the argument that each case is unique and has power in the context of the illumination of what is uncovered in the deep exploration of the subtext, most authors still employ a method to look across cases for trends and commonality. In essence, despite their argument that the case and its context stand alone, they are looking for quantitative trends in the data when the cases are compared to one another. This is especially true when comparing behaviors across multiple cases. In that instance, Giorgi's Descriptive Phenomenological Psychological Method (Giorgi, 2009) for cross-case analysis might be employed to see what common aspects might occur in the interviews with those who were engaged in the decision-making process, or the policy making, or in the investigative process. Giorgi is aware of the potential ability of an interviewer to inject their own bias and suggests some specific guidelines when constructing these descriptive methodologies using a modified Husserlian approach (Giorgi, 2009). Edmund Husserl developed these methods at the turn of the century, and they were aimed at clarifying how events (witnessed, heard, narrated) are perceived by individuals and if there could be clarity in the purpose and objective detailing of questions so as to eliminate subjective bias on the part of the observer as best as possible (Giorgi, 2009; Giorgi, 2010).

Patton (2014) argues that there may not be commonality or trend analysis capable in extreme or deviant examples; that they may be outliers to the events of the social norm and therefore may not have cross-case commonality. But Miles and Huberman (1984) state that this is missing the point. The point is to get the data out there, to examine it, to talk about it, to ponder it. Even the extreme or deviant data points are valid data even if they have no equal for comparison. Ironically, I think part of the answer comes not from the mountains of papers on qualitative analysis, but from Nasim Taleb's work on the Black Swan (2007) and its impact on the highly improbable. If you use Taleb's work as the basis, you can treat the cases as both unique and extreme, until they are not. Taleb argues that this extreme event may have been predictable, had we known the context. We think the black swan is unique or extreme until we meet the second one.

In much the same way, the Apollo 1, Soyuz 11, Challenger, Columbia, and Virgin Galactic mishaps could be viewed as unique and extreme simultaneously. We had 50 flights of the Space Shuttle giving an "n" that would give us comfort that we knew what was going to happen on the 51st. In engineering parlance, they call this "in family." It is akin to stating that we have seen some anomalies on this spacecraft but nothing bad has happened each time we have seen it, so therefore we think nothing bad will happen in the future. It is perhaps the most dangerous line of thinking when addressing risk acceptance in a space program. Therefore, the low number of these extreme, Black Swan, unexpected "in-family" mishaps lend themselves to deep case study as a methodology.

Yin (2018) has written extensively about the use of "Case Study" as a methodology. Stake (2013) however believes that "Case Study" is less a methodology, and more of a strategy for execution. For the purpose of this study, the case study method as described by Merriam (2015) will be used, by examining historical cases in an intrinsic fashion. In this study, “extreme cases” are used to examine deviation from the norm to characterize and understand the outliers in hopes of finding deep contextual data that has yet to be described.

With that strategy and methodology in mind, fatal human spaceflight mishaps have been chosen for this study with the intention of both identifying unique and content rich characteristics of each mishap, but then comparing across all fatal human spaceflight mishaps to look for common themes or distinct differences using a cross-case analysis. In doing so, the study of these fatal spaceflight mishaps is both intrinsic in that they are a unique phenomenon which the author believes has distinguishing features that separate it from other types of mishaps, and inductive in that the reasoning will go from specific instances and examples to an overarching theory and general conclusions.

Unlike many case studies where the researcher is embedded with the subject matter experts to observe the event in real-time in order to gain perspective and ethnographic insight, this study involves multiple extreme cases that have occurred over time. It will concentrate on technical, environmental, forensic and procedural aspects elucidated in the reports, autopsies, and interviews for empiric data as opposed to ethnographic data to establish what is similar and different between spaceflight mishaps, and then how they compare to aviation mishaps and other similar analogs. This aligns with the historical case study examples and allows inductive analysis of those elements under study, borrowing some elements of constructivist approaches and multiple case strategy proposed by Stake (2013), with cross-case analysis and deeply rich contextual development elucidated by Yin (2011), and the approach to historical data and inductive reasoning discussed by Merriam (2019). This approach will be using elements from each of these experts in case study (Yazan, 2015) in order to apply an approach with the best fit to the research question.

Semi-structured interviews were carried out with 15 individuals who were involved in the investigation, interpretation, or evaluation of fatal spaceflight mishaps. The backgrounds of these individuals varied in order to give a variety of lenses and multiple facets to gain a higher understanding of the mishap. The diversity of the skills mix allowed for a holistic viewpoint of the mishap from multiple subspecialty fields and expertise.

Furthermore, additional empirical data was acquired utilizing autopsy reports, accident reports, and official investigation reports. These were analyzed in order to identify features that may be unique, as well as details that needed to be thoroughly explored. Lastly, previously authored texts or articles on the mishaps were also evaluated. These three separate lines of inquiry and data streams were then analyzed for convergence in order to achieve triangulation. Empirical data was managed and stored in NVivo 12 software.

Organization of Data Analysis

The data will be organized such that the interviews of the subject matter experts is first, with coding of their interviews being undertaken primarily. Following the interviews, the data and texts from previous investigative authorities, investigative documents, autopsies, and official records will then be described. New details, unique characteristics, as well as normative findings and deviations will be provided. Coding that comprises all three of the main sources will then be undertaken to look for major themes.

From there, convergence and triangulation will be explored in order to identify where there is congruence, and again identify themes and theories about the differences in human spaceflight that arise from the data. A cross-case analysis will then be pursued looking to look for commonality or dispersion. Lastly, a comparison to the findings noted in the literature review to other types of mishaps will be given, with a heavy emphasis on comparison to aviation mishaps.

Research Questions and Hypotheses

In essence, the main question is whether there are differences or unique characteristics of spaceflight mishaps relative to aviation mishaps. Do they differ significantly from aviation mishaps? Do they differ significantly between each case? Are there forensic differences? Are there physics and environment differences?. The reason for this line of questioning is that the process of mishap investigation is most likely the same. Each is conducted in a systematic way. But it is assumed that the context and understanding of the temporal, engineering, physics, forensics, physiology and pathology of a nominal and off-nominal human spaceflight mission is required to fully comprehend the findings of a spaceflight mishap. This is the essence of the research question and, in light of the rapid evolution of commercial spaceflight, one in which the future mishap investigators will have an interest.

Assuming there are unique differences between spaceflight mishaps and others, then answering the research question must include the identification of environmental and forensic aspects of human spaceflight mishaps. This will be done through extreme case study in order and deep investigation of materials. The goal is to pass on those lessons learned and unique aspects to future human spaceflight mishap investigators or technical authorities. By educating the technical authorities, it is hoped that design changes can prevent future similar occurrences.

The National Transportation Safety Board (NTSB) will be in charge of investigating commercial spaceflight mishaps. Without question, they have a great deal of experience with non-human rated spacecraft accidents. NTSB also has experience with both the Columbia and Virgin Galactic human-rated spaceflight mishaps, but this limited experience pales next to their extensive work in aviation mishaps. In addition, local forensics and medical examiners will be used in commercial mishaps as opposed to the Federal Bureau of Investigation (FBI) Evidence Response Teams and the Armed Forces Medical Examiner. These local entities will most likely have never been exposed to the unique nature of spaceflight, and there are currently no textbooks or extensive bodies of literature from which to draw upon in regard to spaceflight forensics.

This means that many entities that are unfamiliar with human spaceflight physiology, pathology, and forensics as well as potentially unfamiliar with the physics of spaceflight mishaps, will be prime to investigate those mishaps. In addition, the National Aeronautics and Space Administration (NASA) is at its busiest time in history, with more vehicles and programs in development thanks to its Commercial Crew, International Space Station, Gateway, and Artemis programs. Yet, the majority of the technical authorities charged with oversight of these programs were not at the agency during its last fatal spaceflight mishap and may also lack the knowledge of the lessons learned and unique aspects associated with the history of human spaceflight mishaps.

In order to get to this data and answer the overarching research question, semi-structured interviews were conducted utilizing five questions as starting points. However, the interviewees were encouraged to take the interview or the answers to the questions in any direction they chose. The investigator asked follow-up questions to explore an issue more deeply and ensured that the research questions were addressed.

The five questions that were given to the interviewees were the following:

1. *Are there physical or environmental differences between a spaceflight mishap and other mishaps that stand out in your mind that would be important to highlight for future investigators or tech authorities?*
2. *Are there forensic differences that are unique to spaceflight mishaps? If so, what are those forensic differences or unique aspects in spaceflight mishaps that stand out in your mind from the mishap you were involved with?*
3. *For future human spaceflight mishaps, be it commercial, NASA, or military- what are some of the most critical lessons learned that should be relayed to future mishap investigators?*
4. *For a technical authority charged with aiding in human systems design of new spacecraft, are there lessons that stand out in your mind that they should consider based on the mishap that you were involved in?*
5. *What skills should the mishap investigator possess when dealing with a human spaceflight mishap?*

Presentation of Descriptive Characteristics of Respondents.

A multi-specialty group was sought for interviews in order to gain a rich and holistic perspective on each of the mishaps. Individuals with first-hand knowledge of individual mishaps, those who were involved in the investigation, oversight, or study of the mishaps in question, were engaged and consented for the interviews. The goal of the study was transparent to all of the interviewees. Some of these individuals were so prominent, or their titles so exclusive, that it would be readily apparent as to their identities.

To maintain anonymity, the descriptions of their backgrounds have been sanitized. However, this has the unintended consequence of potentially not allowing the reader the appreciation of the depth of their expertise and does not do justice to the level of their skill and knowledge of the subject matter. It was especially important to capture the opinions of those with knowledge and insight into Apollo, Soyuz, and the Challenger accidents, as the potential to lose that insight is ever present as the years wear on and those individuals grow older.

Table 1 below shows the individuals and their general expertise. Some of the more contemporary interviewees that worked on private spaceflight mishaps had non-disclosure agreements in place, and therefore could only speak in general terms without commenting on proprietary equipment, hardware, or specific individuals when discussing those mishaps.

1. A flight surgeon involved in the Apollo program and mishap investigations;
2. A pathologist involved in the Columbia investigation;
3. A flight surgeon involved in a commercial spaceflight mishap investigation;
4. A human factors specialist involved in the Crew Survival Investigation for Columbia;
5. An astronaut involved in the Challenger investigation;
6. An engineer and safety officer involved in several mishap investigations:
7. An FAA medical officer involved in both NASA and private spaceflight mishaps;
8. A pathologist from the Armed Forces Medical Examiner Office involved with a spaceflight mishap;
9. A NASA safety executive involved in a spaceflight mishap investigation;
10. A member of the Quad Agency Working Group who has in depth knowledge of spaceflight mishap investigations;
11. An NTSB investigator involved in the Columbia investigation;
12. A flight surgeon involved in both mishap and mass casualty investigations at Department of Defense and NASA;
13. A former NASA senior executive with oversight and involvement in several NASA mishaps, including spaceflight;
14. A flight surgeon who worked on or has intensive knowledge of the Challenger and Columbia investigations;
15. An engineer involved in the Columbia spaceflight mishap investigation.

Table 1: Interview List of Individuals with Deep Insight of Spaceflight Mishaps

As part of this study, interviews were conducted with individuals who took part in some portion of the spaceflight mishap, were part of the investigation process, or who have thoroughly reviewed data from spaceflight mishaps as part of their official duties.. As mentioned previously, there were 15 individuals interviewed with diverse backgrounds, ranging from NASA engineer to National Transportation and Safety Administration investigator, to Armed Forces Medical Examiner pathologist to former astronaut, and so on.

The diversity of the interviewees allowed for a more holistic approach to answer the questions related to the spaceflight mishap investigation process as the interviewees all had a large breadth of experience but had varied opinions and approaches due to the disciplines of each expert and individual experiences. This allowed for a deep and rich holistic pattern of evaluation of the mishaps under study, but because of their varied backgrounds, it would not have allowed for a Delphi or Modified Delphi study, where the participants are all typically of like subject matter expertise in order to obtain consensus.

All interviewees were consented, and interviews were conducted using Microsoft TEAMS in order to have simultaneous transcription. Transcriptions were converted to Microsoft Word and were then reviewed for accuracy, especially where acronyms, or engineering and scientific terms were used. Each transcript was sent back to the interviewee for review to assure accuracy and for any additional input. In addition, after specific themes were found in the data, those themes were also sent back to the interviewees to elicit their opinions as part of the process of member checking.

Privacy and confidentiality of the individuals were protected during and after the research process. There was no deception at any stage in the research process and participants were made fully aware of the purpose and expectations of the research. A cooperative research process, such as that outlined by Gummesson (2002), was utilized throughout the research process with participants' verification, review, and critique of the transcriptions and empirical data.

The coding of the interviews were combined with the findings from the other three sources and described further.

The collected data from the interviews were analyzed based on the experts' perceptions and experiences with human spaceflight mishaps. The focus was on addressing the research questions using the previously discussed semi-structured questions, and then taking the conversation deeper, while simultaneously allowing the interviewee to take the conversation in the direction they chose.

Limitations and Delimitations

Because of the amount of time that had transpired between many of these accidents, many of those with first-hand knowledge are now deceased. The lack of experience and familiarity of the researcher to code in NVivo was a potential limitation, and hand-coding was also undertaken as a means to confirm the results after the initial coding pass was made in NVivo.

The ability to interview Russian colleagues or obtain data directly from several Russian sources was potentially hampered by current geopolitical tensions over the war in the Ukraine. This may have limited direct empiric data related to the Soviet spaceflight mishaps, and also hampered the ability to interview sources for deeper context or allow signed consents or transcriptions for fear of potential reprisals. Thus, they may lack the amount of convergence and triangulation afforded the United States cases. However, my Russian colleagues have been forthcoming on lessons learned previously, and were deeply valuable during the Columbia investigation, including the sharing of their data from their previous spaceflight mishaps, so that comparisons could be made.

The subject matter can be both graphic and sensitive, as well as potentially traumatizing to remaining surviving family members. For this reason, the manuscript was reviewed by the administration of the National Aeronautics and Space Administration as well as an independent reviewer to ascertain if there were any areas that may be overly sensitive or potentially harmful to the well-being of the surviving family members. This was weighed against the merit and potential benefit of the transparency of the findings in an effort to reveal critical lessons learned, especially for emerging commercial and private space companies and private astronauts.

Lastly, the number of interviewees is weighted toward the Columbia accident investigation. This was not purposeful, but the number of individuals who are available for the most recent NASA human spaceflight mishaps investigation outnumber those from small private mishap investigations or remote investigations in the past. This may have an effect of skewing the results toward those found in Columbia. However, there is a large body of work on past human spaceflight mishaps, which it is hoped will balance or eliminate such skew.

Storage, Coding, and Interrogation of Data in NVivo

Coding in NVivo 12 used the format described by Jackson and Bazeley (2019) and followed the framing, code, and subcode construct depicted by Saldana (2013). The empirical data was first divided into frames based on the semi-structured questions and interviewee responses. The frames were then divided into codes which were then grouped or categorized based on common or repeated responses, as well as specific over-arching subject areas. The data was then further interrogated and subdivided into sub-codes based on the specific responses, using searches, key words, subject areas, and unique, uncharacteristic, or unanticipated answers. Themes and conceptual maps were delineated based on the categorization, and classification of the empirical data and their associations with particular subject areas.

On the initial coding pass, the NVivo software was used. But in subsequent codes, subcodes, and amalgamation of themes, hand-coding was used. It was difficult to flip back and forth through menus on NVivo, and more helpful to be able to see the entirety of the codes and subcodes laid out by hand to enable the ability to move the categories and codes around or regroup them. The need to incorporate hand-coding may have been secondary to the investigator's lack of experience in using NVivo, or the investigator's need to see the codes visually in total.

Further coding was derived from the interviews, document and artifact analysis, journal notes, and in-depth analysis of cases. Raw data was first prepared and organized into units for easier analysis by the Computer Assisted Qualitative Data Analysis Software by transcription of the interviews, and annotating photos, charts, recordings and non-written data. Memos were created and multiple passes of the data were undertaken to gain immersion. Codes and subcodes were created based on keywords, specific terms, quotes, and materials.

In all, over 320 codes and subcodes were generated from the interview transcripts, document research, and raw data. Synonyms and codes that were highly similar were combined. From those codes, the data was then clustered by type into specific codes under categories based on commonality, similarity, or grouping. Preliminary classification and themes began emerging based on the categorization of the raw data. Data was then further reduced into broader categories and themes. Those themes and theories then lead to the final assumptions and organized theories that can be examined across cases and against other mishap types.

The subcodes could be amalgamated based on similarity or synonyms for the same phenomenon, or conversely, they could also be further sub-divided, based on specific discussions or data acquired on physiology, physics, forensics, treatment, or further details.

The document reviews, autopsies, and prior published materials were coded using an inductive approach by instituting thematic coding (Saldana, 2013) into frames and then coded under categories using the NVivo software. An inductive approach and thematic coding (Saldana, 2013) was also used for interpretation of the transcripts and to highlight specific quotes. Both of these occurred in the initial "open" coding of the data. As the data was then clustered under major headings based on themes, axial and thematic coding was undertaken to look for relationships between the open codes, and to identify similar or like characteristics. No A priori coding was utilized.

Finally, selective coding was used to identify those codes that pertained to the research questions, and that allowed for the production of theories or interpretations of the data. This allowed the empiric data to be viewed from an initial descriptive and open standpoint to an interpretative cluster that began to align with themes, and finally to identify established patterns and theories using the selective coding. Although the NVivo software was invaluable in the initial open coding phase, hand-coding was found to be more conducive to the further phases of refinement and clustering of the data based on themes, as the data could be viewed and moved more readily into groups in large pictorial format.

Clusters, Codes, and Themes

The initial framing of the subcodes and codes was undertaken based on the research questions. Those codes that aligned to a particular research question were then placed in that frame. Codes were identified from the literature, from official reports and from the subject matter expert interviews. Subcodes were used for specific elements or descriptive phenomenon relating to the codes. The codes were then grouped into overarching categories. Major themes began to emerge for the categories and codes and are highlighted in the results and analysis.

Qualitative Data Analysis Process

The study of narrative evidence is diverse, with a variety of methodological approaches at one's disposal (Ollerenshaw & Creswell, 2002). As a result, the primary task was to obtain and analyze the data to answer the research questions. The data were collected during interviews with the 15 participants. The interviews were coded in NVivo, which is a qualitative data analysis software developed by QSR international. The analysis followed a 4-phase process as indicated in Figure 1.

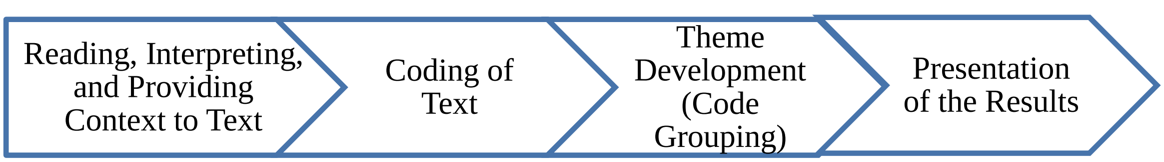


Figure 1: Stages of Analysis

Stage 1: Mining the Data for Codes

During this phase, the transcripts were reviewed multiple times to obtain a thorough understanding of the content, context, and to ascribe key words to identify relevant codes. Data was also analyzed in terms of frequency and synonyms for the same phenomenon, and to see if the keywords were related or spoke to the explicitly stated research questions.

Stage 2: Coding of Text

In this phase of the analysis, the data was carefully reviewed, and sentences and phrases were ascribed meaning in the form of codes within NVivo. All 15 interviews were reviewed and coded using this process. The coding process revealed over 224 codes as shown in Appendix A. The coding process was repeated four times to ensure that no important data were omitted from the coding.. The number of codes in any given transcript is represented with the quadrilateral; the area of the quadrilateral is proportional to the number of codes for each transcript.

Stage 3: Theme Development

The established codes were grouped to form themes in this process, and the grouping was based on the relationship between the codes, codes with identical properties were grouped and categorized as a single theme. The analysis of the collected data revealed 16 themes.

Stage 4: Presentation of Results

The results are discussed in Chapter 4 of this paper, with an overarching theory that explains and gives context to the results. Summation of the multiple cases and any common threads, as well as the unique aspects of spaceflight mishaps will be explored and discussed.

The rationale for this multiple case study design lies in the fact that there may be lessons across each of these extreme cases that are relevant to the research question. Each case will have its own sub-context and own lessons. But there may be trends that emerge, or they may have contrasting disparate lessons. This in part is due to the fact that the vehicles themselves are different (capsules versus winged vehicles) and not all one type of spacecraft. Yin (2014) discusses in detail that in a multiple case study design the subsequent findings may support the hypothesized contrast; in this study, that contrast would be the differences between human spaceflight and aviation mishaps. If the multiple cases each have aspects that support that theory, then they will begin to show the replication of a pattern that would be borne out as large sample sizes occur. This would strengthen the argument that there are unique features to spaceflight mishaps, which the study of a single case study alone would not accomplish (Hedrick et al., 1993).

Because the principal investigator is using both retrospective exploration of case data as well as current interviews with those involved in the mishaps, this will be a multiple case study with mixed qualitative methods. The argument for the mixed methods is that it adds additional data, and holistic features to prevent bias with data that should be complementary to each other. The interviews of those involved with the mishaps should complement the mining of the written reports (Hesse-Biber and Johnson, 2015) and in some respects the survey and interview is nested within the case study.

By interviewing individuals from multiple backgrounds (engineers, astronauts, safety officials, NTSB investigators, FAA officials, and physicians/pathologists) who participated in the human spaceflight mishap investigations on these extreme cases, it is hoped that a deeper context and lessons learned will be found that are currently not in the public domain. The role of the researcher in this case is thus to synthesize all of the reports, autopsies, vehicle data, and interviews into a competent thesis (Creswell, 2017). Otley and Berry (1994) assert that case studies play a central role in exploration. This study will indeed be an exploration of human spaceflight fatal mishaps and will explore the forensic data and lessons learned on the human survivability and tolerance of such mishaps.

Upon completion, the data will be stratified based on any commonality, looking for trends or distinct differences in a cross-case comparison and analysis. Lastly, any common features found in the cross-case data will be compared to the known data on aircraft mishaps to compare and contrast the differences (Figure 2). Yin (2009) describes cases studies as involving one of five methods: experiment, survey, archival analysis, history, and case study. This research will involve four out five of those methods (survey, archival analysis, history, and case study) and integrate them into a single thesis.

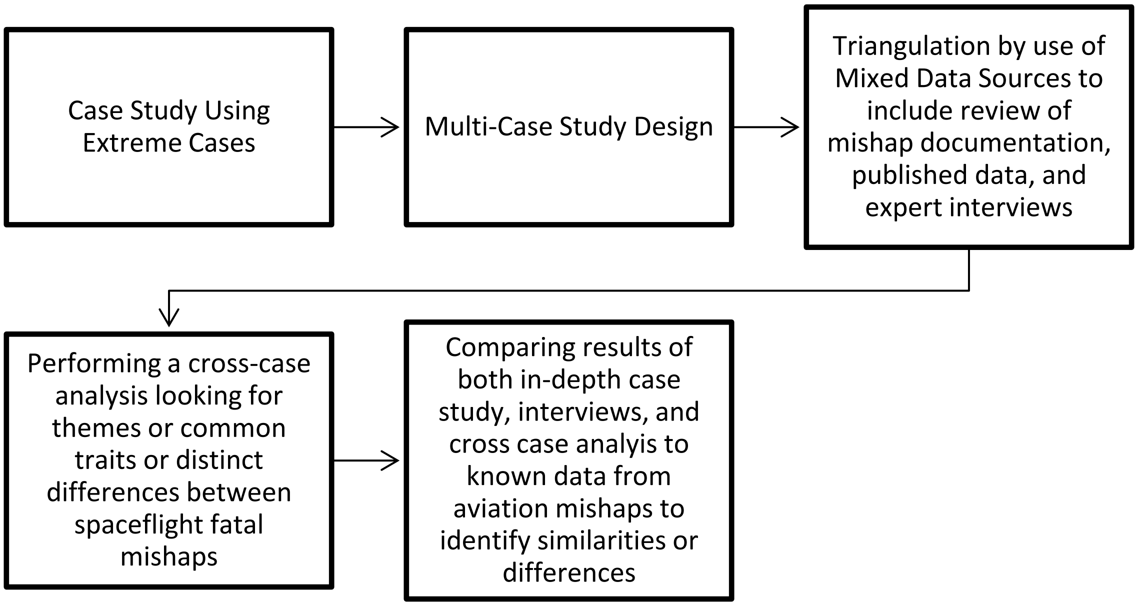


Figure 2: Intended Steps of Analysis

Therefore, the epistemological approach and methods used in this dissertation will be the following:

Research Population, Sample, and Data Sources

The archival records on spaceflight mishaps, Presidential Commission reports, autopsy reports, NASA data archives, NTSB mishap reports, Russian Commission reports, published data, literature and book publications will be used for the initial data research. This will permit archival, historical, and case study analysis in a retrospective review, summation and stratification of the data and lessons learned.

As mentioned previously, a holistic group of individuals (Table 1) who have been involved in the major spaceflight mishaps were interviewed in order to gain insight and context from their personal experiences. Their answers will be non-attributable due to the potential sensitivity of the material.

Data Collection Methods

The written data will be collected and summarized in data sets for coding using NVivo. Archival data that is not sensitive or classified will be saved to the share folders in the NVivo software. Data sharing or transfer agreements were used for proper consent to access data as required.

The interviewees were consented prior to the interview or materials being sent to them. The survey instruments were sent by email to the interviewees ahead of the interview so as to give them time to think about their answers prior to the interview. The interviews themselves were conducted using Microsoft TEAMS web-based voice and video telecommunications software that allowed for recording of the interview and simultaneous transcription. The transcription and recordings were then uploaded into the NVivo software.

Data Analysis Methodology

NVivo was utilized to store and group the data into specific nodes (Hilal and Alibri, 2013). The software was used to analyze for common words, themes, or tendencies in the interview transcripts, archival data, photographs, and autopsies. The data was coded or tagged using both generalized (e.g.- toxicologic) and specific (e.g.- carbon monoxide) labels in order to identify both general and specific trends. According to Bazeley (2017), NVivo allows the researcher to perform five important tasks to help analyze the data. The first and most important of these is the ability to organize the data.

Placing or grouping surveys, archival reports, notes, and dialogue into folders or groups so as to have them available for analysis, vice the historical color coding, taping, sticky labels and manual sorting historically performed by researchers. Second, the software allows for the grouping of ideas and concepts into nodes. Third, it allows you to interrogate or ask questions of the data. It also allows visual representation of the data, but creating grafts in order to show special relationships, and grouping or associations between theoretical data sets. Lastly, it allows reporting by generation of written summaries and reports of the data gathered and the ability to quote transcripts or salient data (Bazeley, 2017).

The data and reports were then used to identify trends, similarities or differences in the forensic, environmental, engineering, or other data in order to derive either commonality or disparities in the causes of death and forensic evidence in human spaceflight mishaps. This data was then compared to the historical data found in the published studies on aviation mishap, and any similarities or disparities noted.

Issues of Trustworthiness

In regard to trustworthiness, unlike quantitative research, this thesis will not have the benefit of instruments of statistical merit with established metrics of validity and reliability. Therefore, it is imperative that this study have credibility, transferability, confirmability, and dependability (Connelly, 2016).

Figure 3 Triangulation of Data for Enhanced Validation and Credibility

By using triangulation and a mixed method approach, the study should have credibility in that multiple sources and methods are used to establish the findings as true and accurate (Fielding, 2012). In this case study, using previously published conclusion from Presidential Commissions and NTSB reports, the researchers' findings when diving deeply into archival documents and autopsy findings, and the interviews/surveys of those involved in the mishaps should produce sufficient triangulation to establish credibility in the findings.

By going into deep detail on each of the case studies, it is hoped that the research will also achieve transferability, in that the findings would be able to be used and applicable to future spaceflight mishaps of similar contexts, circumstances, or situations.

The issue of confirmability is perhaps the greatest challenge. As the researcher is highly engaged in human spaceflight and was present for the Columbia disaster, there is a threat of bias and inability to remain neutral. However, it is hoped that by using the NVivo software for grouping and querying the data, maintaining open questions and allowing the respondents to give their own answers without coaching or the moderator leading them to an answer, that there will be sufficient audit trail in the data and responses to assure neutrality. This will require that the audit trail highlights how an assumption was made, how the data was analysed, the methods for establishing the results, and how the assumptions were made.

Dependability will be established using a method in which the results are repeatable and confirmable by an independent party. This will be established by inquiry audit by having an independent consultant who is versed in NVivo software, is not in the spaceflight business, and has no affiliations to the research subject matter, who has no inherent biases, or conflict of interest review the data and the results and how the assumptions were made. This should allow them to confirm the information from the research report and obtain similar findings or conclusions. The independent inquiry audit should allow this outside independent consultant to review and examine the research process and the data analysis in order to ensure that the findings are consistent and repeatable and thus dependable (Carcary, 2020).

The study was approved by the National Aeronautics and Space Administration's (NASA) Institutional Review Board, which further executed a reliance agreement of reciprocity with the Oklahoma State University's Institutional Review Board. Informed consent will be obtained for all participants prior to being surveyed or interviewed. Because the researcher is an Official in Charge at NASA and therefore provides direct oversight and performance evaluation of the IRB chair at the agency, an alternate IRB chair who is not under the supervision of the researcher was assigned as signatory and presided as chair for this research study to avoid any conflicts of interest.

Summary

This study will focus on the deep understanding of specific physics, environment, and forensic findings in fatal human spaceflight mishaps using an epistemological approach of unique case orientation of extreme spaceflight mishaps. A qualitative approach using the case study method was used, with triangulation of previously published mishap reports, the researchers' findings when researching archival information, reports, and autopsies, and subject matter expert interviews who were engaged in spaceflight mishaps. The summary data was grouped and analyzed using Qualitative Data Analysis software, and methods for coding independently confirmed and corroborated. The data was compared across fatal spaceflight mishaps and then against already established knowns of aviation mishaps to identify similarities or differences.

CHAPTER IV

ANALYSIS, INTERPRETATION, AND SYNTHESIS OF FINDINGS

"Space is for everybody. It's not just for a few people in science or math, or for a select group of astronauts. That's our new frontier out there, and it's everybody's business to know about space."

– Christa McAuliffe

Introduction

As mentioned in the methodology, a qualitative analysis using the extreme cases of human spaceflight mishaps that involved fatalities was chosen for this study. This was undertaken in order to achieve an understanding of the value laden nature and deep context of the human spaceflight mishaps and their potential differences between other mishaps, especially any differences between their aviation counterparts. The growth of the private and commercial human spaceflight industry makes this delineation and characterization especially important.

Frequency of Themes by Research Question

As annotated in Chapter 3, interviews were conducted with 15 individuals with intimate knowledge of human spaceflight mishaps. In the table below, the top themes that emerged from the coding of answers to the questions posed to the subject matter experts are displayed. The number on the right side of the chart lists the number of times a code was mentioned that related to a particular there by the participants.

Themes **(Major themes that arose from the coding of answers to questions)**	**Total References Across All Interviews (number of times a code pertaining to a particular theme was mentioned)**
Research Question 1: Are there physical or environmental differences between a spaceflight mishap and other mishaps that stand out in your mind that would be important to highlight for future investigators or tech authorities?	
Kinetic energy is vastly different in spaceflight mishaps versus their aviation counterparts, especially above the Karman line.	49
The physics of the boundary layer, shock-shock interaction, and plasma are greatly different for spaceflight mishaps compared to aviation or other types.	45
The phase of flight gives differing physical and environmental risks in spaceflight mishaps.	11
Research Question 2: Are there forensic differences that are unique to spaceflight mishaps? If so, what are those forensic differences or unique aspects in spaceflight mishaps that stand out in your mind from the mishap you were involved with?	
The forensic attributes of a spacecraft mishap differ significantly from an aviation mishap.	67
Ebullism above Armstrong's line is a major differentiating factor for spaceflight mishaps.	45
Pressure, temperature, radiation give rise to differing concerns in spaceflight mishaps.	28

Research Question 3: For future human spaceflight mishaps, be it commercial, NASA, or military- what are some of the most critical lessons learned that should be relayed to future mishap investigators?	
Scene safety: Untrained spaceflight mishap responders may be harmed.	26
Fundamental attributes of a spaceflight investigation differ from aviation mishap investigations.	24
Physical attributes of a spacecraft mishap differ significantly from an aviation mishap.	18
Knowledge of the spacecraft systems is critical to understanding the potential causality of spaceflight mishaps.	76
Research Question 4: For a technical authority charged with aiding in human systems design of new spacecraft, are there lessons that stand out in your mind that they should consider based on the mishap that you were involved in?	
Standards and requirements should be dictated by best practice and not influenced by social or political pressures.	36
The addition of "survivability" to fault tolerance and reliability must be a hallmark of spacecraft design.	24
Research Question 5: What skills should the mishap investigator possess when dealing with a human spaceflight mishap?	
Investigators should possess the requisite training and experience in mishap investigations.	84
Investigators should keep an open mind and avoid leaping to conclusions.	66
Investigators should be objective.	45
Investigators should have a knowledge of the spacecraft systems and mission profile.	44

Table 2: Major Themes that Appeared Based on Codes with High Frequency

Research Question 1

Research Question 1: Are there physical or environmental differences between a spaceflight mishap and other mishaps that stand out in your mind that would be important to highlight for future investigators or tech authorities?

Theme 1: Kinetic energy is vastly different in spaceflight mishaps versus their aviation counterparts, especially above the Karman line.

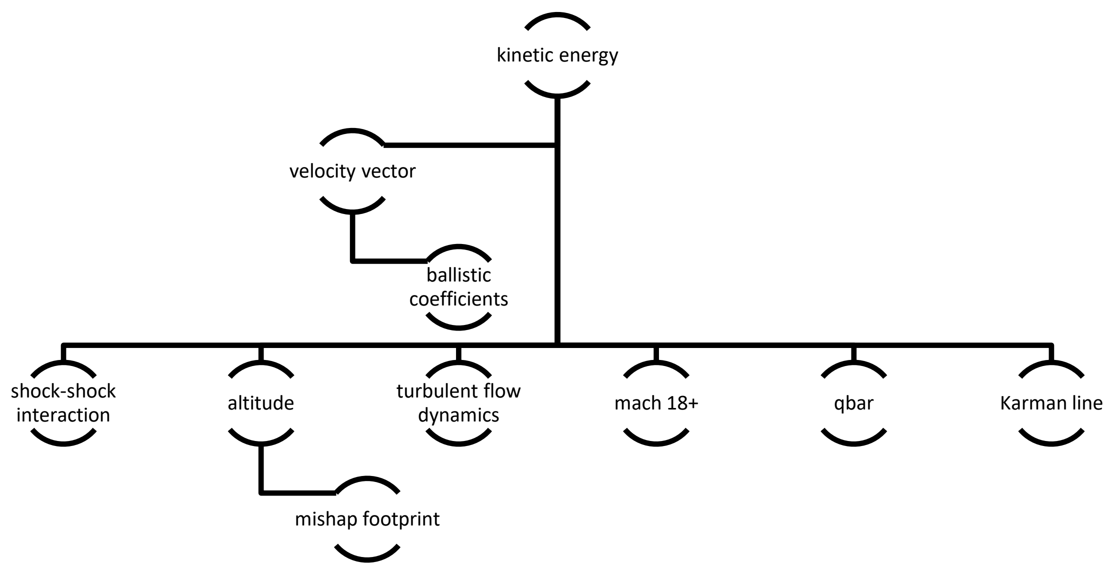


Figure 4. Codes Associated with Theme of Kinetic Energy

The velocity of a spacecraft as it attempts to gain orbital velocity on launch or as it re-enters the atmosphere on re-entry is much higher than that of an aircraft. The orbital velocity of a spacecraft to maintain low earth orbit is 17,500 mph. Upon re-entry the spacecraft lowers its speed in order to enter the atmosphere and to take advantage of atmospheric drag. But even then, the re-entry speeds for a vehicle are quite high. As Expert 09 stated, "*the velocity of Columbia when the vehicle came apart was on the order of Mach 18.*" That is roughly 13,340 mph. For comparison, the SR-71 Blackbird had a velocity of 2,200 mph. This kinetic energy increases for exploration missions, with the Apollo (and soon to be Artemis) spacecraft returning from the Moon and re-entering at velocities approaching 25,000 mph. Any amount of turbulent flow, or disruption in the ballistic coefficients and/or center of gravity of a spacecraft re-entering at those speeds could be catastrophic. If a vehicle were to come apart at those speeds and at that altitude, the footprint for the mishap would be very large, as it was for Columbia. In fact, Columbia debris was spread across several states. This was also identified by over 86% of the interviewees as a potential factor that separates spacecraft mishaps from aviation or other mishaps.

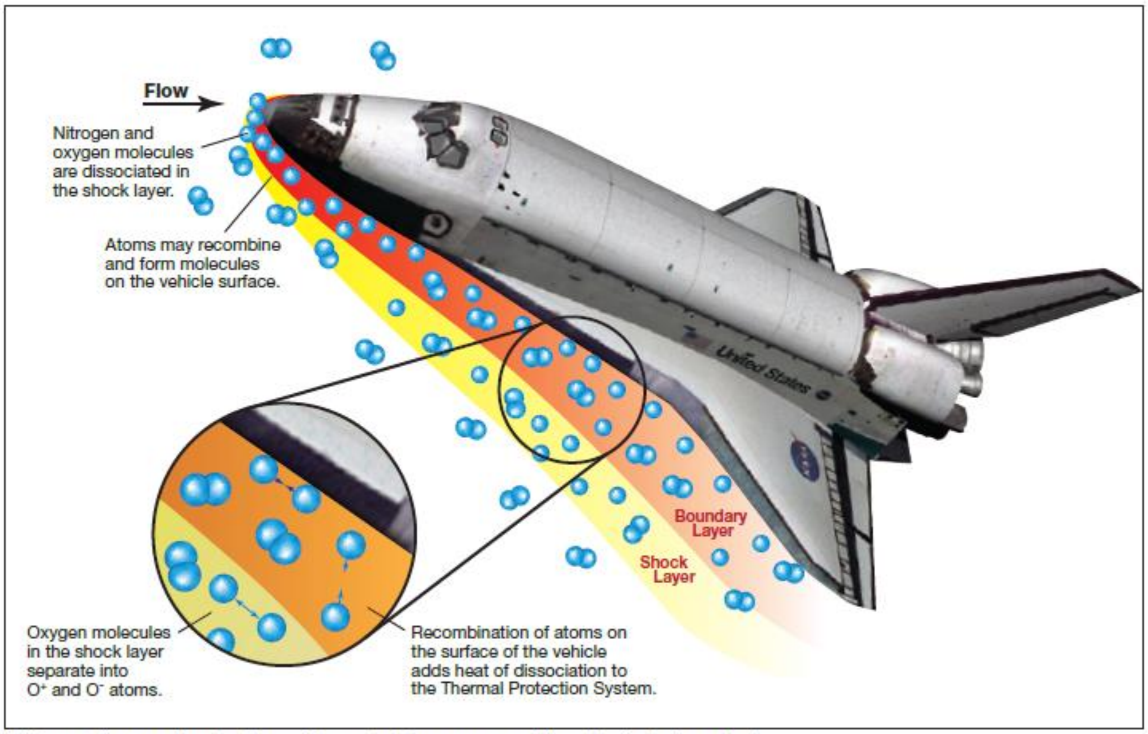
The velocity vector of a spacecraft was also identified as a code that affects the kinetic energy of a spacecraft. If the spacecraft re-enters too shallow, it will skip off the atmosphere. If it comes in too steep, it will superheat and risk burning through its thermal protection system with catastrophic consequences. Apollo 13 had a re-entry corridor that was 2 degrees wide. In order to avoid skipping off the atmosphere they could re-enter at an angle of attack no less than 5.3 degrees, and no steeper than 7.7 degrees (Lovell & Kluger, 2006).

In addition, the unique interface with the plasma of the atmosphere and boundary layer as the vehicle re-enters is something not experienced by aircraft, and this phenomenon typically occurs above the Karman line. The Karman line is the boundary layer between Earth's atmosphere and outer space. This is typically at 62 miles above the

Earth, or 100 kilometers, and is where the “thin blue line” of our atmosphere is now negligible. The speeds of spacecraft re-entering the atmosphere above this line are an order of magnitude different than aircraft. Even suborbital spacecraft, such as Blue Origin, which have attained the altitude of 100 kilometers above the Earth, are not re-entering the atmosphere at speeds that orbital or exploration vehicles are. The top speed of Blue Origin was Mach 3, versus the Space Shuttle re-entering at Mach 18.

Theme 2: The physics of the boundary layer, shock-shock interaction, and plasma are greatly different for spaceflight mishaps compared to aviation or other types of mishaps.

As mentioned above, a vehicle traveling at orbital or exploration speeds (beyond low Earth orbit) has tremendous kinetic energy upon re-entry. In order to slow the vehicle, much of that kinetic energy is converted to heat energy upon re-entry to Earth’s atmosphere. Both the winged spacecraft and capsules begin to engage air particles in the atmosphere at very high speeds, where the kinetic energy is converted to heat when the molecules of air are rapidly impacted and ripped apart. This separation of the molecules into individual atoms and free electrons creates the shock layer. Temperatures reach over 10,000 ^{o} F in this shock layer creating a plasma-like matter environment. The compression and recombination of atoms close to the spacecraft create a boundary layer, that acts like a buffer to the shock layer, which lowers the temperature next to the skin of the spacecraft’s thermal protection system to around 3,000^{o} F. Vehicles traveling at higher speeds, such as a capsule returning from a lunar mission at 25,000 mph, will see higher temperatures (close to 3,600^{o} F) at the interface of the heatshield and the boundary layer. In the case of Columbia, the hole in the carbon-carbon leading edge of the left wing allowed plasma to enter and the temperatures exceeded the melting point of the aluminum frame (1220°F) with catastrophic consequences (Davis, 2014). These temperatures, and the physics of plasma, are something not seen in other types of mishaps such as aviation mishaps.



This image illustrates how the Thermal Protection System protected the orbiter's aluminum shell.

Figure 5: Boundary Layer and Shock Layer, from *Loss of Signal*, Davis, 2014.

Shock-shock interaction is defined as a "mechanical wave of large amplitude that propagates at a supersonic velocity" (Lin, 2020). The interaction of two shock waves causes major localized changes in pressure, temperature and energy at the intersection of these two waves. As Columbia lost structural integrity of its wing, it began to tumble and interact with the plasma and shock waves (Davis, 2014).

You have shock-shock interaction, which literally cleaves things like a laser. It is precise. It's not a tearing, but a laser-like phenomenon. It's really amazing. You *could see one piece of metal that was pristine and the part next to it, right next to it, cleaved like a laser had cut through it. Now that is all happening above Mach 5 (Expert 03).*

Although shock waves occur in aircraft at hypersonic flight, the phenomenon of shock-shock interaction, has not been identified in those mishaps. This phenomenon, with the intersection of very high temperature shock layer and shock wave interactions, appear to be specific to high velocity/high altitude spacecraft mishaps.

The velocity of a spacecraft, both on launch and re-entry, can interact with the atmospheric pressure of the atmosphere. This creates a dynamic pressure wave. For the Space Shuttle, as it ascended it burned propellant causing it to lose mass. The thrust was the same but because the mass was steadily dropping, the vehicle was accelerating at greater speeds. As the Space Shuttle accelerated through the thicker denser portions of the atmosphere it would encounter increasing dynamic pressure on the vehicle, known as Q-Bar. To prevent damage to the structural integrity of the vehicle, the Space Shuttle would throttle back it's engines to around 70% as it reached "Max Q" or maximum dynamic pressure at around 36,000 feet. The maximum dynamic pressure is a consequence of the static pressure of the atmosphere, and the dynamic pressure of compression of the air from the high velocity spacecraft. This pressure would be high on the nose and leading edges of the wings of the spacecraft as it rose through the atmosphere.

Once the Space Shuttle reached a higher altitude where the air is thinner and it is beyond Max Q, the engines throttle back up ("go for throttle up") to 100%. The spacecraft continues to lose mass while maintaining thrust, which accelerates it even further so that it can obtain the 17,500-mph required for a circular Earth orbit. Hypersonic vehicles like the X-15 and SR-71 also experienced maximum dynamic pressure when flying at speeds above Mach 1.3 at lower altitudes. This means that the Q-bar, or dynamic pressure is not unique to a spacecraft or potentially a spacecraft mishap. But the speeds and kinetic energy of spacecraft are many times that of their aviation counterparts and they reach that Q-bar much faster (Vu & Biezad, 1994).

Theme 3: The phase of flight gives differing physical and environmental risks in spaceflight mishaps.

> *You know, I think of it in terms of mission phases, right? So, you have things that occur on the ground like with Apollo 1 and you have things in the phase of flight for ascent like Challenger, you have things that are on descent, like Apollo Soyuz or Red Bull. So, you have to think about the phase of flight (Expert 03).*

93% of those interviewed mentioned codes related to, or directly mentioned the phase of spaceflight as a variable that greatly influenced the findings in spaceflight mishaps.

As Figure 6 shows, the risks, physics, and forensics change based on the phase of flight of a spacecraft.

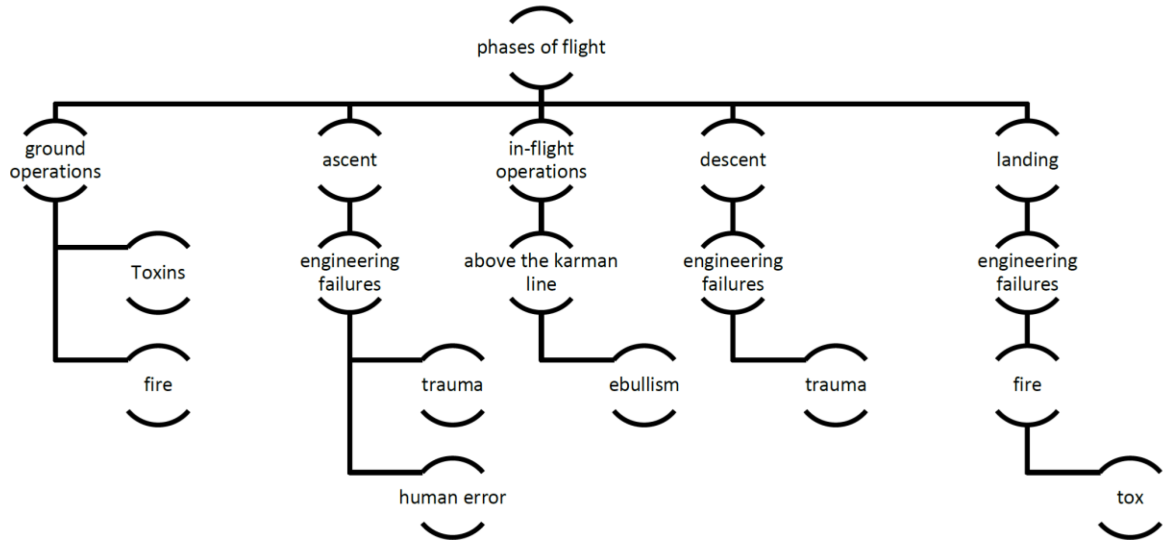


Figure 6: Codes Associated with Theme for Phases of Flight

For ground operations, testing, and pre-launch, toxins and fire predominate as the main risks for the crew. Apollo 1 was a prime example. Toxins and fire are certainly not unique to spacecraft, but they can occur in a pressurized enclosed environment, and atop of a rocket carrying large amounts of volatile fuels, making their occurrence more perilous and perhaps more difficult to combat or navigate.

Toxins alone can be broken down into multiple subcodes based on the interviews and examination of multiple historical documents (Figure 7). Hydrazine is a common hypergolic fuel that when added to nitrogen tetroxide, creates a reliable combustion agent. It is also highly toxic. Hydrazine is also found on aircraft, namely the Auxiliary Power Unit of the F-16. But it is much more common as a fuel for spacecraft thruster engines.

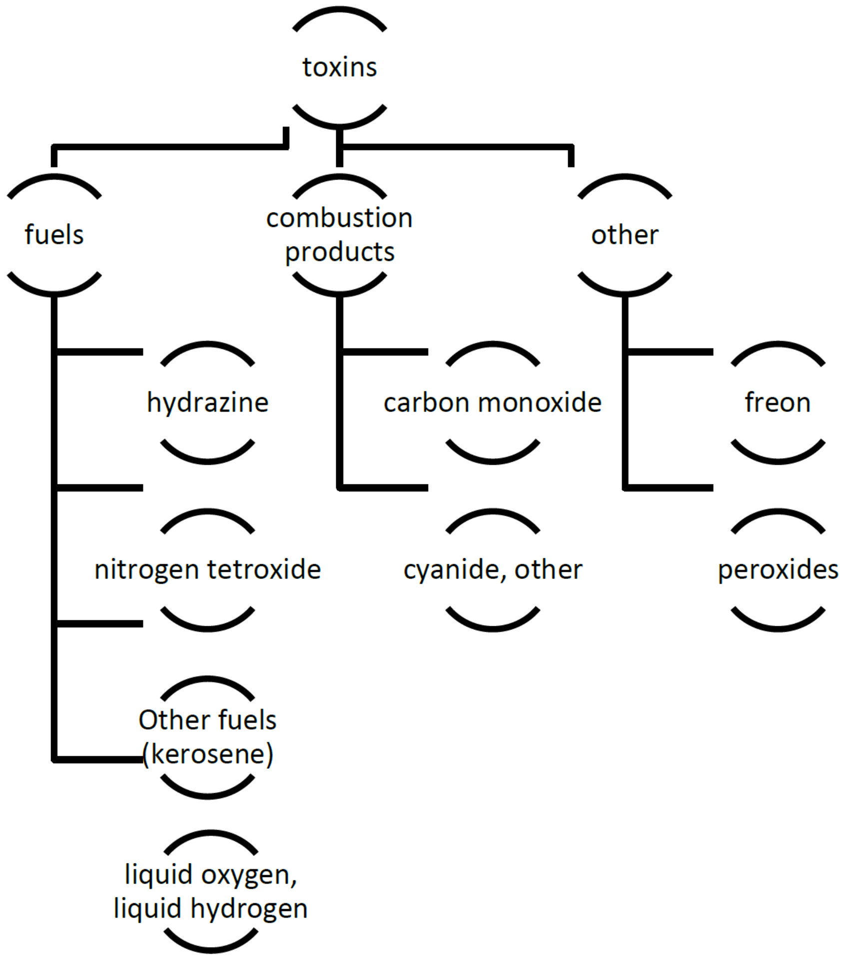


Figure 7: Codes Associated with the Theme of Toxins

Expert 12 relayed the case of Apollo- Soyuz, where upon landing and post-flight evaluation the Commander stated that at about 26,000 feet:

> *There was a yellowish-brown colored smoke which smelled like RCS (reaction control system fuel) that filled the cabin. The smoke was so thick that I had a hard time seeing the other crewmembers or the dials in front of me. The smoke cleared very fast.*

It turned out this was nitrogen tetroxide which had entered the cabin when a command to open the pressure equalization valves was given too early before the thruster fuels had time to dissipate. Within 16 hours, the crew was wheezing and becoming increasingly short of breath (Nicogossian, 1977). Chest x-ray showed a chemical pneumonitis was occurring, and pulmonary edema was present. The crew were then transported to Tripler Army Medical Center in Hawaii, placed on oxygen and high dose steroids, and hospitalized until they fully recovered (Nicogossian, 1977)). Although fortunately not an example of a fatality, and thus beyond the scope of this paper, it does highlight the toxicologic risks in spacecraft that could potentially turn fatal.

Combustion products and pressure were responsible for the deaths of the Apollo 1 crew. They represent another group of subcodes related to toxins. The fire and smoke on the Mir Space Station after the solid perchlorate oxygen generation canister ignited is yet another example (Lucid, 1998). The fire on Mir was so hot that molten metal was puddling near the blaze. Fortunately, the crew, including astronaut Jerry Linenger, were able to extinguish the blaze and allow the air scrubbers to clear the air over time (Lucid, 1998).

One could argue that the death of the Apollo 1 astronauts was an industrial accident and should not be included in this manuscript. It’s the very reason the mishap report is entitled Apollo 204 (the test vehicle designation) instead of Apollo 1. The agency and the Presidential Commission (known as the Apollo 204 Board) regarded the accident as an occupational accident since the vehicle was not in the midst of launching to space. But the vehicle was filled with 100% oxygen, and over-pressurized above ambient and on its own power. The crew were fully in their suits. The plugs out test mimics the launch environment down to the countdown and systems checks. So, it has been included in this assessment because it was, for all intents and purposes, the same conditions that would have been seen or used on launch. Figure 8 shows the codes obtained both from the interviews with the subject matter experts, but also from the individual research that lend themselves to the cause of the demise of the Apollo 1 crew.

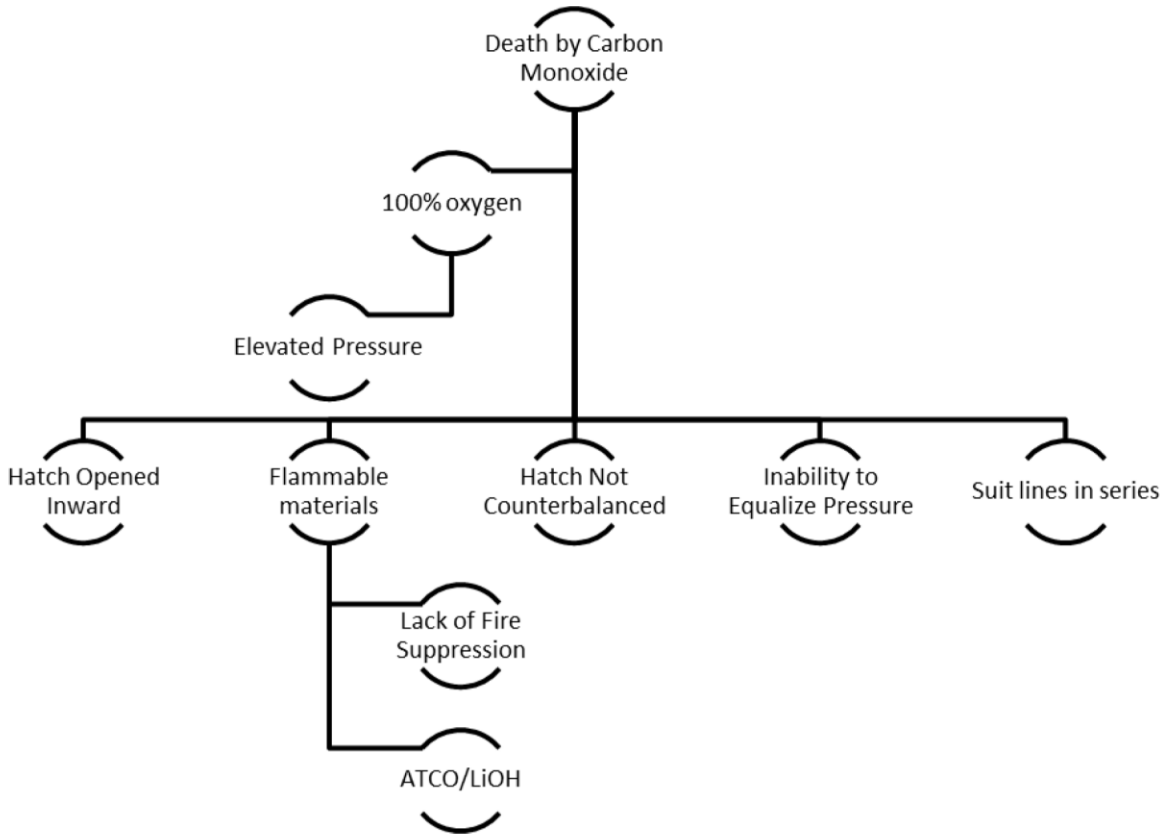


Figure 8: Codes Associated with the Contributors to Apollo 1 Cause of Death

The Apollo 204 Board (the name for the Presidential mishap investigative body for the accident) reported that the fire began in the "lower forward position of the left-hand equipment bay" (Seamans, 1967).

This would have put the fire well below the astronaut couches to their far-left side. The fire would have been fed by the 100% oxygen atmosphere which was already at 16.7 psi. The higher pressure and 100% oxygen were a requirement of pre-breath to unload nitrogen from the astronaut's systems prior to the capsule going down to 5.0 psi in orbit, as a means to prevent decompression sickness.

The fire spread up the panels and across the Raschel nets (nylon netting used to hold items) and Velcro, both of which were highly flammable under those conditions. As the fire spread up the wall and across the ceiling, the molten Velcro and Raschel nets burned and dripped flames throughout the cabin, igniting more material. The capsule experienced a rapid rise in temperature and pressure. In general, according to Gay-Lussac's Law, the pressure would have risen to over 30 psi as the temperatures rapidly exceeded 400-500 degrees in the fixed volume of the capsule (Ladino & Rondon, 2015). The shell and sides of the capsule, designed to withstand pressures of up to 29 psi (Seamans, 1967), ruptured minutes into the fire. Bursting of aluminum tubing in the coolant systems showed evidence of the rapid and extreme intensity of the fire, which was continuing to be fed by 100% oxygen.

Contrary to what most laypersons believe, the crew did not burn to death. Rather, they succumbed to carbon monoxide and other gases. The third degree burns for each crewmember were 36%, 40%, and 23% (Seamans, 1967). Although burns greater than 40% of body surface area have been found to have a higher mortality, the majority of those patients succumb sometime after the acute event, as opposed to the extremely short time in which the Apollo 1 astronauts perished (Jeschke et al., 2015). From the first crew voice transmission indicating there was a fire to the last transmission of the crew was a period of just 21.8 seconds (Seamans, 1967). How could carbon monoxide have killed the crew so quickly? The clues lie in the autopsy and the engineering report.

The autopsy shows that the amount of carbon monoxide in the lungs of all three astronauts was greater than 58%. What is intriguing is that the percentage falls as the other organs are sampled, with the quadriceps muscle having between 7 and 27%. This means that the heart did not beat long enough for the carbon monoxide to equilibrate in all of the tissues. Within a few breaths, the astronauts asphyxiated and had lethal dysrhythmias. The reason for this is several-fold. First, the astronaut suit loops were in series and not parallel, which meant that once the suit or suit loop was breached in one astronaut the carbon monoxide would be pulled into the air in the loops of each of the astronaut's suits. They were in essence all connected. Second, the CO_2 canisters that were connected to the suit ventilation loops contained activated charcoal. Unfortunately, they began to burn rather quickly and produced a massive amount of carbon monoxide (Seamans, 1967). Third, it is well documented that carbon monoxide diffuses rapidly across the pulmonary membrane and binds with the iron moiety of the heme molecule of hemoglobin (Ernst & Zibrak JD, 1998). The heme molecule contains iron and binds (reversibly) the oxygen for transport between the lungs and the tissues.

Carbon monoxide's affinity for that molecule is over 240 times that of oxygen (Weaver, 1999), and that binding also causes an allosteric change in the heme molecule such that it prevents the other oxygen binding sites from now off-loading their oxygen (Clardy et al., 2021) causing a left shift of the oxyhemoglobin dissociation curve (a graphical representation of how oxygen is offloaded to the tissues under normal pressure), meaning that the tissues can't get oxygen. But there is a third element to this that typically does not happen in most carbon monoxide cases: pressure. The pressure in the cabin rose dramatically. The cabin was rated to withstand a pressure of 29 psi. The cabin ruptured with a second or two of the last transmission and the cabin pressure was well over 29 psi. This means that it was not just a high level of carbon monoxide, but carbon monoxide at over two atmospheres of pressure. This would have driven carbon monoxide quickly into the cells, saturated the heme molecules and disrupted oxidative phosphorylation at the mitochondrial level (Hardy, KR & Thom SR, 1994). This would have made the carbon monoxide act more physiologically like that of cyanide, and hence the rapid effect on the cardiac cells. This is why the astronauts suffered rapid cardiac arrest and the heart did not beat long enough to equilibrate the carbon monoxide throughout the tissues. This is another critical point. Most medical examiners would see carbon monoxide poisoning at normal 14.7 psi. They would not be familiar with the consequence of carbon monoxide at higher pressure, such as over 29 psi. Further, the engineers working the mishap who knew of the high pressure would typically not converse with the medical examiner, and vice versa. That silo of information between the medical community and the engineering community prevented the medical examiners from having a critical piece to the puzzle. This elevated pressure in the face of high carbon monoxide makes this unique to the spaceflight environment and could cause confusion as the results of the serum or tissue carbon monoxide are examined. Figure 9 delineates the codes found upon deeper exploration of the mishap documentation and autopsy report.

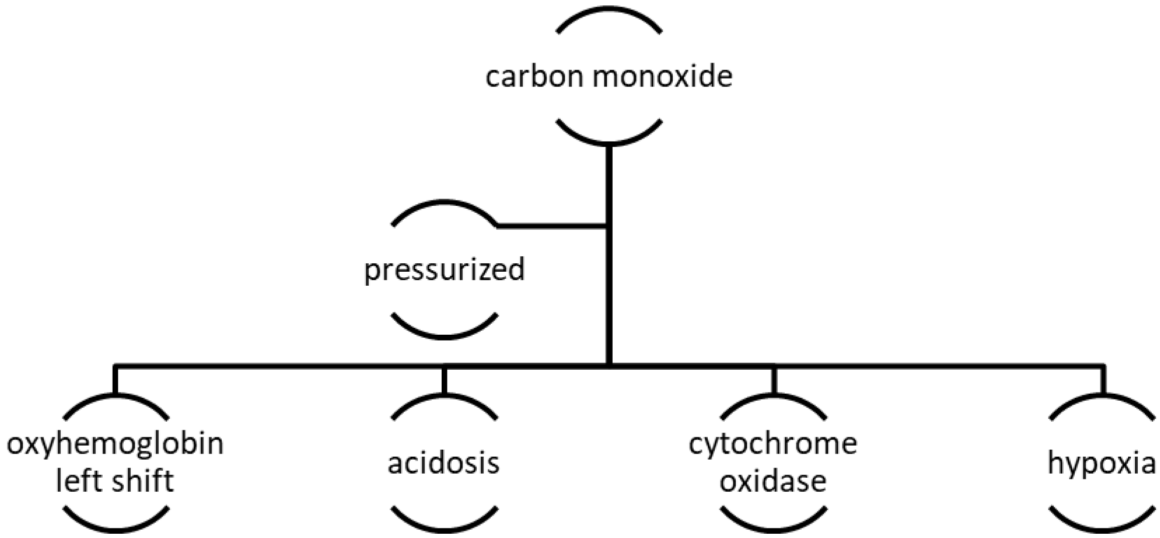


Figure 9: Codes that Align with the Lethality of Carbon Monoxide in Apollo 1

In addition to combustion products, coolants, such as Ammonia and Freon are also potential toxins on board a spacecraft (and are in use by commercial spacecraft) should a leak occur in the enclosed environment. Aviation mishaps may have toxins and combustion products as well, but the pressurized enclosed environment of a spacecraft and the number of chemicals required to heat, cool, energize, oxygenate, scrub, and fuel a spacecraft make this a larger potential hazard that could be found in spaceflight mishaps.

Ascent failures for a spacecraft have typically involved an engineering failure (such as the failed O-ring on Challenger), engine failures or guidance failures. The Virgin Galactic in-flight mishap was secondary to a number of causes surrounding a human factors error, which ultimately caused the structure of the spacecraft to fail when the feathering of the wings was initiated too early (See, 2016).

The majority of the those interviewed mentioned that the Karman line was a potential major difference between spaceflight and aviation mishaps. In particular, the potential for the vehicle to lose pressure and subject the occupants to ebullism was mentioned, in addition the high kinetic energy and temperature from re-entry forces.

Research Question 2

Research Question 2: Are there forensic differences that are unique to spaceflight mishaps? If so, what are those forensic differences or unique aspects in spaceflight mishaps that stand out in your mind from the mishap you were involved with?

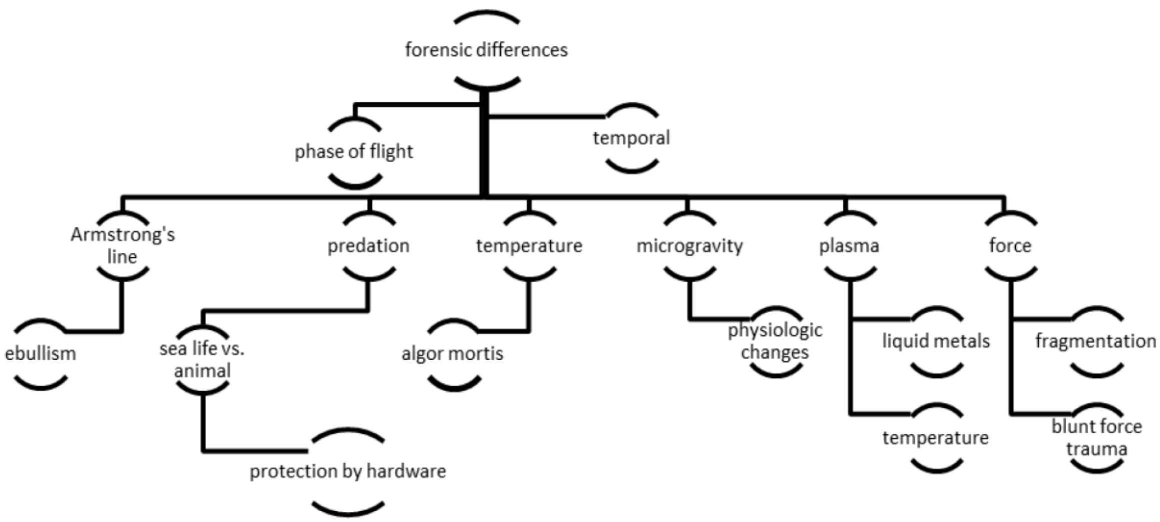


Figure 10: Codes that Align with the Theme of Forensic Differences in Human Spaceflight Mishaps

Theme 4: The forensic attributes of a spacecraft mishap differ significantly from an aviation mishap.

One hundred percent of the interviewees remarked that there are differences between human spaceflight mishaps and other mishaps. The literature and official reports also substantiate this fact, with NASA's Loss of Signal (Davis, 2014) being perhaps the most comprehensive review of the forensic findings in the Columbia mishap showing significant differences from what would typically be found in an aviation accident. It should be noted that it was a separate undertaking by the Space Life Sciences Directorate at NASA and not part of the official investigation report. This transparency for the lessons learned was not seen to the same degree in the Challenger accident. Of all the official Presidential Commission reports, the Apollo 204 report (Seamans, 1967) was the most comprehensive in terms of including the autopsy results, lab findings, and cause and manner of death of a spaceflight crew in the actual investigation report itself. Multiple unique findings in forensics of spaceflight mishaps were found when reviewing these documents as well as other records and subject matter expert interviews, which warrant discussion.

The interviewed participants explained that forensic evidence in spaceflight mishaps is so unique that it cannot be confused with or compared to aviation mishaps, but most especially if the anomaly occurred above the Karman line (62 miles or 330,000 feet), which in turn is well above Armstrong's line (63,000 feet) where the atmospheric pressure is so low that water boils and bodily fluids become gas and vapor. Multiple subjects reiterated that the pathological exposures and condition of the crew members is unique and foreign, especially to pathologists and investigators with limited knowledge of spaceflight mishaps. The effects of ebullism and plasma, temperature, shock-shock interaction, and molten metals make it nearly impossible to identify the crew member's remains without the use of dental records or DNA analysis. The participants explained that in most cases, a spaceflight mishap occurring above the Karman line is characterized by much higher acceleration forces, temperatures, and ebullism. These in turn can cause gross anatomical changes as well as unique skin and tissue changes that are typically not seen in aviation mishaps. Examples of this theme are evident in the following interview excerpts:

> *That's a difficult one to get your head around and probably the most important one. You have to be observant because there's, you know, that high altitude environment is very hostile to the human body and tissue. The altitude and speed of the spacecraft are unlike anything they (medical examiners) have seen or experienced, in terms of its impact on tissue* (Expert 12).

> *Several folks thought that the remains looked like a certain person. And they said it's this one. And I said, why do you say that? They said, 'because it sort of looks like that person'. Well, it turned out that wasn't the case. It was someone else entirely. So, I said there's no way until we have an absolute identification of this that we are going to guess. We will wait for confirmation from the dental records or the DNA* (Expert 06).

> *The skin looked like elephant skin. It turned out it was a combination of the effects of ebullism, the exposure to molten metals, and the temperature and pressure changes. It was unlike anything anyone had seen before, including the pathologists at AFIP (Armed Forces Institute of Pathology)* (Expert 03).

> *The shock-shock interaction was something truly unique. You'd have a piece of the vehicle that was pristine, and right next to it was a piece that looked like a laser had cut through it. That was where the shock wave interaction occurred. That could occur on metal, on tissue, on any part of the vehicle. I don't think any*

> *medical examiner would know what to make of it if they saw injuries from the shock wave interaction* (Expert 04).

The participants articulated that forensic investigations of spaceflight mishaps cannot be carried out solely by experienced aviation mishap investigators, as experience in aviation mishaps is grossly inadequate for a spaceflight mishap investigation. It must be augmented with expert consultancy or subject matter expertise in human spaceflight and also with spacecraft mishap experience. Ebullism and shock wave or plasma interactions are not seen in the aviation mishap or medical examiner community.

Expert 03 explained:

> *That's what caused the skin changes that AFIP saw, and NASA had to go up to AFIP and help them understand the phenomenon they were looking at because they had not seen it before.*

Expert 06 explained:

> *It looked like pachyderm skin, like elephant skin. We figured out it was a combination of the ebullism and the mist of molten metal from the vehicle coating the skin, and then a change in the tissue upon re-entering the atmosphere.*

This was further corroborated by Expert 08:

> *We had a dermatopathologist on our staff. The guy literally is a skin pathology expert. He said he had never seen anything like it.*

Multiple participants explained that forensic investigation differences they believed were unique to human spaceflight were characterized by the following:

Major Forensic Differences Highlighted by Participants
Unique skin changes caused by ebullism, shock-shock interaction, molten metal depositions and extreme hypobaric and temperatures.
Unique respiratory damage due to ebullism
Remains subjected to extremes of temperature
Deposition of molten metal onto the remains
High kinetic energy causing limbs to be separated by flail and deposited miles from each other due to the high altitude and trajectory when the incident occurred.
Bubbles from ebullism in every tissue: brain, spinal cord, muscle, fat, lungs, heart.
Hollow organ expansion and overpressure from gas expansion (Boyle's Law)
High thermal followed by cold exposure once entering the atmosphere.
Exam and evidence extend beyond cause and manner
Changes in tissues brought about by prolonged exposure to microgravity
Need for temporal association of when injuries occurred to help mishap investigation
Potential differences in usual markers of death (livor mortis, algor mortis) due to space environment

Table 3: Major Forensic Differences Highlighted by Interviewed Experts

Furthermore, the forensic pathology is complicated by body exposure to molten titanium, aluminum, and beryllium. Additionally, there are bubble formations in all of the tissues; this is likely due to the triple point state of liquid (nitrogen, carbon dioxide, water, etc.) rapidly vaporizing from the lack of atmospheric pressure. There were also other changes, and nuances seen on pathology examination that were unexpected.

Expert 12 stated:

There were a host of changes seen both in Soyuz 11 and Columbia. The microgravity environment and the ebullism impacted the livor mortis and the *algor mortis. It impacted the skin and tissue. There were massive amounts of lactic acid in the system for the Soyuz crew as there was also in Columbia crews.*

Perhaps one of the biggest differences was mentioned by Expert 12:

A typical medical examiner is looking for 'cause' and 'manner' of death, cause and manner, that's it. They are not looking for how the forensics fit into the mishap picture, or to see if the forensic findings can shed light on what happened temporally with the vehicle, just cause and manner.

An example of this would be the medical examiner or coroner writing that the cause of death was hypovolemic shock and manner of death was blunt force trauma for a mishap victim. Both are true, but they do not lend any context or give any clues as to when an event occurred, how it occurred, or shed any light on the temporal aspects/timing of the events of a mishap.

An NTSB, NASA, or Department of Defense investigation typically is trying to take the findings (including the forensic findings) and put them into context to inform what happened with a mishap. The pathologic evidence of ebullism is a great example. The findings of bubbles in all of the tissues would alert the medical examiner to ebullism, which in turn tells investigators the crew was exposed to vacuum above Armstrong's line at the very least. So, the investigators know that the vehicle had an issue or malfunction at a very high altitude, at least above Armstrong's line and potentially above the Karman line. That context can then lead investigators to look at particular systems within the spacecraft for failure analysis.

The life support systems must be evaluated as part of the mishap and may give clues or evidence as to what the crew was experiencing and the timing of the anomaly. In the case of the Challenger accident, when the vehicle exploded, many assumed the crew were killed instantly. This was not the case. As flame burned through the O-ring and damaged the strut attaching the booster to the external tank, the booster began to swivel. It ruptured the external tank, causing a fireball of over 300,000 gallons of hydrogen and over 100,000 gallons of oxygen. Despite the explosion, the G's imparted to the vehicle were not lethal to the crew nor would they have caused serious injury and were on the order of 12 to 20 G's in the vertical axis (Kerwin, 2009). The explosion disarticulated the crew cabin from the remainder of the vehicle. Shayler (2000) states that the crew was on oxygen, and normally he would be correct. There was oxygen that flowed into their clamshell helmets, except the oxygen tanks were under the payload bay, and the lines carrying the oxygen were severed.

Emergency air bottles had to be activated by hand and were available. The crew cabin separated at around 48,000 feet. It is doubtful that the cabin maintained a sealed integrity due to being ripped from the attachment points and pierced by shrapnel from the explosion (debris was found imbedded in the frame between the two forward windows). In all likelihood the cabin was losing pressure, but at what rate we can't be certain. Because of the upward momentum, the cabin continued to an altitude of around 65,000 feet.

Assuming the cabin integrity was compromised, and the crew was now on emergency air, not oxygen, they would have had a Time of Useful Consciousness of less than 5-9 seconds (see table 5). Dr. Joe Kerwin's report to Admiral Truly supports that the forces at breakup were insufficient to have caused serious injury to the crew, and that crewmembers most likely (but not certainly) lost consciousness in the seconds following the breakup (Kerwin, 2009). Even with the emergency air packs on, they would not have remained conscious at that altitude, as the packs contained air, not oxygen. There would not have been enough atmospheric pressure or oxygen concentration to sustain consciousness. Unfortunately, the crew cabin was so significantly damaged by the impact with the ocean that no definitive evidence could be obtained regarding whether the cabin maintained or lost pressure.

Expert 10 stated:

> *We sent the air bottles off to the Air Force Life Support lab. They came back with a report that there was a certain volume of gas lost or consumed in three of the bottles. It was consistent with the crewmembers having breathed down that gas, but we could not say definitively that is what happened. It was speculative. We didn't want to speculate. We just knew that three of the PEAP's (personal egress air pack) had been activated.*

The Challenger crew module impacted the Atlantic Ocean two minutes and forty-five seconds after the explosion and break up, hitting the ocean at a velocity of 207 miles per hour with forces over 200 G's upon impact (Kerwin, 2009). As the chart below shows, cardiac trauma, aortic tears, and organ laceration would have resulted in the crew dying immediately upon impact (modified from Tejada, 2004).

Organ Tolerance and Damage Associated with G Loads	
Pulmonary Contusion	25 G's
Vertebral Body Compression	20-30 G's
Fracture Dislocation of C1 on C2	20-40 G's
Aortic Intimal Tear	50 G's
Splenic Rupture	50 G's
Aortic Transection	80-100 G's
Pelvic Fracture	100-200 G's
Cardiac Rupture	150-200 G's
Vertebral Body Transection	200-300 G's
Total Body Fragmentation	350 G's

Table 4: Organ Tolerance/Damage Associated with G Loads. Adapted from Tejada, 2004

The Armed Forces Institute of Pathology (AFIP) performed the autopsy of the remains of the Challenger crew. The vehicle came apart on launch on January 28th, 1986, but the crew cabin was found on the ocean floor nearly 40 days later on March 10th. One would expect after being submerged that long in sea water that the remains might have been skeletonized by sea life and the environment (Anderson, 2004). However, the crew module was somewhat protected by layer upon layer of wiring and cables that enveloped the module such that the crew were relatively intact, but tissues had become severely degraded by the sea water and time spent submerged. This made any cause and manner of death impossible to declare with certainty for the pathologists at AFIP, and any insight into the temporal events preceding the impact elusive (Kerwin, 2009).

Expert 10 stated:

> *When I got down to the crew module, it was wrapped in wires and cables. It took some time to gain entry and took time and care to remove the crew.*

Although these issues are not solely the domain of spaceflight mishaps, it does bring about the point once again that the forensics and evaluation of the life support equipment are important in spaceflight mishaps and may or may not shed light on the sequence of events of the mishap.

Theme 5: Ebullism above Armstrong's line is a major differentiating factor for spaceflight mishaps.

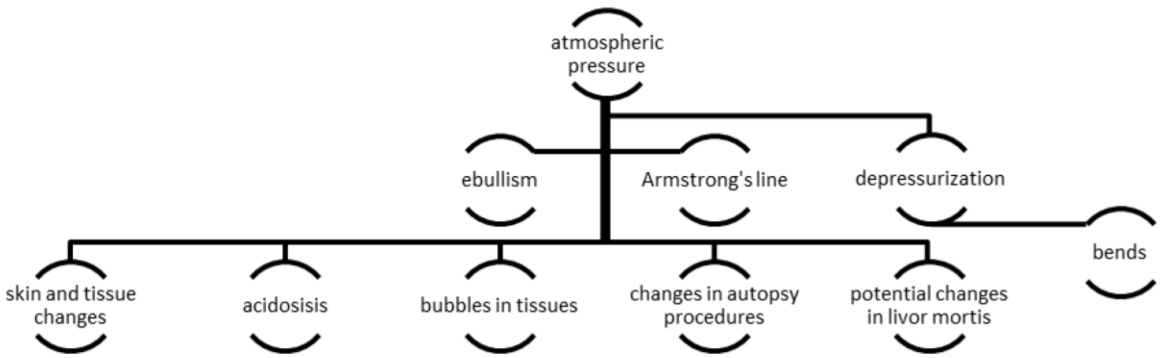


Figure 11: Codes Associated with the Theme of Forensic Changes Due to Atmospheric Pressure

Ninety three percent (14/15) of those interviewed mentioned ebullism as one of the starkest differences between spaceflight and other mishaps. As mentioned previously, ebullism is the rapid movement of liquids to a gaseous state due to a lack of ambient pressure (Murray et al., 2013). Ebullism occurs typically when the human body is exposed to vacuum or extremely low atmospheric pressures, which occurs above Armstrong's line (62,000 feet). Although related to decompression sickness in which nitrogen comes out of liquid into a gaseous phase, this involves far more than just nitrogen, with liquid water and other fluids all coming to vapor point due to the sudden loss of atmospheric pressure (Norfleet, 2008). Such a phenomenon is not seen in aviation accidents due to those accidents occurring at lower altitude within the atmosphere.

The quote from Expert 12 speaks to the lack of frequency in which it is seen when he stated:

> *Honest to God, when your doc called up and asked if there were signs of ebullism we thought he was mispronouncing embolism. We had never seen ebullism and didn't honestly know what it was or what it looked like.*

Data indicate that although they were aware of the loss of control of the vehicle, none of the crew of Columbia lowered their helmet visors (Davis, 2014). The rapid depressurization of the vehicle incapacitated the crew in seconds, and they were deceased rapidly thereafter due to asphyxia and ebullism (Davis, 2014). The changes seen in the tissues was not something that could be identified through the literature or any medical textbook. There simply were not enough cases of ebullism for pathologists to have a benchmark.

To their great credit, the Russian medical leadership sent the autopsy of the Soyuz 11 crew to the NASA flight surgeons so they could use it for comparison. The Soyuz 11 crew had also succumbed to asphyxia and ebullism as a result of a rapid loss of pressure in their capsule when pressure equalization valves errantly opened after separation from the service module (Shayler, 2000). Air-filled spaces rapidly expand in such a low-pressure environment such that tympanic membranes, pulmonary alveoli, and the small bowel are in danger of rupturing due to the rapid expansion of air (Boyle's Law). Boyle's Law states that as pressure decreases, the volume of a gas expands. Air bubbles from ebullism also expand, causing distention of tissue and rupture of blood vessels. The Russians also did something that is normally not done in a typical autopsy: they opened many of the organs under water in order to identify bubbles in the organ from dysbarism (nitrogen bubbles from the bends) or ebullism. For example, they opened the heart under water and indeed bubbles arose from the chambers.

Expert 02 explained:

> *That was something pretty ingenious that the Russian pathologists had done, and something unexpected. Most pathologists and examiners would not think to open those organs under water or saline to look for bubbles. We passed on that detail to AFIP (Armed Forces Institute of Pathology) but that really was something that we learned from them as a result of their experience with Soyuz 11.*

The Soyuz 11 crew had been having a successful mission docked to the Salyut space station. They had performed a 29-day mission aboard the space station, performing experiments, using an Orion telescope, and collecting data. The mission was not without incident as a fire had broken out onboard the Salyut spacecraft due to a short in the wiring of a science experiment. There was tension between the crew and ground due to a packed schedule, and tension between the commander, Dobrovolskiy, and one of the more seasoned cosmonauts, Volkov. They had packed the spacecraft with samples for return and were preparing for undock.

When all men had moved to the Soyuz, the commander moved to seal the hatch between descent module and the orbital module. As Ivanovich (2008) explains, this hatch would be the only hatch separating the men from space after detachment of the orbital module. However, when Dobrovolskiy rotated the lever arm to seal the hatch, the “hatch open” light remained lit. Both Dobrovolskiy and Volkov opened and attempted to reseal the hatch several times and checked the seal area for any foreign object debris. Each time, the “hatch open” light continued to illuminate. The cosmonauts had found that the hatch ring barely touched a sensor, one that when depressed would turn off the hatch light. The ground instructed them to place tape over the sensor and close the hatch and check it for tightness. This turned off the “hatch open” light. But this issue increased the tension with the crew (Ivanovich, 2008).

The ground control reduced the pressure in the orbital module later in the day to verify the integrity of the hatch seal in the descent module, and it proved to be secure. The crew prepared for the braking maneuver, which is required to slow the spacecraft and allow it to descend. The braking maneuver is followed about 15-18 minutes later by the separation of the orbital module, and then about six minutes after separation from the orbital module the descent program begins.

Much of the re-entry is automatic with thrusters to assure the trajectory and then drogue chute deployment prior to the main parachute deployment at around 30,000 feet. The full canopy is deployed by about 16,000 feet. Shortly thereafter, the pressure equalization valves open to allow the capsule and the atmospheric air to be of equal pressure. The four retrofire rocket are fired at about 3-4 feet off the ground to slow the descent even further just before landing. The majority of this series of events is pre-programmed into the computer with altimeters and sensors aiding in the sequence and timing. The crew acts as a back-up to the computerized program.

The Moscow Mission Control (TsUP) did not receive any communications from the crew during the braking maneuver. This was unusual, but secondary to one of the tracking ships being out of position and unable to receive the communication (Ivanovich, 2008). As scheduled, seven minutes after the braking maneuver, the vehicle oriented with the Orbital module on top and the propulsion module on the bottom in preparation for separation of both from the descent module. Per Ivanovich, the twelve explosive charges fired to separate the module as did the additional six that would separate the propulsion module. The main radio antenna was in the propulsion module and communications with the crew would be by a VHF antenna in the descent module hatch. Normally, the crew would be giving call backs to TsUP to let them know that separation occurred nominally and to assure them that they were aligned for re-entry prior to a comm black out when they hit the plasma interface. This time there was silence.

The drogue chute deployed as did the main parachute in nominal fashion. The crew would normally make contact with the ground rescue forces while under the main parachutes on descent, but this time, again there was no communication. The braking thrusters fired, and the spacecraft had a nominal soft landing and then came to rest on its side, having been pulled over by its parachute. The rescue forces and medical personnel approached the silent capsule and found all three crewmembers dead in their seats.

The rescue forces started CPR on the Soyuz 11 crew, as the crew was still warm to the touch. This may have been secondary to heat transfer to the vehicle, and the fact that ebullism (the boiling of fluids at vacuum) may have created heat in the tissues. The ground forces did not yet know that the crew had died before entering the atmosphere and had died of ebullism. The exposure to vacuum, which took place above the Karman line, was a major factor in why the Soyuz 11 crew’s cause of death was different from what is typically seen in aviation accidents. The Time of Useful Consciousness would have been exceedingly short, a matter of seconds. Because of the initial issue with getting a good hatch seal, the crew may have mistakenly thought the issue was with the hatch. Fog would have filled the air due to the change in pressure and temperature. By the time the crew would have realized the valves were open to vacuum, they would have lost consciousness and would have quickly suffered cardiac arrest from ebullism shortly thereafter.

From the reports of the rescue forces that arrived immediately after the Soyuz 11 landing, we know there was blood coming from the nose and ears of all crewmembers, and dark blue patches on their faces. Dobrovolskiy was still warm. The medical team immediately began cardiopulmonary resuscitation. Photographers, who were deployed to capture what was to be a triumphant return, now photographed the tragic mishap. They attempted defibrillation of each crewmember and administering cardiac medications, but none of the three were to be resuscitated. Unbeknownst to the rescuers, the cosmonauts had been dead for over 30 minutes, and had spent close to 12 minutes at vacuum (Ivanovich, 2008). The team attempted resuscitation for close to an hour. At one point, flight surgeon Dr. Levan Stezhadze, placed a needle into the cardiac chamber, but instead of drawing back blood, he was surprised when he drew back air bubbles (Ivanovich, 2008).

The Soyuz 11 crew had died rapidly from asphyxia and ebullism. The cabin recorder showed the pressure had gone from over 760 to less than 50 mmHg in under 115 seconds. But under closer examination, the commission believed the pressure dropped to zero in short as 30-40 seconds (Ivanovich, 2008). As mentioned previously, a valve at the top of the descent module, meant to equalize pressure in the atmosphere, had erroneously opened with the shock of the explosive bolts for module separation.

The Time of Useful Consciousness (TUC- see Table 5 from Carlyle, L, 1963) for the crew would have been less than 5-9 seconds (Carlyle, 1963) once the pressure was below 150 mmHg (2.9 psia, equivalent to 40,000 feet altitude). But in a sudden decompression, the TUC is typically halved, due to the sudden outflow of oxygen and elevated heart rate using up oxygen that is currently in the tissues (Carlyle, 1963). It should be noted that TUC is the time of “useful” consciousness, meaning for the person to be cognitively able to take action, versus totally unconscious. The air would have been clouded with vapor from the rapid decompression and the crew would have most certainly thought it was the errant hatch at first and might have reached for it, before realizing it was the valve above. They had turned off the radios and devices that were making noise, most likely in an attempt to isolate the leak by the whistling sound. But by that time, they were already a few seconds into this crisis. They would not have had time to figure it out quickly enough and close the valve manually before being incapacitated by hypoxia and the ebullism that was ensuing. Total unconsciousness and death would have followed soon thereafter.

The crew were not wearing pressure suits, as at that time the crews flew in regular flight suits. Today the Soyuz crew fly in launch and entry pressure suits called Sokol, which have a pressure of 5.8 psi and are oxygenated as a mitigation to prevent such events happening again.

Altitude	Time of Useful Consciousness
15,000 feet	30 mins or more
18,000 feet	20-30 mins
25,000 feet	3-5 mins
30,000 feet	1-3 mins
35,000 feet	30-60 seconds
40,000 feet	15-30 seconds
45,000 feet	9-15 seconds
50,000 feet	5-9 seconds

Table 5. Time of Useful Consciousness. Carlyle, L. (1963)

The three men were taken to Burdenko Military Hospital in Moscow for the autopsies, the same morgue and autopsy suite where Komarov was taken. The forensic findings on the autopsy match ebullism completely. Bubbles were found in every tissue including the brain, spinal cord, bone, muscle, and blood. No nitrogen was found in the serum.

The nitrogen, oxygen, water vapor, and carbon dioxide had come into a gaseous phase due to lack of pressure, essentially boiling, leaving bubbles in every tissue (Ivanovich 2008). Hemorrhages were found in the brain and lung, owing to the expansion of the bubbles from the lack of pressure rupturing small vessels. In air-filled organs such as the middle ear, sinuses, lungs, and intestines, the lack of pressure would cause a massive and rapid expansion of the gas due to Boyle’s Law (DeHart, 2003). The blood seen running from the ears and nose would have been secondary to rupture of the middle ear from gas expansion, and damage or rupture to the sinuses. The tissues contained a massive amount of lactic acidosis, most likely from the ebullism. The bubbles would prevent blood flow, essentially acting like clots in the vessels and together with the hypoxia of the tissues, would have caused a massive acidosis. The lactic acid level was over 20 times normal (Ivanovich, 2008), which is far more than would be expected in mere hypovolemic or hypoxic shock.

One puzzlement was that Dobrovolskiy was warm at the scene, which precipitated the rescue crews thinking they had just perished and starting cardiopulmonary resuscitation. The temperature at vacuum would make the internal environment very cold, so this was a finding difficult to explain. However, the vehicle re-entered through plasma which would have heated the capsule, and astronaut body temperature on long duration missions is found to run slightly higher than terrestrially (Stahn, 2017). This is another important finding, in that often a medical examiner will attempt to define the time of death using body temperature, usually from the liver or a rectal temperature. The cooling of the body and coming to homeostasis with the surrounding environment, known as algor mortis, is usually a linear decline in temperature that can be estimated by the Glaister equation (Glaister, 1925). The Glaister equation is 98.4°F minus the rectal or internal (taken by inserting a probe into the liver) divided by 1.5°F (Glaister, 1925, Hachem et al., 2020). This gives a rough estimate of the time of death.

Of course, many variables come into play, such as atmospheric temperature, the type of surface the body is lying upon, etc. However, in space, heat is transferred only by irradiation and conduction. Little to no convection occurs. This is another important point for future investigators, especially a medical examiner who responds to the scene of a human spaceflight mishap. Many variables, including the phase of flight, astronaut physiological changes, the temporal events of the death, whether the death occurred in space or below the Karman line, and the environment of space may impact the temperature and pressure, which in turn would alter the cooling of a body. This may account for the crew of Soyuz 11 still feeling warm, despite having died 30 minutes or more prior to being removed from the capsule and despite the exposure to the cold vacuum of space.

Another feature of the autopsy was the unusual pattern of the livor mortis. Livor mortis is the pooling of the blood in gravity dependent areas after cessation of cardiac outflow. The capillaries in the gravity dependent areas become engorged with settling blood, causing a bluish discoloration (Spitz et al., 2006). This pattern can be impacted by pressure, such as a tight garment, or by other factors. Livor mortis is typically a gravity dependent process. This process would look or act vastly different in microgravity or the absence of gravity if it occurred in space. In the Soyuz 11 crew, it took on a fern or speckled pattern, most likely due to the bubbles in the vasculature interfering with individual capillary settlement. The blood settled into the backside, probably after the crew were laid out upon the steppes of Kazakhstan to perform resuscitation. But the bubbles in the tissues persisted, interfering with the normal settling in the capillaries. This is yet another important feature for a medical examiner of future space flight mishaps.

Most of the changes or amendments to the normal forensic patterns of death that would occur in space are speculative at best until animal studies or additional research and study occurs in microgravity. But certainly, as human beings venture further out in the solar system to explore, there is an increasing probability that such knowledge may be needed. Ebullism, however, has already been seen in two accidents with a total of 10 astronauts/cosmonauts. At the very least, pathologists and medical examiners will have to become familiar with the signs of ebullism.

Theme 6: Pressure, temperature, and radiation give rise to differing concerns in spaceflight mishaps.

One hundred percent of the interview participants listed extremes in temperature, hyper- and hypobaric pressure, and radiation as unique features of human spaceflight mishaps. Radiation in particular was one subject that many of the subjects discussed in detail, and in-depth research of the cases was also revealing.

The rescue helicopter flight surgeons describe the bottom of the capsule being completely burned through (Siddiqi, 2020) when they arrived on the scene of the Soyuz 1 impact, with the capsule still on fire. What Siddiqi (2020), Grahn (2008), and Zak (2019) do not mention or perhaps did not realize is that the bottom of the Soyuz contained the "Kaktus" radar altimeter on its first flight of the Soyuz (Nebylov, 2012).

The altimeter used gamma rays from Cobalt-60 as a means to determine altitude from the ground using backscatter (the Russians converted from Cobalt-60 to Cesium-137 in the 1970's). The altimeter had several failures, both in testing and in operations, in which it failed fire the soft-landing rockets. In this particular instance on Soyuz 1, the rate of descent may have been more than the landing computer program could reconcile, and the firing occurred after impact. But the scene had a hot fire, one that burned through the bottom of the metal of the spacecraft with molten metal dripping into the fire. Unfortunately, that included the container holding the Cobalt-60. It is doubtful that the Russians had a Geiger counter in the field, or that they used one on Komarov's remains initially. It is highly probable that the surrounding scene, including the remnants of the spacecraft, soil, and Komarov's remains, were contaminated to some extent with Cobalt-

60. This is a critical lesson learned for those providing emergency response and those investigating spaceflight mishaps: there may be a danger of radioactive substances. Spacecraft increasingly use radioactive materials in radar altimeters, thermal generators, and power generators.

The likelihood that a spacecraft mishap scene could be contaminated in the future grows ever more likely. Investigators, forensic evidence gathering teams, and medical examiners should be aware or cognizant that radiation or radioactive materials pose a threat. This is a critical finding in this research that has not been described in the literature previously but is an important point to educate future mishap investigators or medical examiners on as they take on the role in commercial spaceflight mishap investigation. A Geiger counter is typically not part of an autopsy evaluation or scene survey. Komarov’s remains were taken to Bordenko hospital and photographed in the morgue prior to his cremation (Siddiqi, 2020). There is no record available for review as to whether his remains were checked for radioactive contamination. He was cremated shortly after examination. However, a large memorial to Komarov made of earth and concrete now resides over the crash site, which may be an indication of potential remediation or protection of the public at large from remaining radioactive contamination in the soil.

Research Question 3

Research Question 3: For future human spaceflight mishaps, be it commercial, NASA, or military- what are some of the most critical lessons learned that should be relayed to future mishap investigators?

Theme 7: Scene safety: Untrained spaceflight mishap responders may be harmed.

Again, 100% of the experts interviewed were in concurrence and mentioned this as a concern. Expert 04 relayed the following: *"We were sifting through parts and one of the guys holds up this mildly mangled part and several of us realized it was part of a pyrotechnic device. He had to gently lower it into an explosive containment box."*

The theme and subcodes regarding scene safety that were identified in the interviews are noted in Figure 12 below. Radiation sources, toxic pressurized gasses, and pyrotechnic devices from hatches and other hardware may be part of the mishap scene and require both specialized equipment and knowledge to handle and render these items safe or inert. Jagged edges from sharp metal, syringes from experiments, and other hazards require that the proper protective equipment be used when collecting or examining a spacecraft mishap. Thermal injuries may also be a risk as pressurized ammonia may be very cold, or radiation sources may be hot to the touch. Snakes, scorpions, black widow spiders, and other wildlife threats have all been encountered at spaceflight mishap scenes. Expert 05 stated: "*In reality we were there to help do the medical investigation and evaluate the human factors, but we ended up having to take care of several of the mishap team who either had lacerations, spider bites, or other injuries in addition to our primary mission".*

Theme 8: Fundamental Attributes of a Spaceflight Investigation Differ from Aviation Mishap Investigations.

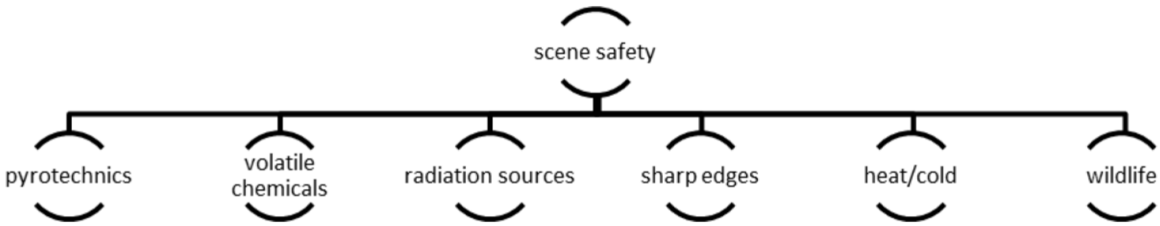


Figure 12: Codes that Align with the Theme of Scene Safety

Expert 08 stated:

> *First you have to know the phase of flight it occurred in. You could have a mishap on the ground phase, like Apollo 1, that was 40 square feet of material to examine, or you could have a Columbia accident that was 2,000 square miles. That is a fundamental difference for sure. There is no aviation mishap that spans 2,000 square miles.*

Expert 14 stated:

> *It is a high visibility accident. It's above the fold. Congress wants answers, the public wants answers. The press is out there. Onlookers are out there. It's damn near a carnival atmosphere.*

Expert 10 stated:

> *NASA sent astronauts into the field to help with finding remains, vehicle parts, etc. I am sure this was done out of honoring our fallen. But it was not a smart*

thing to do psychologically. I was used to seeing body parts and anatomy, but I tell you, it kinda messed me up a little going into my next flight.

Several of those interviewed stressed the fundamental differences between a spaceflight mishap and other mishaps. The allure, excitement, and public perception of human spaceflight may help to explain part of this difference. In the case of Columbia, there were pressures from the press, who wanted interviews and information from those in the field, and pressures politically as state and federal politicians jockeyed for airtime and the limelight. The footprint of Columbia was enormous and required a large number of people, equipment, and time.

But as Expert 10 remarked, there was also a psychological impact on sending astronauts and NASA personnel into the field. Even those who had been through warfare or had medical expertise and had seen raw anatomy and body parts, felt they were impacted. NASA implemented a brief conversation with the psychologist upon return from the field for those individuals in an attempt at Critical Incident Stress Debriefing. But several of those interviewed felt this was not enough, and perhaps it was a mistake to send crewmembers, especially those who were assigned to future Space Shuttle missions, into the field.

Expert 15 stated:

> *The physics are different. You have to know something about the physics of spaceflight. It does not work like an airplane on re-entry or launch. Somebody who is used to aviation mishaps might jump to a conclusion based on what they know, and this is fundamentally different".* Expert 08 stated: *"I needed a scribe*

out there. Somebody who could write down or take photographs next to me. Sometimes there were things I was looking at that only in hindsight or after I obtained more information or asked questions that it became clear. It would have helped if I were not the photographer, the note taker, the student and the investigator all in one. Because I was learning about the spacecraft as we went. Having that administrative or ancillary support would have been incredibly valuable.

Four of those interviewed stated that task saturation for the investigator was higher in a spaceflight mishap investigation than in other mishap investigations they had taken part in. They felt this was partly due to the outside influence (press, politicians, Headquarters wanting information, etc.) and partly due to the fact that they were taking notes, having to make phone calls to arrange equipment, taking photos, and in some cases providing medical care for the mishap team. Additional ancillary support for those tasks would have been incredibly valuable and should be considered for spaceflight mishap investigations.

Theme 9- The physical attributes of a spacecraft mishap differ significantly from an aviation mishap.

One hundred percent of those interviewed mentioned codes that aligned with this theme. In an aircraft accident, all aircraft have the same basic structure: a fuselage, wings, flaps, rudder, elevator. A spacecraft has a multitude of variation. It can be a lifting body, a winged spacecraft, a capsule, and the parts or thrusters may be exceedingly different between those types.

Expert 15 explained:

We had several weeks of a course put on by the United Space Alliance back in the days of the shuttle program to familiarize us with the vehicle. We had a familiarization manual for both the Space Shuttle and the space station. You could literally look up what the function of any part was or what it did with all the schematics associated with it. In commercial crew, and thus far in Artemis, we don't have anything like that. The technical authorities have to go on what they hear or know in meetings and reviews.

Expert 14 explained*:*

The technical authorities have to know the systems across multiple vehicles and architectures now as opposed to a single type of vehicle. They need to know the physical attributes and characteristics of each of those vehicles.

Expert 14 further explained:

The manual pressure equalization valve was a good example. We had to fight for that requirement and only from the knowledge of Apollo 1 and other mishaps would you know that you needed that valve. That it was imperative to have that ability to equilibrate the pressures across the hatch rapidly.

In short, the technical authorities who have oversight of the development of the new spacecraft must be familiar with the characteristics and physics of each type of vehicle and must have studied past mishaps and how the nuances of each can be avoided in the design of new spacecraft and architectures. This is necessary to prevent a recurrence of the same mistakes or risk.

Theme 10: Knowledge of the spacecraft systems are critical to understanding the potential causality of spaceflight mishaps.

Expert 08 stated:

> *One of the best practices in the Columbia mishap investigation is that Wayne Hale (the NASA head of the Mission Management Team for the Space Shuttle Program) briefed us or had engineers who had knowledge of specific systems brief us every morning. They did not try to infer causal relationships. They were there to just brief us on what these systems did, what they looked like, and when they were important in certain phases of flight. Essentially, we had Space Shuttle school every morning. I can't begin to tell you how important that was.*

Expert 07 stated*:*

> *This is one of the risks with commercial spaceflight, they have proprietary systems that they do not want their competition to know. They are not transparent in all of their architecture or engineering because they want to maintain a competitive advantage. So, it will be imperative that they have engineers and representatives at the mishap to help explain their systems.*

Research Question 4

Research Question 4: For a technical authority charged with aiding in human systems design of new spacecraft, are there lessons that stand out in your mind that they should consider based on the mishap that you were involved in?

Theme 11: Standards and Requirements Should be Dictated by Best Practice and not Influenced by Social or Political Pressures

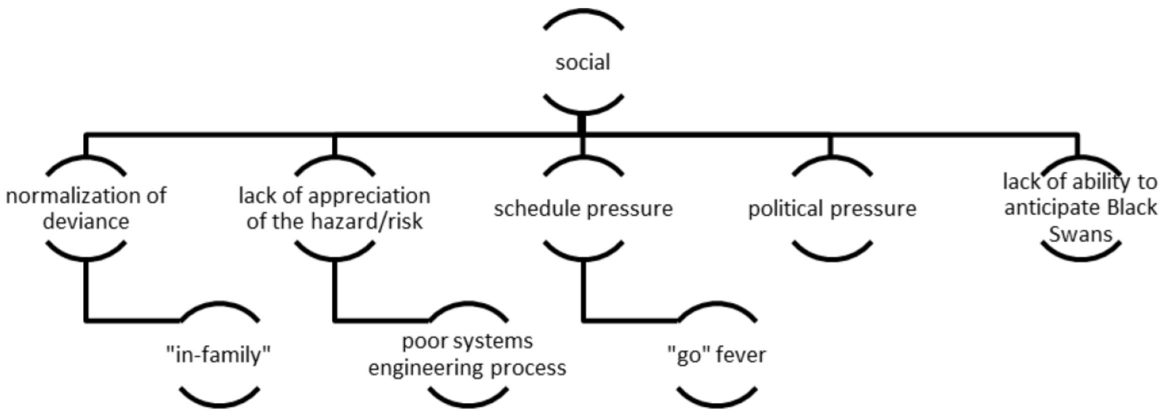


Figure 13: Codes that Align with the Theme of Social Contributors to Spaceflight Accidents

Expert 10 stated:

> *This is a highly volatile environment and I think one of our biggest risks is that we start to take things for granted, and we all get on the bus to Abilene and accept a risk that perhaps we should not accept. We don't want to be the person to slow down the ops tempo. We normalize deviance. The words I hate the most that I see when there is something we don't fully understand but nothing catastrophic has yet happened, is 'in family'."*

Expert 07 had a similar sentiment*:*

> *Oh God, the worst thing I can hear in a review is 'in family'. That is short for we don't know, we don't fully understand it, but we don't think anything bad will happen. I remember it being used at a readiness review for Columbia when describing the foam strike from the bump out. It was 'in family'. Now I cringe when I hear someone use that phrase.*
>
> *The longer you are doing something that has unexpected results or unbounded phenomenon that you did not expect to happen or can't really explain or start to dismiss…the more the risk is compiled (Expert 07).*

Normalization of deviance was brought up several times by the interviewees as a risk for technical authorities working on spacecraft in development. In particular, the need to "go along to get along" or not draw the ire of a program manager was noted as a particular risk in this area. Cost and schedule are always a concern, and with nearly every spacecraft development there is inevitably a General Accounting Office report, Inspector General Report, or Congressional hearing that discusses how the spacecraft is overbudget and behind schedule. But the technical authorities working on a vehicle must keep themselves objective and above this fray.

Anticipation of "Black Swans" (unforeseen or unlikely but high consequence events) are something that technical authorities should plan for and have as an attribute, in order to anticipate worst case scenarios and write requirements and plans to mitigate the risks to the crew as best as possible (Taleb, 2007).

In summary, those interviewed identified the spaceflight environment as highly volatile, and cautioned against any technical authority taking any fully unexplained phenomena for granted. A healthy dose of skepticism is warranted, and findings that are not fully understood must be fully vetted. Cost, schedule, political, and other pressures must be set aside in order to focus on the requirements needed to maintain the survival of the crew in off-nominal situations.

Theme 12: The addition of "survivability" to fault tolerance and reliability must be a hallmark of spacecraft design.

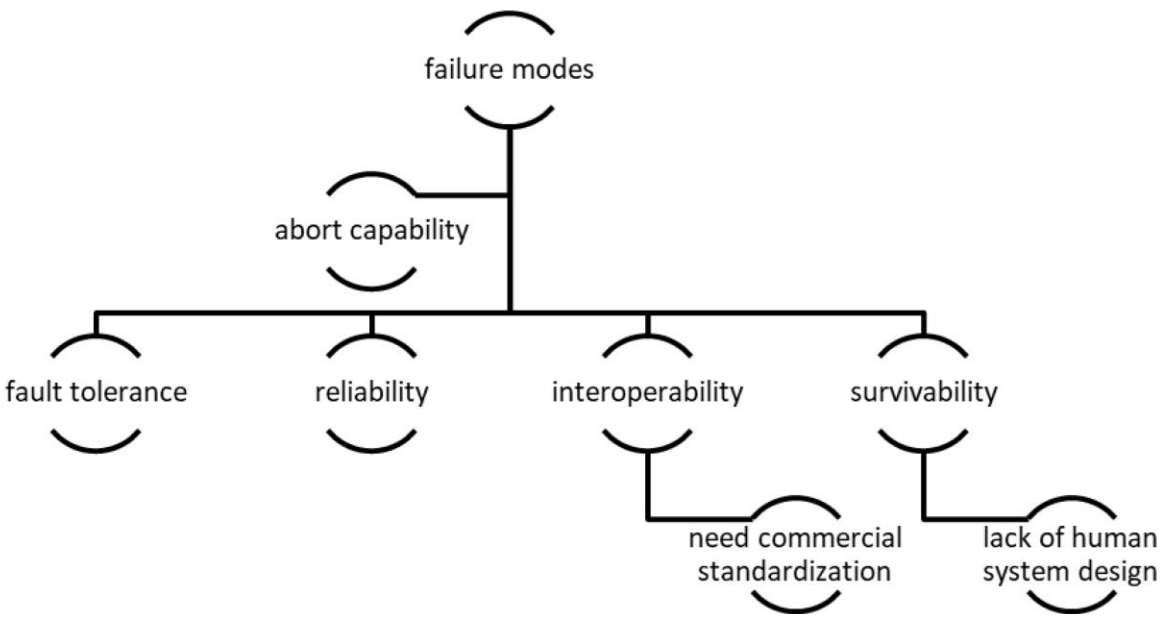


Figure 14: Codes that Align with the Theme of Failure Modes

As previously indicated, in addition to identifying causation for a mishap, one of the main objectives of an investigation is to identify and mitigate the causes in order to prevent the reoccurrence of a future mishap. Participants explained that their exposure to the spaceflight mishaps led them to highlight the need to develop a spacecraft that increases the chances for survivability as part of the design objectives. The participants believed that tools, such as artificial intelligence, can be used to automate some processes to eliminate human error. Several participants highlighted examples from the automotive industry that are already in use such as airbags, crumple zones, braking sensors, and "smart systems" that have been shown to decrease mortality. They explained that building the spacecraft around crew survivability is essential for safer future designs. This can only be achieved after thorough understanding of how the design of the accidental spacecraft failed and affected the crew members.

All of the interview participants indicated that the knowledge gained from mishap investigations should be used for the design and development of better spacecraft with higher likelihood of crew survival.

Exp 01 stated:

> *You can see that might help us then to design a better spacecraft. That's the whole purpose of closing this loop, right? To learn the mechanisms of injury and how space changes them or impacts them….so we can design a better spacecraft.*

Expert 03 stated*:*

> *We talk about reliability and fault tolerance of critical systems, and we talk about loss of crew as a metric, but we don't think of survivability as something that must be maintained. We need to shift to talk about reliability, fault tolerance, and survivability in the same sentence and have those three terms run together.*

Expert 15 stated*:*

> *We don't design a spacecraft for a human in the same way the automotive industry does. We design it around the mission architecture, and the engineering and vehicle then drive the human requirements and standards…often an afterthought.*

Four of the participants mentioned interoperability specifically as a potential needed future requirement. At present, NASA has a docking standard that is open source and used by all vehicles that dock with the international space station. But the participants felt that it needed to go further in the future, such that the FAA should consider having some standards of interoperability so that one commercial crew vehicle could rescue the crew from another. Currently, no such standard exists.

Expert 11 explained:

> *You know, the Space Force might be similar to the Coast Guard in the future. It would be good if they had a rescue capability for human spacecraft and their crews. I don't know if it will ever happen or not. But ideally, you'd want a rescue capability as you begin sending more and more private folks to space.*

Abort capability was one of the major codes discussed by the majority of those interviewed. Two of those interviewed pointed to the success of the Russian Soyuz aborts, including one in which a NASA astronaut was aboard, as proof of abort system capability being a necessary feature in human spacecraft. To date, there have been four launch aborts (three Soyuz, one Blue Origin) of human-rated spacecraft that were not mere tests of the abort system (Zak 2016, Harwood 2022). The first such abort, Soyuz 18, occurred when the second stage failed to separate and caused an anomalous trajectory in the spacecraft. The launch escape tower had already been jettisoned, but the Soyuz service module engines fired to lift the capsule from the rocket and initiate an abort (Shayler, 2000). All of the crewmembers survived with minimal injuries.

The second was the only historical pad abort to date, when the Soyuz T-10 caught fire on the pad after a fuel valve failed and leaked fuel on the pad. The launch escape system fired a mere two seconds prior to the rocket exploding (Shayler, 2000) and pulled the crew away from the rocket, landing them safely several miles away under parachute canopy. Per Clark (2021), the crew experienced over 15 G's when the escape rocket motor fired but landed safely without injury.

The third was Soyuz MS-10 in 2018, which US astronaut Nick Hague and Russian cosmonaut Aleksey Ovchinin were aboard. The mishap occurred when one of the boosters hit the core second stage, damaging the second stage of the rocket and knocking the rocket off trajectory (Bodner, 2018). The launch escape system pulled the capsule free of the rocket, and the two crewmembers landed in Kazakhstan without any serious injuries (Bodner, 2018).

The last abort happened in September of 2022 when the Blue Origin spacecraft suffered a rocket malfunction, causing the capsule abort system engines to ignite and carry the capsule away from the rocket, and landing the capsule safely in the desert (Harwood, 2022). No passengers or crewmembers were aboard this capsule, but the vehicle was a human-rated capsule. Had a crew been aboard, they would have survived and been safely returned to Earth.

One expert mentioned that he felt capsules were safer because of their abort capability. Although generally this is true, even winged vehicles and spacecraft could have an abort system built into them. The Space Shuttle initially had ejection seats for the pilots during test flights, but other escape systems were entertained in the design phase, including a crew module escape system (Hallion, 1983). The F-111 abort escape capsule system, the original B-1 bomber escape capsule, the B-58 Hustler escape pod system, and the XB-70 Valkyrie are notable examples of entire crew modules or pods being used for escape systems of winged aircraft, as opposed to ejection seats (Sadler, 2003).

In each of these examples, the crew of a winged aircraft escape the vehicle through the ignition system and separation of a crew module from the remaining vehicle or aircraft, often at high altitude and supersonic speeds, allowing the entire module to parachute back to Earth. In both the Xb-70 and B-58 Hustler, the escape pods were pressurized, which would allow the crewmembers to use standard life support equipment as opposed to high altitude pressure suits (Phillips, 1973). NASA studied the concepts of a crew escape module for the Space Shuttle and had increasingly lively debates on the subject with the Aerospace Advisory Panel (Cowing, 2003). But ultimately, such systems were deemed to impart too much mass, weight, and volume to the orbiter and were abandoned. The Hermes spaceplane concept, initially developed by the French, had a crew escape module as part of its original design. The spaceplane never came into existence, however. But the concepts that were put forward show that a crew escape capability is feasible from winged spacecraft, not just capsules.

Research Question 5

Research Question 5: What skills should the mishap investigator possess when dealing with a human spaceflight mishap?

Theme 13: Investigators should possess the requisite training and experience in mishap investigations.

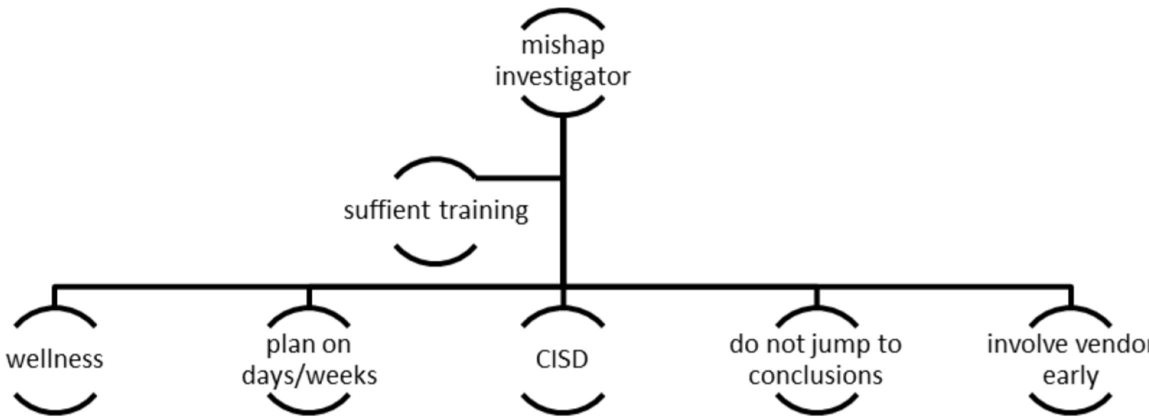


Figure 15: Codes that Align with the Theme of Mishap Investigator Attributes

The majority (12/15) of the interview participants expressed that a core challenge to the identification of causation is the potential utilization of untrained personnel for the investigation. It hampers the investigative process and often leads to an inconclusive and/or misleading investigation. Thus, it is crucial to only use well-trained investigators, i.e., investigators who have knowledge of the investigative process, but who also possess comprehensive knowledge of spaceflight physics, spacecraft components and those that can interpret both spaceflight-related engineering faults and crewmember injuries.

Expert 07 stated:

> *You can't just let them do their own normal thing because they will draw conclusions based upon evidence that they had no understanding of …which they have no understanding of the physics or the physiology or the vehicle, and that means they will try to fit it in a box…a box they know or have experience and understand and they will come to the wrong conclusions.*

Expert 11 stated:

> *Too often this is a pick-up game. Who is available to do the mishap? Instead, it should be a group of people who are well trained on the vehicle, the mishap procedures and process, and who know the technical aspects. In my mind, the technical authorities should have a dedicated group of mishap team members. They have provided the oversight to the development of the vehicles. They reviewed this vehicle in the readiness review. They should know this vehicle and the risks inside and out. There is probably nobody more suited to participate in the mishap investigation.*

The interviewed experts explained that a proper investigation is a painstaking and time-consuming process that cannot be rushed. A rushed investigation could lead to inadequate details regarding the vehicle anomalies, the sequence of events, the state of the crew members, a lack of in-depth survival reports, and limited detail about the event leading to the mishap.

Expert 04 relayed the following story:

> *I was out in the field and a group of folks called us over because they thought they had found some remains. I went over and bent down and looked at the bone and thought it looked more like deer. I picked it up with my bare hands and examined it and asked this lady from the FBI standing behind me what she thought. She said, 'I think you just put your DNA all over a potential piece of evidence'. It turned out that it was not remains, but the point was made. They were going to need to use mitochondrial DNA to identify the remains and I had just put touch DNA all over it. I should have used gloves. A trained person should have been handling any potential remains. I was not trained in field investigative or forensic techniques, and it showed".*

The sheer size of a spaceflight mishap may be overwhelming, and a large number of volunteers and other untrained personnel may be needed because of the size and scope. But where possible, trained experts should be used in order to preserve evidence and decrease the risk of contamination of the scene.

The analysis further revealed that spacecraft investigators must be well-trained professionals from diverse fields in human spaceflight; investigators must by dynamic, open-minded, and capable of acquiring and analyzing new information with precision and speed. They must also be mentally prepared to spend multiple weeks at the scene of the mishap.

Expert 003 indicated:

> *First, and I say this from first-hand experience. They must pay attention to the consequences to their wellness. We sent people out in the field that had personal relationships with the crew or were assigned to fly next. We thought we were doing that for respect and to honor our fallen colleagues. But we underestimated the toll on the human psyche. We also sent folks out there who had diabetes and cardiac issues and they had no business being out there. They were a risk to the team and themselves*.

The participants also indicated that the following qualities in the table below are ideal for investigators:

Identified Ideal Traits for Mishap Investigators
Highly inquisitive
Ability to remove personal judgments or sentiments
Biohazard and toxin consciousness
Wild animal and dangerous pest consciousness
Excellent data gathering skills
Knowledge of the spacecraft physics and environment
Knowledge of spacecraft components and technology
Staying above public perception
Sticking to only factual information
Transparency
Intrinsic knowledge of the mission, procedures, and operations leading to the mishap
Ability to think outside the box

Table 6: Identified Ideal Traits for Mishap Investigators

As the figure below shows, codes in addition to the training were identified by the participants as being important in the investigation, especially in regard to assets that aid the investigator. For example, the use of drones and Unmanned Aerial Vehicles to survey large swatches of land or difficult terrain was mentioned.

Expert 06 stated:

> *They didn't exist at the time for* Columbia*, but now you could use those small drones to survey a lot of land rather quickly to identify vehicle parts or potential remains. They have the ability to take photos and geotag locations. Some even have spectral imaging capability that could identify heat sources or other*

methods to identify spacecraft debris. This would be a technology that a future spaceflight mishap investigator might need. We might need a specialized drone team to deploy. It would be good to get the mishap teams familiar with this technology and its capabilities before the next accident.

Expert 08 stated:

The iPhone now can take incredibly detailed pictures, and there are apps that you can download that will place the GPS location, the altitude, the direction, the time and date, and annotated data right onto the photo. That would be incredibly helpful when you are going back over photos or evidence a week or two later to assemble a report or put the puzzle pieces together. You still have the official photos but taking as many pictures as possible with notes attached and data attached, that would be incredibly useful for the individual investigator's ability to recall or interpret what they saw.

Although previously mentioned, several of the subjects again reiterated the importance of administrative support when out in the field or during an investigation. Expert 06:

You know, I had someone who was there to make the calls, arrange the transport of remains, answer the phone, write down when samples came in, and just keep a log of everything we were doing. That was incredibly important.

Three of the interview participants mentioned that having a large space to reconstruct or lay out the spacecraft parts was incredibly helpful.

Expert 06 stated:

> *Whatever room you think you will need, double it or triple it. It was helpful to have an area to layout the spacecraft. We also used that same technique for remains. We had an outline of a body and would mark off the parts that we had found so we knew how much of a body or remains were unaccounted for. But you have to have a lot of room for all the personnel, the support folks, the parts, the investigators, and the subject matter experts.*

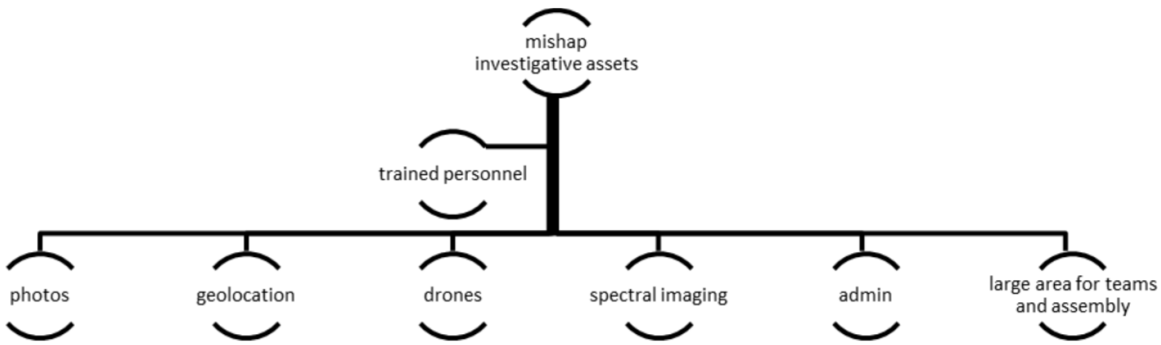


Figure 16: Codes that Align with the Theme of Mishap Investigative Assets

Theme 14: Investigators Should keep an open mind and avoid leaping to conclusions.

The theme is related to the characteristics of published investigative reports, the ethical consideration that hampers the quality of the report, and the dedication that is required to complete an impactful investigative report. According to the participants, factors that reduce the quality of mishap report may be the limited education and experience of investigators. They further explained that the preparation of the report is methodical, thus, education and experience are needed in the research and documentation of the research findings. The report must be free from bias, including political pressure or other attempts to bias the investigators. The lack of these qualities may make the report vague and non-transparent.

An example of this theme was evident when Expert 07 stated:

> *You know what? What were the things that allowed it to come to fruition for the Columbia report to be so transparent? I think it was a few people that had an absolute determination that this had to be published.*

Expert 08 stated:

> *I would also talk to the folks that work on the vehicle or mission day to day and I would ask them. What do you think caused the accident? You'd be surprised what you hear. 'Well, I didn't like that system from the get-go, or we brought this up to management several times…'. You can start to get an idea of what was happening culturally there, and what might have happened or what problems were ignored. You have to be a good listener, but also not be afraid to ask the question….what do you think happened?*

Expert 08 further stated:

> *I would also get Peer Group reviews. I think this important. You get a collection of experts, peers, and they can review the data and they may have more thoughts or ideas than you might have yourself. It keeps you intellectually honest and often they think of things that you might not have thought of.*

Another unforeseen problem arose regarding ethical considerations with regards to data gathering. One participant explained that originally in the Challenger mishap, they needed data on dysbarism and human physiologic impacts of exposure at altitude. Unfortunately, some of the previously recorded data on dysbarism was from Nazi experiments. There was a great deal of hesitation to use any of that data because of how it was obtained.

Expert 10 stated:

> *We struggled at times as we looked for historical data. There were papers where prisoners were used to assess what the Germans needed as they worked on jets, pressurized cockpits and ejection seats, and that sort of thing in World War II. But it was data. It was data that looked at how altitude impacts the human body. We got into pissing contests about the ethical and moral implications of how the Germans obtained that data, and whether or not we should include it or even review it because of its implications and moral considerations.*

In this case, having an ethics board or panel would have been valuable as a resource for the mishap team, and may be valuable as mishap investigators wrestle with issues in the future.

Issues regarding privacy, non-disclosure agreements for private spacecraft companies, data that may cause liability, proprietary data, and other issues may arise as a consequence of private or commercial spaceflight that were not necessarily considerations for government spaceflights. Having members of the legal community available may also be of benefit to the mishap investigative team.

Theme 15: Investigators should be objective.

Expert 10 stated:

> *You have to go where the data leads you. Regardless of your personal opinion. You have to go where it leads you".* Expert 08 stated: *One of the best ways to maintain objectivity is to have a standardized process for the investigation. You standardize the evaluation, the equipment, the search grid methodology, the chain of custody, the modeling of the accident. The more you standardize the process the less chance you have of someone going off and freelancing beyond the bounds of objectivity.*

Expert 08 further stated*:*

> *Don't allow one person to dominate the conversation. Usually, the loudest, most vocal person has an agenda. He or she is trying to sway the decision or investigation in one direction or another and you have to tune them out, or if necessary, shut them up. But don't let the loudest voice dictate the direction.*

Expert 08 addressed the assumption of fault by stating:

> *Don't assume fault. Don't assume all the questions will be answered and that things will be forthcoming. But don't get into the fault business. The mishap investigation is an objective assessment of what was the most likely reason for the failure of the vehicle to perform the operation it was intended to perform. Stay out of the blame and fault business.*

Pre-planned preparation was mentioned as a means to maintain standardization and objectivity as well. That pre-planning extends from how the mishap is performed, to the salvage operation and recovery of remains.

Expert 10 explained:

> *In Challenger, we didn't have a contract or a forethought about salvage operations in the water. The Navy SupSalv (Supervisor of Salvage and Diving) was in charge of getting the debris up from the ocean floor. They were probably ok for getting vehicle parts, but they were ill-prepared for recovering remains. They used hard hat divers at a depth that scuba would have been more appropriate. They had platforms and were trying to put remains on the platforms and remains were falling off. It was not ideal. We should have practiced this before a mishap, we should have had objective procedures in place.*

Expert 06 stated:

> *We had to invent some procedures for handling remains on the fly. We had to order refrigeration trucks. We had to think about how and when the remains were going to be sent to AFIP (Armed Forces Institute of Pathology) and whether we were going to send them in batches or wait until we had a certain percentage of remains. We had to figure out the chain of custody for those remains as well. I think we did a good job. But it would be helpful to have those procedures outlined ahead of time".*

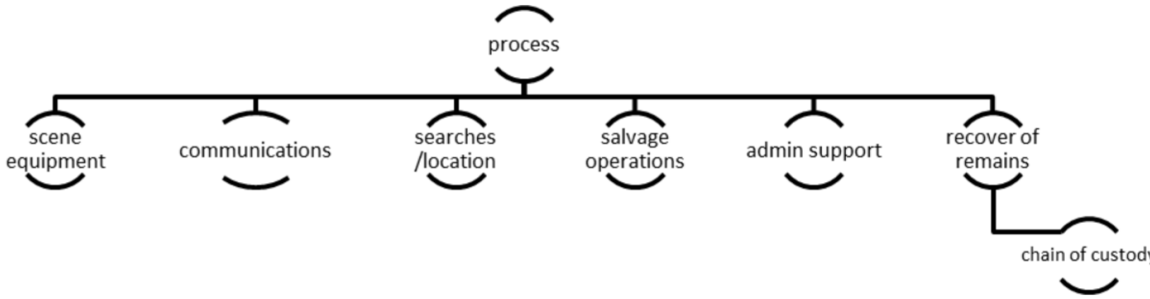


Figure 17: Codes that Align with the Theme of the Mishap Process

As figure 17 shows, there were multiple codes from the interviews that aligned with the theme of standardizing the process in order to maintain objectivity and clarity. Those include communications, scene equipment, how searches are conducted, how salvage operations and collection or remains are recovered, administrative support, and chain of custody.

The recovery of remains needs to be handled swiftly and objectively. Expert 08 stated:

> *The other thing you need to consider is getting the medical or pathology guys out there quickly and removing the bodies as soon as possible. It has a psychological impact to those investigators...I had a team that came to me….we had a crash and for whatever reason, the FBI was being very thorough…now, I am not saying thorough is bad…but these guys…these guys were painstakingly slow. The bodies sat in the wreckage for three days. By day three I had some investigators say that they just could not go back out there until those bodies were removed. That is also hard for families, for the companies, for anyone out there to have those bodies out there for any length of time.*

The lesson here being to not underestimate the psychological impact of having remains at the scene. In addition to the psychological impact, the heat, predators, insects, and elements begin to take a toll on the remains, making the job of the medical examiner even more difficult. Removing them as quickly as possible, after all the photographs have been taken, is better for the team, for the families, and for the medical examiners.

Theme 16: Investigators should have a knowledge of the spacecraft systems and mission profile.

At first glance this might seem repetitive to the previous discussion that mishap investigators should be well-trained. But there were multiple codes and discussions by the participants in this area. Several of those interviewed felt that the technical authorities themselves should also be engaged in the mishap investigation. Expert 09 stated:

> *Historically, after Columbia we have had the technical authorities oversee the building of vehicles and another group investigate mishaps. They are both in their own silos. But the technical authorities know the vehicles. They accepted the risk. I think it prevents a feedback loop to educate the technical community when you separate those functions.*

Expert 13 stated:

> *In Apollo the space suit supply lines for oxygen and scrubbing were in series, meaning they were all connected. Once you had a breach in a single line or a single suit, the carbon monoxide was getting into the breath air of every astronaut. The life support system lines were not separate or in parallel. So, an investigator would need to know this fact. This was not something the medical*

examiner was aware of. But a person doing the investigation needed to be fully aware of how this system worked.

Expert 11 stated*:*

We do a great job of simulating missions and having the flight control team respond to anomalies. But we don't simulate a mishap beyond a tabletop. We should simulate mishaps in the field to give people practice on the procedures, but also to challenge their knowledge of the vehicle and systems. I think this would cause the technical authorities to go back and look at some of those systems with new eyes.

Triangulation

As mentioned in Chapter 3, the three sources of data for this research were the official mishap investigative reports, independent research of archival data, autopsies, and previously published works, and interviews of subject matter experts. Where all three of those sources mentioned a particular code or theme, it was considered as "strong triangulation". Whereas when two out of the three source streams mentioned a code or theme it was considered "moderate triangulation". Where a single source reported on a theme, it was considered to lack triangulation.

The table below shows the codes that were identified in each category.

Codes with Strong Triangulation		
Normalization of Deviance	Kinetic Energy	Shock-Shock Interaction
Thermal Injuries	Plasma	Parachutes
Barotrauma	Crew Escape	Depressurization
Catastrophic Event	Loss of Crew	Nitrogen Tetroxide
Hydrazine	Carbon Monoxide	Chemical Toxicity
CISD	Contamination	Crew Survival
Ejection Seats	Radiation	DNA
Crew Survival	Life Support Equipment	Engineering Analysis
In Family	Political Pressure	Cost and Schedule Pressure
Crew Remains	G loads	Impact
Re-Entry	Angle of Attack	Phase of Flight
Personal Protective Equipment	Life Support	Pressure Suits
Recovery Operations	Root Cause	Thermal Protection System
Acceleration	Bends	Bubbles in Tissues
Codes with Moderate Triangulation		
Scene Equipment	Communications	Chain of Custody
Salvage Operations	Mishap Process	Aerodynamic Flail
Partial Pressure	Ebullism	Armstrong's Line
Karman Line	Arterial Gas Embolism	Atomic Oxygen
Cause and Manner	Bracing Injuries	Ammonia
Forensic Pathology	GPS	Human Factors
Freon	Escape Pod	Deceleration Injury
Injury Analysis	Q bar	Hypoxia
Incapacitation	Medical Examiner	Mission Management Team
Barotrauma	Restraint Systems	Boundary Layer
Vacuum	Propellants	Mishap Footprint
Search Grid	Atmospheric Pressure	Fault Tolerance
Reliability	Abort Capability	Interoperability
Human System Design	Pyrotechnics	Hatch
Acidosis	Skin Changes	Molten Metal

Table 7: Codes with Strong to Moderate Triangulation

Triangulation in qualitative research is often associated with reliability or validity of the data by using multiple methods or data sources in qualitative research to develop a comprehensive understanding of phenomena (Patton, 1999). Merriam (2002) states that reliability can be defined as dependability and consistency in the empiric data when multiple sources describe the same phenomena.

However, caution must be taken not to confuse reliability, validity and importance. Miles and Huberman (1984) describe triangulation as a means to increase both validity and reliability, in that the data is ascertained and confirmed by multiple sources. Although triangulation lends weight to the evidence in the form of validity from multiple sources, there are times when even evidence or data acquired from a single source is important. That single source may have context that was not shared with the masses, or included in the final report, but none the less be extremely important. The discovery of the likely contamination from the radiation source on Soyuz 1 mishap secondary to its first use on that flight as a radar altimeter is a case in point. No previously published sources discussed this as part of the mishap, although several engineering sources discussed the Soyuz 1 being the first flight of the "Kaktus" altimeter (Nebylov & Yanovsky, 2012). Arguably, potential scene contamination or exposure to radioactive material to both the first responders, mishap investigators, and medical examiners is an important piece of data, despite it not having triangulation.

Likewise, the discovery that pressure changed the behavior and toxicity of carbon monoxide, causing it to be much more lethal in a short amount of time in the Apollo 1 mishap, is an important piece of data, despite not having been mentioned in the literature or official reports and not having triangulation. Therefore, the qualitative researcher must use caution, as triangulation is an important part of the process to show validity in the results, but assumptions cannot be made about the importance of the data based on the absence of triangulation.

Analysis of Triangulation

Clearly the data shows that there are indeed differences between spaceflight mishaps and aviation and other types of mishaps. There are unique aspects to the physics, the engineering, the forensics, the potential footprint of a mishap, and risks such as radiation, toxicologic, and pressure that may be exclusive to spaceflight. When codes and themes are sorted or evaluated based on which are unique to spaceflight versus other mishaps, there is a trend that begins to emerge, at least in regard to causes of crewmember mortality and fatal spaceflight mishaps. It appears that there are three main determinants as to whether a spaceflight mishap will have significant differences from aviation mishaps in regard to mortality: kinetic energy, phase of flight, and the Karman line.

The kinetic energy is vastly higher for spacecraft than for aircraft, the phase of flight (ground, ascent, re-entry, descent, landing) will also determine the amount of energy impacted or differing hazards or risks, and the Karman line being above Armstrong's line and having the thermal conditions upon re-entry, appears to play a significant role. The Virgin Galactic accident was below the Karman line and had one survivor. It did not have the requisite kinetic energy of a spacecraft re-entering the atmosphere, and the astronaut pilots were not exposed to vacuum. No astronauts have survived when the catastrophic vehicle failure has occurred above the Karman line. There are other codes that are unique to spaceflight, such as ebullism, but ebullism occurs depending on the phase of flight, and is above Armstrong's line and certainly above the Karman line. Thus, although there are a multitude of unique codes or findings for human spaceflight fatal mishaps, the three factors that most determine those findings appear to be kinetic energy, phase of flight, and the Karman line.

Cross-Case Comparison

There are those that who suggest that capsules are safer than winged spacecraft as evidenced by their launch escape systems and the successful aborts of multiple capsules. But when the data regarding fatal spaceflight mishaps is evaluated, there are multiple fatalities in capsules as well. Since capsules carry fewer occupants than winged vehicles historically, the sheer number of fatalities are smaller for capsules than their winged vehicle counterparts. But the assumption that a capsule is “safer” cannot be made based on the data. In addition, when looking across spaceflight mishaps, they all occurred for different reasons. There is no commonality in the cases, with exception of the physics and ramifications of exposure to vacuum in several cases. But the data shows there is no overriding theme for spaceflight mishaps, such as parachute failure. Each accident had its own unique causality. There were some elements that were similar between fatal human spacecraft accidents, such as schedule pressure or normalization of deviance, both in the Soviet space program and U.S. space program. But there is no clear trend of causality between the systems architecture of any of the spacecraft. From the data, one might be tempted to state that engineering failures were contributory to all spaceflight accidents, but even that statement is not true. The Virgin Galactic accident was a human factors error that caused the dynamic vehicle break-up.

Comparison to Aviation Mishaps

The report from NATO cites that "70-80% of all deaths and injuries in decelerations are from face and head injuries caused by the head striking surrounding structures" (Tejada, 2005). Multiple trauma, with head injury being the most prevalent, is the leading cause of death in aviation mishaps, while the next most common cause or factor is post-crash fire (Tejada, 2005). The table below shows the fatal spaceflight mishap events. Unlike their aviation counterparts, the majority of spaceflight deaths are not the result of multiple trauma (including head injury) and post-crash fire. In fact, the incident rate in those cases approaches 44% versus the 70-80% in aviation mishaps.

When looking at the cause of death associated with human spaceflight fatal mishaps, on first blush it does not appear that there is a statistically significant difference between those mishaps and aviation mishaps. This would seem incongruent with the data already presented that clearly shows forensic, physical, and environmental differences.

However, as mentioned earlier, the main features that begin to determine or differentiate the substantial differences comes down to the kinetic energy of the vehicle at the time of the mishap, what phase of flight the mishap occurred, and whether it was above the Karman line and therefore also above Armstrong's line. These are the most distinguishing features. Below the Karman line, blunt force trauma and fire are seen in spacecraft accidents just as they are in aviation accidents. The table below shows the cause of death for each of the spaceflight missions.

Mission	Failure Mode and Phase of Flight	Cause of Death
Soyuz 1 *Number of crew: 1* *Number of casualties: 1*	*Parachute failures* *(below the Karman line)* *Re-Entry*	*Deceased from high impact multiple blunt force trauma*
Soyuz 11 *Number of crew: 3* *Number of casualties: 3*	*Valve opens in space* *(above the Karman line)* *In Space*	*Deceased from decompression, ebullism*
Apollo 1 *Number of crew: 3* *Number of casualties: 3*	*Spark in high oxygen environment* *(below the Karman line)* *Ground Operations*	*Death from asphyxiation from carbon monoxide, secondary injury from fire*
Challenger *Number of crew: 7* *Number of casualties:7*	*In-flight dynamic break-up of vehicle* *(below the Karman line)* *Ascent*	*Death from high impact multiple blunt force trauma, secondary injury from decompression*
Virgin Galactic *Number of Crew: 2* *Number of casualties: 1*	*In-flight dynamic break-up* *(below the Karman line)* *Ascent*	*Death from multiple blunt force trauma, secondary injury of decompression at altitude, one survivor*
Columbia *Number of crew: 7* *Number of casualties: 7*	*In-flight dynamic break-up of vehicle* *(above the Karman line)* *In Space/Re-Entry*	*Death from asphyxia with ebullism. Shock wave interaction.*
X-15 *Number of crew:1* *Number of casualties: 1*	*In-flight break-up at 62,000 feet* *(below the Karman line)* *Re-Entry*	*Blunt force trauma, post-crash fire*

Table 8: Phases of Flight, Failure Mode, and Cause of Death for Human Spaceflight Accidents

This means that ten out of twenty-three of the fatalities align with the mean cause of death also seen in aviation, that being blunt force trauma and secondary post-crash fire. A simple sign test, where the positives are those cases that align with aviation and the negatives are those that do not, can be performed in order to assess if there is binomial distribution and if there is a statistically significant difference. When the observed number of positive difference scores (those that align with the aviation cause of death) = 10 and the observed number of negative difference scores (those that do not align with the aviation cause of death) = 13, the two-sided p value is equal to 0.678. That is, the probability of finding the observed number of positive difference scores of 10 or a more extreme number, if the null hypothesis were true, is equal to 0.678. This is above the alpha of 0.5 and thus if you relied solely on a quantitative analysis, you would be led to be believe there was no statistically significant difference between the causes of death in aviation and spaceflight mishaps.

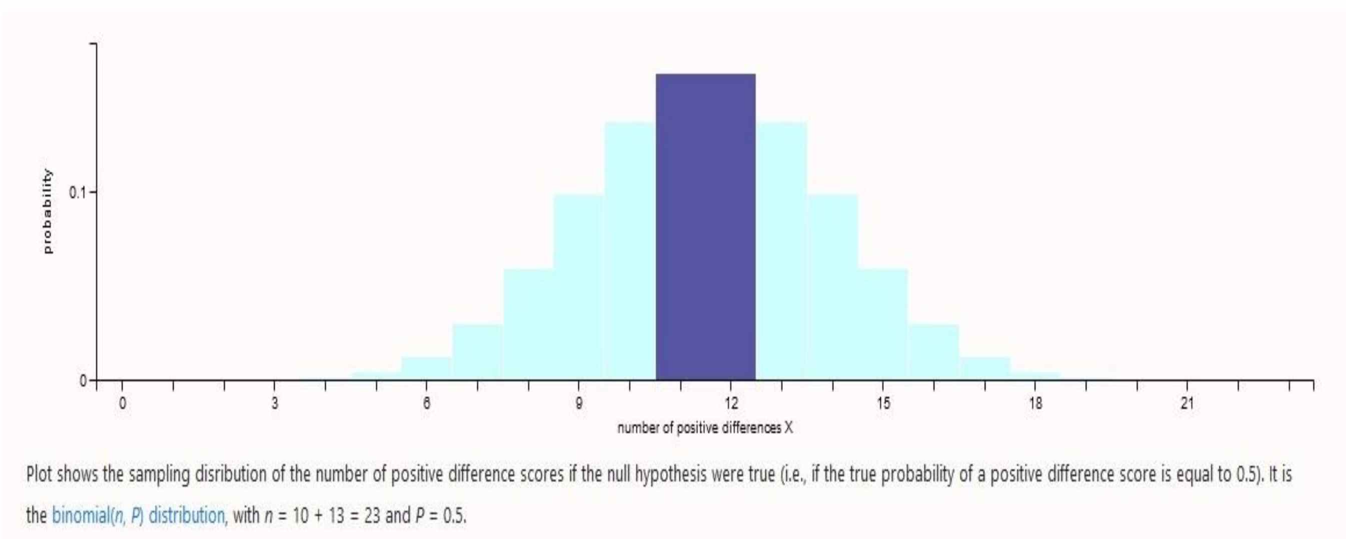


Figure 18: Binomial Distribution of Human Spaceflight Accidents Showing Statistically, the Odds of Having the Same Cause of Death as Aviation Accidents Have a Random Probability

But such an analysis ignores the vast differences annotated and described in the interviews and review of the data. This is the value of the qualitative analysis for such a small sample size, in that the variables outlined in the sections above clearly show multiple unique differences between the two. Only by separating out the phases of flight, kinetic energy, and specifically when the mishap occurs above both Armstrong's line and the Karman line do the profound differences between aviation and space mishaps become apparent, both quantitatively and qualitatively. If the same test were run using only those accidents where the incident occurred above the Karman line, there would not be a binomial distribution and the null hypothesis would not be met, and the cause of death would be radically different than aviation cases 100% of the time.

The amount of kinetic energy in a spacecraft accident is vastly different from that of an aircraft. A spacecraft on launch or landing is typically either accelerating and in the midst of breaking the sound barrier prior to maximum dynamic pressure or entering the atmosphere at several times the speed of sound and attempting to decelerate. The energy imparted to the vehicle and the subjects inside if the spacecraft encounters a break-up is extremely high (Davis, 2014). In the case of Columbia, the vehicle encountered Shock-Shock wave interactions. In Columbia, the vehicle became unstable and entered into the shock wave of hypersonic re-entry in an abnormal attitude, which cause an oblique shock wave. The two shock waves together caused massive heat and pressure forces on the vehicle and the occupants. This force interaction compresses and distorts the spacecraft materials and tissues along the line of where the two forces interact like that of a wave. This caused what appears as almost laser-like precision to cuts and damage to both vehicle and tissue due to the intense heat and pressure along that line of interaction (Hung et al., 1997). This would not typically be seen in an aircraft accident.

In addition, the G forces, especially those in Gx and Gz, would be much greater in a spacecraft accident than an aviation accident. This causes the multiple blunt force trauma, where exceedance of 50G may cause aortic tears, and exceedance of 100G's transects the aorta, displaces the spleen and lacerates the liver. Total body fragmentation occurs at over 350 G's (Tejada, 2005). Such speeds and G forces would typically not be seen in aircraft accidents but could be easily obtained in spacecraft accidents.

The chapter on human tolerance in the NATO manual has a table that describes the direction of the force, the occupant's inertial response, and the tolerance level. The table was amended by adding in the applicable spacecraft accident and the estimated G forces in that vector. You can see from the table that tolerance levels were exceeded in all but the Virgin Galactic accident, in which there was a sole survivor.

Direction of Accelerative Force	**Occupant's Inertial Response**	**Tolerance Level**	**Spacecraft Accident and G level**
Headward (+Gz)	Eyeballs Down	2-25 G	Virgin Galactic 20-35G's
Tailward (-Gz)	Eyeballs Up	15G	Columbia 100+ G's
Lateral Right (+ Gy)_	Eyeballs Left	20G	Columbia 200+ G's
Lateral Left (-Gy)	Eyeballs Right	20 G	X-15 40+ G's
Back to Chest (+Gx)	Eyeballs Out	45 G	Soyuz 1 300 G's
Chest to Back (-Gx)	Eyeballs In	45G	Columbia 250 G's, Challenger over 250 G's.

Figure 19: G loads Associated with Human Spaceflight Accidents, Adapted from Tejada, 2004

Excessive G loads, especially those imparted on impact, cause disruption of the aorta from tearing at attachment points, large heavy organs to be torn from their arterial roots like the spleen, or lacerations in large organs due to coup and counter coup injuries like the brain or liver (Tejada, 2004). This again lends evidence to the kinetic energy difference in spacecraft being a potential determining factor as to why there are such differences in the findings between spacecraft and mishap accidents, especially forensically.

Comparison to Undersea Mishaps

Asphyxia may be the only commonality between spaceflight mishaps and undersea mishaps in terms of cause of death. One is due to exposure to vacuum, the other to drowning or lack of oxygen in the breathable space. However, they may eventually have more in common with the risks for planetary habitats and space stations, where keeping individuals alive in an enclosed space for prolonged periods of time are common to both.

However, the ability to rescue a stranded spaceflight crew may have commonality with the ability to rescue a stranded submarine crew. Issues such as docking hatches that mate or have standardization, as well as issues of maintaining a crew in an enclosed environment for a prolonger period awaiting rescue have commonality. Hamilton et al. (2008) describes the commonality between the STS-400 Space Shuttle rescue mission (devised in the event of a stranded Space Shuttle on a Hubble repair mission) and a stranded submarine. To prepare for that mission, NASA had worked with the submarine rescue community (Hamilton et al., 2008). Although not the focus of this study, the topic of spaceflight rescue and its commonality with submarine rescue may be needed for future study as the commercial and international human spaceflight industry continues to expand.

Summary

The data shows that indeed there are unique and distinct environmental and forensic findings and aspects of fatal human spaceflight mishaps. The greatest environmental difference is secondary to the physics required for spacecraft orbital flight and re-entry, with speeds topping Mach 18. Even the SR-71 and other high-altitude aircraft that exceed Mach 3 are dwarfed by the sheer kinetic energy imparted by a re-entering spacecraft. The suborbital spacecraft are similar to high altitude aircraft, but even their risk begins to change above Armstrong's line with the potential exposure to vacuum if an anomaly occurs. The Karman line, which is further above the surface of the Earth, is an altitude usually associated with orbital flight, and thus both the combination of the potential exposure to vacuum as well as higher kinetic energy and exposure to plasma is responsible for many of the unique features identified. The Phase of Flight in which the anomaly or mishap occurs is also an extremely important determining factor for the type of features seen in fatal human spaceflight mishaps.

Shock-Shock interactions, also termed shock wave interaction, is a unique physical feature of hypersonic spaceflight mishaps. Its ability to cut through metal with laser-like proficiency in a specific area, while leaving the adjacent materials intact or unharmed, is something not seen elsewhere. The temperatures seen in re-entry spacecraft mishaps, with metal literally becoming molten mist, is another hallmark and difference between spaceflight and other mishaps.

Forensically, there are a host of potential unique features in fatalities associated with human spaceflight. The high kinetic energy may separate body parts by hundreds of miles. Shock-shock interactions may lase through a body part with laser-like proficiency. Ebullism is probably the greatest difference, with bubbles in every tissue and expansion of tissues as bodily fluids literally come to a boil and turn to vapor.

Mishap investigators must be knowledgeable of the engineering differences, the physics of spaceflight, the physiology and forensic differences of spaceflight, and be steeped in the knowledge of the mishap investigative process. A knowledge of that vehicles system must be obtained, either by a close working relationship early on with the vendor or through expertise with the spacecraft itself. Technical authorities should heed lessons learned from previous spaceflights and incorporate changes into future design and builds, taking survivability of the crew into account in addition to the tried-and-true fault tolerance and reliability that are typically used in system design.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

“On a plaque attached to the NASA deep space probe we [human beings] are described in symbols for the benefit of any aliens who might meet the spacecraft as “bilaterally symmetrical, sexually differentiated bipeds, located on the third planet in a solar system on one of the outer spiral arms of the Milky Way, capable of recognizing the prime numbers and moved by one extraordinary quality that lasts longer than all our other urges—curiosity.”

\- ***David Wells***

Introduction

The rapid expansion of private and commercial spaceflight means that reaching the heavens is no longer the domain solely of governments. With that change also comes a change in responsibilities, shifting mishap investigation oversight from Presidential Commissions to the National Transportation Safety Board, field forensic work from the Federal Bureau of Investigation to local law enforcement, and moving the autopsies from the Armed Forces Medical Examiner to the local coroner and medical examiners. The data shows that human spaceflight has its own unique physics, environment, hardware, engineering, physiology, and forensics. In those unique features comes the challenge of recognition and situational awareness of those differences in order to ensure the mishap investigation is identifying the proper elements of causality, but also to avoid potential dangers to the mishap team or medical examiner personnel. It also requires recognition and understanding of the risks for individuals new to the development of spacecraft, so that preventable maladies from past lessons can be learned and engineered out of the vehicle. It is imperative to identify these features in order to pass on lessons learned and knowledge that may have been insular to government organizations, especially to those groups that will now inherit responsibility for a domain in which they may have insufficient exposure, knowledge and expertise.

Summation of Key Findings, Discussions, and Recommendations

The research identified several key themes from interviews and review of historical data. In addition, several new findings were discovered on review of the evidence in deeper context. The potential contamination of Soyuz 1 with Cobalt 60 from the Kaktus altimeter has not previously been identified in the literature. Nor has the additive effect of pressure on carbon monoxide been previously discussed for Apollo 1, as a rationale for why the carbon monoxide was lethal so quickly. Multiple themes related to unique aspects of human spaceflight mishaps were identified from interviews of subject matter experts, which have implications both in designing and building new spacecraft and in future mishap investigations.

A brief discussion will follow each of the identified themes with recommendations for how these may be addressed.

Research Question 1: Are there physical or environmental differences between a spaceflight mishap and other mishaps that are important to highlight for future mishap investigators or technical authorities?

Theme 1- *Kinetic energy is vastly different in spaceflight mishaps versus their aviation counterparts, especially above the Karman line.*

Theme 2- *The physics of the boundary layer, shock-shock interaction, and the plasma are greatly different for spaceflight mishaps compared to aviation or other types of mishaps.*

Theme 3- *The phase of flight gives differing physical and environmental risks in spaceflight mishaps.*

Discussion

The research shows that phase of flight (ground ops, launch, orbital cruise flight, docking/undocking, re-entry, landing) and type of flight (suborbital, orbital exploration) were found to have a dramatic effect on the risks and the environment seen in a spaceflight mishap. Velocities upward of Mach 18 can be seen on re-entry for orbital flight, and even higher for exploration class missions further from Earth. This has a profound effect on a spacecraft and potentially the occupants if an anomaly occurs above the Karman line. The physics of the boundary layer and shock layer interactions, or shock on shock interactions, occur at supersonic speeds. But at hypersonic speeds (greater than Mach 5) such as in spacecraft, the compression wave against the boundary layer and propagation of the shock wave heats up the surfaces as the molecules in the front leading edges of the vehicle are severely compressed (Babinsky & Harvey, Eds, 2012).

The thermal protection systems are designed to accommodate where the shock-shock interactions normally occur on a vehicle's surface. But if the vehicle acquires an abnormal attitude due to an anomaly, such as that which occurred in the Space Shuttle Columbia mishap, it can have severe consequences as the superheating and pressure occurs on the spacecraft surfaces, and as high-pressure shock waves collide on elements not designed for that kind of intense heat or pressure. The resultant shock on shock interactions can cause severe thermodynamic properties, resembling an almost laser-like proficiency in distorting surfaces (Harvey, 2012). A mishap investigator must be cognizant as to the patterns that can occur at supersonic and hypersonic speeds. This may also be important for a medical examiner, as a vehicle breaking up at hypersonic speeds may subject the ejected occupants to shock-shock interactions, which may have similar laser-like wounds from excessive heating and pressure.

Toxins, radiation, and pressure in spacecraft may compound the effects or present a catastrophic hazard to the crew in a mishap. A simple toxin, like carbon monoxide, has its potential lethality greatly amplified by pressure. That pressure drives the toxin into the cells more rapidly and systemically than would otherwise have been encountered. Radiation sources are not only a hazard for the crew, but also a hazard to mishap investigators, fire fighters, EMS personnel, salvage operators, and medical examiners. Knowledge of the type of sources, the containment, the half-life, and protective and treatment measures is imperative when dealing with a spacecraft with a known radioactive source.

Recommendations

Training must be undertaken so that future mishap investigators will be able to recognize the characteristic findings of shock-shock interactions upon a vehicle, with a rudimentary understanding of the physics involved. This will be necessary to understand and model the attitude of the vehicle or the dynamics of flight, especially when either of those are abnormal. It is also imperative to understand when an anomaly or malady leading to a mishap occurred in regard to the phase of flight, as each phase has its own characteristic findings. This is especially important for anomalies or mishaps that occur above the Karman line.

NASA should work with the National Transportation Safety Board, the Federal Aviation Administration, and others to develop course material that will educate agencies, private entities, and commercial spaceflight companies on the physics, environment, risks, forensics and tell-tale signs to look for in a spaceflight mishap.

Research Question 2: Are there forensic differences that are unique to spaceflight mishaps? Is so, what are those differences or unique aspects in spaceflight mishaps?

Theme 4- *The forensic attributes of a spacecraft mishap differ significantly from an aviation and other mishaps.*

Theme 5- *Ebullism above Armstrong's line is a major differentiating factor for spaceflight mishaps.*

Theme 6- *Pressure, temperature, radiation give rise to differing concerns in spaceflight mishaps.*

Discussion

In a first-of-its-kind document, NASA documented many of the tissue findings from Columbia in the book entitled *Loss of Signal* (Davis, 2014). This was a milestone in both its transparency and its education of the findings, many of which had not been seen before. The deep review of spaceflight mishap is still a valuable exercise, as evidenced by the discovery of new information related to the potential for radiation contamination in Soyuz 1, and the role of pressure causing enhanced toxicity of carbon monoxide in Apollo 1. It is rare that engineers and medical examiners converse or compare notes, yet each may hold insight or context that the other needs. Cross-talk among all members of the mishap team is paramount. Ebullism was something the Armed Forces Institute of Pathology had not seen before the Columbia accident. To their great credit, the Russian medical community shared their autopsy of Soyuz 11 so that comparison could be made in the findings, and to help educate the United States on what the Russians had already learned about ebullism.

Toxins have played a role in risk in human spaceflight. Although not part of this study, the nitrogen tetroxide inhalation injury to the Apollo Soyuz crew was identified as a key example of this risk. The enclosed environment of a spacecraft can make this especially hazardous. Most exposure limits assume an 8-hour workday or settling of particulates with gravity. But in microgravity the astronauts have multiple potential routes of exposure (inhalation, consumption, dermal) and the enclosed environment may give them prolonged 24-hour per day exposure.

Recommendations

The data shows that ebullism, as a pathologic entity, was by far the outlier and greatest forensic difference in spaceflight compared to aviation and other mishaps. Whereas the bends, decompression, and altitude related hypoxia are well known in the aviation community, ebullism was not well known. It is not mentioned in any of the mainstream forensic pathology textbooks. It is not encountered on a regular basis by pathologists, coroners, or medical examiners. The rapid evolution of liquid gases to vapor at vacuum above Armstrong's line causes bubbles to occur in nearly every tissue of the body. The findings from Soyuz 11 and Columbia should be documented in the literature and sections on decompression and ebullism should be added to the mainstream forensic pathology textbooks.

NASA should work with the Armed Forces Medical Examiner (AFME) to develop a guide to include a list of procedures on what tissues need to be examined, what samples should be drawn, and how the organs should be evaluated in a human spaceflight mishap. NASA and AFME should also develop a primer on what findings to look for in ebullism in spaceflight mishaps that occur above Armstrong's line and certainly above the Karman line. The Russian pathologists opening certain organs under water to look for bubbles in the organs is one such example of a modified technique taking into account potential ebullism. A list of the blood samples needed for toxicology, bone changes that may be anticipated from microgravity, and brain and eye changes from Spaceflight Association Neuro-ocular Syndrome are examples of the specific lessons and direction that local medical examiners may need.

Coursework or material should include the fact that medical examiners may need to take into account how the microgravity environment associated with spaceflight, or alternatively, the high G- environment associated with re-entry may change the tradition findings of liver mortis, algor mortis, and other forensic benchmarks that are gravity dependent or influenced.

Recovery, chain of custody, and field assessment of remains should have specific standards set in order to maintain a common approach and should be performed by trained personnel.

NASA should create training materials to educate the toxicology, fire response, medical, and forensic community on the toxic hazards that could be associated with spaceflight and the changes that could come about with temperature and pressure applied to those toxins.

Research Question 3: For future human spaceflight mishaps, be it commercial, NASA, or military, - what are some of the most critical lessons learned that should be relayed to future mishap investigators?

***Theme 7**- Scene safety: Untrained mishap responders may be harmed.*

***Theme 8**- Fundamental attributes of a spaceflight investigation differ from aviation mishap investigations.*

***Theme 9**- The physical attributes of a spacecraft mishap differ significantly from an aviation mishap.*

Theme 10- *Knowledge of the spacecraft systems are critical to understanding the potential causality of spaceflight mishaps.*

Discussion

The mantra of "do no harm" in medicine applies to mishap investigations also. The event has already happened, but one of the first tasks is to prevent any further injury and to ensure the scene is safe. Highly pressurized vessels filled with volatile gases, fuels, pyrotechnic devices, radiation sources, jagged metal, blood, and wildlife all add to the potential risk to those in the field performing a mishap investigation. Scene safety is paramount in order to prevent additional incidents or harm to personnel.

There are several fundamental differences between spaceflight and other mishaps, such as aviation. Depending on the phase of flight, type of mission (suborbital versus orbital or exploration class), and altitude of the anomaly, the footprint for the mishap may be extensively larger. In the case of Columbia, it was spread over several states. The amount of personnel and logistics required for an investigation of that magnitude is immense. The types of hazards (toxins, radiation, pyrotechnic) may be very different. Large salvage operations at sea, such as in the Challenger accident, may require ships, equipment, and logistics that are typically not seen in aviation accidents with a smaller footprint.

Recommendations

Training is required in order to prevent harm, be it to field teams, medical examiners, or others. Currently there is no training platform from NASA, the FAA, or the NTSB that addresses the preparation and training for spaceflight mishaps that are available to commercial, private, defense, or international partners to train their personnel. Much as crash, fire, and rescue teams train at an airport for potential aircraft mishaps, training materials and guidance should be made available to communities that support commercial or private spaceflight activities and those communities should simulate or practice their field response to a spacecraft mishap.

NASA and the U.S. Fire Administration should work with the NTSB and FAA to develop training materials to educate those communities that may have to respond to spaceflight mishaps. This education needs to cover materials science, scene hazards, safing of pyrotechnic devices, toxicologic hazards, pressure vessel hazards, and potential radioactive sources. First responders may need additional equipment, such as Geiger counters when responding to a human spaceflight mishap.

NASA should work with the U.S. Fire Administration on field modules and hands-on exercises that could be taught to communities to help educate them on these potential hazards.

Because the footprint of a spaceflight mishap that took place at high altitude may be considerably large, the NTSB should consider the use of drone and Unmanned Aerial Vehicle technologies to help bound the size of the mishap, geolocate spacecraft debris, and identify potential locations of debris and remains.

NTSB investigators should have special training on spacecraft systems as well as a database of subject matter experts who are skilled in particular spacecraft systems that can be called upon to augment their investigative process.

Vendors should assure the investigators have insight into their hardware and systems, and if necessary be prepared to have a team deploy to help educate the field team investigators on those systems.

NASA should be prepared to help with sophisticated modeling, using its wind tunnels, supercomputers, and NASA Engineering and Safety Center personnel, in an effort to help the NTSB model or identify root cause in human spaceflight accidents, be they government or private.

Research Question 4: For a technical authority charged with aiding and oversight of human system design of new spacecraft, are there lessons they should consider?

Theme 11*- Standards and requirements should be dictated by best practice and not influenced by social or political pressure.*

Theme 12- *The addition of "survivability" to fault tolerance and reliability must be a hallmark of spacecraft design.*

Discussion

The independent technical authority came about as a result of the Columbia accident investigation. The technical authority process is part of a checks and balances between safe operation of the spacecraft and the many concerns that a program manager may have. Whereas the program manager may be concerned with budget, schedule, and other pressures, the technical authorities are concentrating solely on the technical standards and risk mitigation for the mission and vehicle. The interviewed experts described that the technical authority must be deeply knowledgeable about the vehicle design. They must also be free of influence and bias from the political, economic, and schedule pressures that often burden a program manager in order to maintain that independent view. Many of the past books and studies on spaceflight mishaps focused on the flaws in leadership and decision making that preceded an accident. But in reality, there were many technical errors that occurred as well.

As vehicles move from carrying government highly-trained “right stuff” astronauts to the general public as passengers, additional standards and regulation will be required to keep the public, pilots, and occupants safe. At NASA, the main focus of concern is the safety of the crew, but also the execution of the mission. The Federal Aviation Administration has a different lens, in that it is focused on the safety of the public. For example, NASA has a surveillance program that looks at the health of the astronauts throughout their lifetime, in order to assess the risk burden and toll of human spaceflight. The FAA has no such program for pilots, but instead is concerned with making sure the pilot is healthy at the time of flight in order to prevent any accident or untoward impact a crash or incident would have on the public. NASA is not regulatory, whereas the FAA is. Because of those different lenses, the FAA will not have the same focus as NASA has had toward private or commercial spaceflight.

Recommendations

Mishap investigations by their nature are looking for the root cause of an accident. But spaceflight mishaps must have a feedback loop that informs the design of the spacecraft, so that correction and remediations can be made to increase the safety of the crew. In addition to the mishap investigation, NASA has a separate team to execute and provide a crew survival investigation. This investigation looks specifically at all of the human systems design and human factors interfaces involved in a human spaceflight mishap with an eye toward making recommendations that will improve the likelihood of crewmember survival on future mishaps. This is one best practice that should be taken up either by the National Transportation Safety Board, the Federal Aviation Administration, or the vehicle vendor themselves.

Risk can be managed, but never truly eliminated. Systems engineering usually seeks to have back-ups in critical systems through fault tolerance, and in critical systems that cannot be duplicated, highly reliable hardware or systems in order to prevent failure. But crew survivability must be an additional metric. Both the automotive industry and the general aviation community have begun to design vehicles where the occupants survive even when the vehicle does not. Air bags, intelligent braking systems, curtain airbags, lane departure warnings, crumple zones, structure failure points around the occupants are all examples of occupant protection or prevention of accidents in the automotive industry aimed at occupant survival even when the vehicle is a total loss. In the aviation community, there is probably no better example than the airframe parachute. If all of the aircraft systems fail, the pilot can deploy an airframe parachute to lower the aircraft and crew to the ground under the canopy. The crew are much more likely to survive.

Spacecraft have taken survivability into account when placing the launch escape systems on the spacecraft. But there are few other systems or intelligent systems aimed at crew survival. If a parachute fails, artificial intelligence could sense the increased descent rate and increase the thrusters prior to impact by a percentage to account for the loss of the parachute. We have proven that a booster can be safely returned to Earth and land on a pad using thrusters and smart systems. The same type of systems could be used to back up the parachute systems.

As mentioned previously, pressurized suits that provide oxygen and a psi above 5.8 would prevent the majority of bends cases and provide pressurized oxygen and also increase some occupant protection from trauma. Human rated spacecraft that ventures above the Karman line, have supersonic speeds, or engage in docking/undocking should have pressurized suits. Blue Origin and Virgin Galactic both allow their private astronaut passengers to wear jumpsuits versus pressurized spacesuits. This is no doubt to allow them to be comfortable and prevent the expense and overhead of pressurized suits. But the data supports that critical vehicle events have happened above the Karman line where such suits would be lifesaving.

If the crew of Soyuz 11 were in pressurized suits instead of shirt sleeves, they would have survived their sudden depress. The potential for micrometeoroid impacts to the hull of a ship that could compromise the integrity and cause rapid decompression are ever increasing as debris continues to fill the orbit around the Earth. Anti-satellite tests by several countries have added to micrometeoroid debris risk to human-rated spacecraft. This makes pressurized and oxygenated suits increasingly more important above the Karman line in the event of an unexpected decompression. Life support and systems to ensure crew survival are paramount for technical authorities and designers of new human-rated spacecraft to take into consideration. Where aircraft have wings, rudders, flaps and systems in common, spacecraft may not have a great deal in common between one another. One spacecraft may be a winged vehicle, another a capsule. One may have its abort system as an escape tower on the top of the rocket, another may have thrusters or rockets on the bottom of the spacecraft to propel it away from a rocket. One may land like a plane on a runway, another parachute onto land, and another parachute into the sea. This means the technical authorities must be familiar with the physical attributes of all human spacecraft and the individual risks that each design imparts, and standards documents must be written in such a way to take into account the myriad differences in design. Commercial and private companies have declared many of their systems and engineering as proprietary. This decreases the insight into the workings of those systems.

Technical authorities with oversight of these vehicles should be given insight into proprietary systems. This may require legal waivers, non-disclosure agreements or other instruments to allow the type of insight required. Likewise, in a mishap, the vendor should be prepared to give insight into such proprietary systems to investigators from the NTSB or FAA and have subject matter experts available to brief the operation of hardware.

Technical authorities, both at NASA and commercial companies, should use the Haddon Matrix to identify pre-event, event, and post-event targets to lessen the risk to the spacecraft occupants. The Haddon Matrix was conceived by Robert Haddon, Jr. in 1968 as a means to identify and control the many contributors to injury, severity, and outcomes (Haddon, 1968). It is a brainstorming tool used in public health toward injury prevention and outcome improvement. The matrix assesses the contributing factors for the host, agent, physical environment, and social environment against the time phases of pre-event, event, and post-event. An example for human spaceflight is below:

	Host	Agent (spacecraft of equipment)	Physical Environment	Social Environment
Pre-Event	Training of the crew for contingencies, ensuring the crew is in good physical health, avoidance of fatigue	Systems engineering and safety processes, systems check, simulations and drills.	Weather, micrometeroid environment, solar storms,	Prevention of cost and schedule impacts into risk decisions, development of relationships with tertiary care centers. Develop contracts for salvage
Event	Restraints, human tolerances, visors closed and suits intact, capability to evacuate	Pressurized suits in case of decompression, crumble zones, shock absorption and seat stroking, thruster compensation, parachute deployment	Availability of emergency pressurized oxygen, hatch opening, pressure equalization, winds aloft, sea state	Communications during emergency, relationships with those responding, handling of press
Post-Event	Astronaut health post-crash, ability to extricate, communications with rescue forces	Fire suppression, raft deployment, buoyancy of spacecraft, emergency beacon and signal reception, ability to shut off valves	Availability of rescue forces to rapidly intervene, and trained personnel at trauma centers to care of injured astronauts	Addition of Crew Survival Investigation in addition to NTSB mishap investigation in commercial or private spaceflight mishaps

Table 9: Example of a Haddon Matrix Being Used for Human Spaceflight

Dr. Adrian Lund, former President of the Insurance Institute of Highway Safety stated that they also used the Haddon matrix to target interventions in people, vehicle, or environment that can affect crash likelihood, severity, or recovery (personal email communication, 2022).

NASA and private industry should have rigorous study of previous mishaps and close calls, and use a process aimed specifically at crew survival. Although NASA programs are required to do a crew survival analysis, there is no specific methodology in systems engineering process aimed at survival enhancement. Fault tolerance and high reliability are methods used for risk mitigation in high consequence systems. But there is no exclusive process (e.g.- Six Sigma, Lean) aimed at survival enhancement. NASA should benchmark off of the National Highway Traffic Safety Administration, the automotive racing industry and others to develop a process whereby the astronauts survive, even when the vehicle does not. This Survival Enhancement Process (SEP) should take a holistic approach to spacecraft vehicle design and augmentation of systems to enhance survival of the occupant.

In using this Survival Enhancement Process, NASA and commercial companies should reverse engineer mishaps and close calls in order to identify potential targets for enhancement. This should be done by the engineers who are engaged in the vehicle design recognizing that a standard design solution may not be reasonable, as each vehicle may have differing systems or requirements and therefore may have differing means of mitigation risk depending on their individual hardware. For example, in the fatality involving the Apollo 1 crew, the following areas could be identified for survival enhancement:

Issue Identified in Previous Mishaps	**Survival Enhancement Changes to Design**
Inward opening hatch could not be opened against pressure	Hatch opens outward and is counterbalanced so as to be opened despite pressure
Hatch had multiple steps to open which took valuable time	Hatch now requires a two-step process
Pressure rapidly built up in the vehicle, which enhanced the lethality of carbon monoxide and impacted the ability to open hatch	Rapid commanding of pressure equalization valves (atmospheric equalization valves) possible by crew to prevent pressure buildup in case of fire and emergency evac
Life Support scrubbing material was a source for high carbon monoxide when burned	Life support moved from charcoal based to amine scrubbing capability. Fire suppression close to high potential flammable materials
100% oxygen environment was highly flammable	14.7 psi pressure and normal 21% oxygen atmosphere. Can increase oxygen and decrease pressure gradually on orbit to meet pre-breath standards.
Crew oxygen and life support were in series which caused all crew to inhale carbon monoxide when one suit lost integrity	Created ability for suit life support to be isolated.
Communications from the crew cabin were poor	Communications enhanced, fire suppression systems added, and enhanced caution and warning added

Table 10: Example of the Survival Enhancement Process Being Applied to a Human Spaceflight Design

In the automotive industry, the National Highway Traffic Safety Administration has a specific document entitled: Human Factors Design Guidance for Driver-Vehicle Interfaces. This document outlines the interface of the vehicle with the occupant to enhance safety through standardized warnings, visual interfaces, auditory interfaces, assessment of driver workload, haptics, and system integration. NASA, in concert with the Federal Aviation Administration, should work to develop similar guidance that can be used by private and commercial entities to develop systems architectures to enhance spacecraft occupant safety.

In addition to guidance documents, the automotive industry also has motor vehicle safety regulatory standards. NASA is not a regulatory agency, but NASA does have its own standards for NASA spaceflight vehicles. The Federal Aviation Administration (FAA) should develop the equivalent of these standards for commercial spacecraft. The FAA currently has airworthiness standards and certifications under Part 21, as well as a document highlighting "Established Practices for Human Spaceflight Occupant Safety". But Congress has limited its power to establish standards in order to not restrain the growth and development of this fledgling industry. Unfortunately, this has allowed multiple potential gaps in the safety and standardization of new human commercial vehicles. Commercial vehicles that dock, integrate or perform missions for NASA must comply with vigorous NASA standards (e.g.- SpaceX) whereas vehicles that do not are currently unbounded by standards on human rating (e.g.- Blue Origin, Virgin). Therefore, the FAA should consider the development of human spaceflight safety standards, essentially the space equivalent of airworthiness standards.

Research Question 5: What skills should the mishap investigator possess when dealing with a human spaceflight mishap?

Theme 13*- Investigators should possess the requisite training and experience in mishap investigations.*

Theme 14*- Investigators should keep an open mind and avoid leaping to conclusions.*

Theme 15*- Investigators should be objective.*

Theme 16*- Investigators should have a knowledge of the spacecraft systems and mission profile.*

Discussion

The subject matter experts interviewed had a great deal of experience in some of the most traumatic human spaceflight mishaps in history. Their experience and recommendations stem from their lessons learned, their own mistakes, and an eye toward the future. Much of the codes and themes in this area were weighted toward the subject art of decision making, avoiding blame, and keeping an open mind. But another theme and code emerged in regard to knowledge of the vehicles, their operations, and the risks that each imparts. Based on their recommendations and stories, the old adage of "see one, do one, teach one" could be replaced with "learn one, practice one, do one". Technical knowledge of the vehicle and knowledge and familiarity of the mishap investigative process are paramount. But the wisdom and emotional intelligence to not leap to conclusions most likely comes with time and experience.

Recommendations

Currently, the majority of mishap exercises at NASA and commercial and private providers are tabletop exercises. NASA, NTSB, and the FAA should collaborate on field exercises for mishap investigation. Where possible, local law enforcement evidence gathering teams, fire departments, emergency medical services, and medical examiners should be included in these exercises much as they are in mass casualty exercises.

NASA, NTSB, and FAA should develop a human spacecraft training academy whereby subject matter experts on vehicles, both government and commercial, could lecture and train mishap investigators on the vehicles, subsystems, operations, and hazards.

Investigators should perform simulations that incorporate lessons learned, reinforce the need to maintain an open mind and avoid blame, and allow the investigators to sharpen their investigative skills and gain familiarity with the mishap investigative process. Virtual reality, scene reconstruction from drone and scene video, and other advances in technology allow the potential for training future mishap investigators using real cases.

Administrative support should be given to those in the field at the outset of a mishap, to enhance logistics, capturing of data, and prevent the task saturation of the investigator.

Where possible, contracts and services should be put into place prior to a mishap in counties known to support launches and landings. This will prevent a last-minute flail in trying to get those services or items real-time (e.g., salvage services, contracts for refrigeration of remains, mutual aid agreements, communications plans, etc.).

Summary

This research has shown there are many differences in the physics, environment, engineering, and forensics of a human spaceflight mishap. But it has also shown that those depend greatly on the phase of flight, the type of mission, and whether or not the incident or anomaly occurred above or below the Karman line. Multiple best practices were identified, as well as many gaps that need to be filled.

As commercial and private spaceflight continues to rapidly rise and evolve, the responsibility for responding, investigating, and reporting on human spaceflight accidents will fall to the National Transportation Safety Board, local law enforcement, fire departments, and emergency medicine services, and local field forensic teams and medical examiners. These entities must become knowledgeable on human spaceflight vehicles, hazards, and unique mishap features in order to maintain their own safety, and to assure the integrity of the spaceflight process.

The deep exploration of spaceflight mishaps as part of the qualitative case study process has uncovered several features that have not been previously published or described. It has also identified new areas that will require further research.

The implementation of the recommendations that have come about due to this research will help to educate, train, and prepare future mishap investigators as well as educate technical authorities charged with oversight of vehicle development. This should help provide a continuous feedback loop to enhance the safety of future human spaceflight, both government and private.

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APPENDICES

APPENDIX A: INFORMED CONSENT FORM

NASA INSTITUTIONAL REVIEW BOARD (IRB)

CONSENT TO BE A PART OF A RESEARCH STUDY

ABOUT THIS RESEARCH CONSENT FORM

You may be eligible to take part in a research study.

Please take time to review this information carefully. Talk to the researchers about the study and ask any questions you have. **Make sure you fully understand what will be expected of you and the risks associated with participating in this study.**

Taking part in this study is completely **voluntary**. The decision to participate is yours. You may also leave the study at any time. If you leave the study before it is finished, there will be no penalty to you.

1. GENERAL INFORMATION

The study title is: *IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES*

The study team includes: *Dr. J.D. Polk, Chief Health and Medical Officer, NASA and Doctoral Candidate in Aviation and Space at the Oklahoma State University*.

2. STUDY PROCEDURES

The purpose of the study is to identify areas and trends in human spaceflight fatal mishaps and where those mishaps have sufficient differences from their aviation counterparts. As commercial spaceflight continues to escalate, the likelihood of a spaceflight accident in the future continues to rise. The National Transportation Safety Board, local law enforcement, local coroners, and others who are not routinely engaged in human spaceflight or spacecraft development will be tasked with investigating the mishap. This study will hopefully identify key features that those individuals tasked with investigation will need to know and will also potentially identify trends that will be important *considerations for technical authorities charged in overseeing spacecraft vehicle development. The latter of which may prevent future human spaceflight accidents.*

As part of the study, I am interviewing individuals who were involved in the mishap investigations in some way, in order to gain a deeper context on the nuances and differences between spaceflight mishaps and aviation mishaps, as they pertain to the environmental and physical forces, life support, physiology, and forensics. The goal is to better inform future mishap investigators, but also to gain critical insight that may be valuable for technical authorities in the hopes that future spacecraft can be more safely designed based on lessons learned.

The interview will be accomplished by video and be approximately forty minutes to an hour using Microsoft TEAMS and with the transcription activated to capture and transcribe content. The transcriptions will be de-identified and replaced with codes that are kept under cipher and encryption. The recordings will then be destroyed.

Prior to use or analysis, the participants will be given the opportunity to review their interview transcript and redact/correct information or withdraw consent for use of their data entirely (member checking). The de-attributed inputs will be placed into a qualitative analysis software called NVivo to look for common themes and comments among all interviewees and identify trends. Every effort will be made to keep the comments anonymous.

3. RISKS

The interview/survey questions are general and open in nature but discussing the mishap may bring back emotions that occur with recollection this event. The participants may stop at any time during the interview if they feel uncomfortable. As mentioned previously, prior to use or analysis, the participants will be given the opportunity to review their interview transcript and redact/correct information or withdraw consent for use of their data entirely (member checking). The de-attributed inputs will be placed into a qualitative analysis software called NVivo to look for common themes and comments among all interviewees and identify trends.

Privacy will be maintained and information de-attributed with names replaced with codes and the cypher kept encrypted and known only to the principal investigator. The video interview will be destroyed immediately after the transcription is validated or corrected by the participant. The cypher and any personally identifiable information will be kept in the Office of the Chief Medical Officer, behind a cipher door, locked cabinet, and encrypted.

The participants will also be forewarned that there is a small chance that someone might be able to identify an input if they knew the participants role or they have discussed their thoughts previously in an open forum.

4. PRIVACY AND CONFIDENTIALITY

Your privacy and the confidentiality of your information will be protected in the following ways:

> *Any identifiers collected as part of this study will be promptly removed from your information and replaced with a code that is stored separate and securely from the data. Only the Principal Investigator will have access to the key linking the study data to the participant's name.*

Study data that have been stripped of any information that could identify the participant (de-identified) will be used in the NVivo software to identify trends for spaceflight mishaps and may be made public via publication or used for future research purposes.

Audio/video recordings will be destroyed promptly after the transcription has been reviewed by the participant and successfully updated in the NVivo qualitative software and will not be shared or used beyond this project.

All personally identifiable information, including the name and contact information (email) of the participant will be on an encrypted drive and any personally identifiable information will be destroyed after study completion.

You will have the opportunity to review this transcript and request revisions or retractions.

You may withdraw from the study at any time prior to publication, and your information and data will be destroyed within 30 days of notification with confirmation when complete.

CONTACT INFORMATION

If you have any questions you may contact the Principal Investigator, *Dr. J.D. Polk*, at james.d.polk@nasa.gov, or 202-358-1959 or the NASA Institutional Review Board (IRB) at:

Office of Research Assurance: Research Integrity & Protection of Human Subjects
2101 NASA Parkway
Mail Code SA
Houston, Texas 77058
Visit: https://irb.nasa.gov/

Email: NASA-IRB@nasa.gov

I have been provided information about this research study, including potential risks and benefits and agree to participate as a research subject.

Signature of Subject: ___________________________________ Date: _________________

Name (Print legal name): ____

APPENDIX B: LETTER TO PARTICIPANTS

IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES

Dear Trusted Spaceflight Colleague

I am conducting a study as part of my Doctoral Studies program in Aviation and Space at the Oklahoma State University. The purpose of the study is to identify areas and trends in human spaceflight mishaps and where those mishaps have sufficient differences from their aviation counterparts. The premise is that the environment, physical forces, physiologic and forensic findings in human spaceflight mishaps are sufficiently unique and would need to be taken into consideration when performing a mishap investigation, and when serving as a technical authority in the development of new spaceflight vehicles.

Because you have been a part of a spaceflight mishap, I would like to interview you in order to gain your perspective and lend context to the published records, reports, and archival data on human spaceflight mishaps.

As commercial private spaceflight continues to escalate, the likelihood of a spaceflight accident in the future continues to rise. The National Transportation Safety Board, local law enforcement, local coroners, and others who are not routinely engaged in human spaceflight or spacecraft development will be tasked with investigating the mishap. This study will hopefully identify key features that those individuals tasked with investigation will need to know and will also potentially identify trends that will be important considerations for technical authorities charged in overseeing spacecraft vehicle development. The latter of which may prevent future human spaceflight accidents. Your identity will not be revealed in any publications, presentations, or reports resulting from this research study and your comments will be non-attributional. They will be aggregated with the answers from other participants to look for trends that would constitute unique aspects to take into consideration in human spaceflight mishaps.

We will collect your information through an interview utilizing video teleconferencing technologies using Microsoft TEAMS in order to have a transcription for data mining purposes. This information will be de-attributed and input into a qualitative analysis software called NVivo for the purpose of looking for trends.

This information will be stored by the researcher on an encrypted drive with restricted access. When the study is completed and the data have been analyzed, the list of names of study participants will be destroyed as will any recordings of the interview and transcript. The NVivo and aggregate data will be kept indefinitely by the National Aeronautics and Space Administration for the purposes of maintaining data for future historical research. This informed consent form will be kept for three years after the study is complete, and then it will be destroyed. Your de-attributed data collected as part of this research project, may be used or distributed for future research studies, but you will be informed if this occurs.

The following five questions will be asked during the interview:

1. *Are there physical or environmental differences between a spaceflight mishap and other mishaps that stand out in your mind that would be important to highlight for future investigators or tech authorities?*

2. *Are there forensic differences that are unique to spaceflight mishaps? If so, what are those forensic differences or unique aspects in spaceflight mishaps that stand out in your mind from the mishap you were involved with?*

3. *For future human spaceflight mishaps, be it commercial, NASA, or military- what are some of the most critical lessons learned that should be relayed to future mishap investigators?*

4. *For a technical authority charged with aiding in human systems design of new spacecraft, are there lessons that stand out in your mind that they should consider based on the mishap that you were involved in?*

5. *What skills should the mishap investigator possess when dealing with a human spaceflight mishap?*

Your participation in this research is voluntary. There is no penalty for refusal to participate, and you are free to withdraw your consent and participation in this project at any time. The alternative is to not participate. You can skip any questions that make you uncomfortable and can stop the interview/survey at any time.

I’d be honored if you would allow me to interview you for this study in order to help educate future spaceflight mishap investigators. It is also hoped that this information will be invaluable to spacecraft technical authorities charged with oversight of spacecraft development, in order to make spacecraft safer for future astronauts, both government and civilian.

Thank you for your consideration,

APPENDIX C: NASA INSTITUTIONAL REVIEW BOARD LETTER

NASA Institutional Review Board (IRB)
2400 NASA Parkway
Houston, TX 77058
https://eirb.jsc.nasa.gov
https://irb.nasa.gov

NOTIFICATION OF EXEMPT DETERMINATION

March 18, 2022

TO: James Polk

james.d.polk@nasa.gov

FROM: Jennifer Ensley Gorshe, CIP

IRB Coordinator, NASA Institutional Review Board

TITLE: IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES

Study eIRB Number:	STUDY00000458
Method of Review:	Exempt (2iii)
Type of Review:	Initial Study
IRB Disposition:	Approved
Determination Date:	3/18/2022

NASA Institutional Review Board (IRB)
2400 NASA Parkway
Houston, TX 77058
https://eirb.jsc.nasa.gov
https://irb.nasa.gov

Risk Level:	No greater than minimal risk
FWA Number:	00019876

- The NASA IRB has determined that this protocol meets the criteria for Exempt review per 14 CFR 1230.104(d).

- **Investigators are responsible for updating their Conflict of Interest forms annually within the eIRB and maintaining active CITI training certificates.**

  - A MOD should be submitted to the e-IRB annually to attach the updated COI forms and CITI certificates.

- Exempt research protocols expire 5 years following the initial determination. If a Principal Investigator (PI) wishes to continue an exempt project beyond 5 years they are required to request re-certification prior to the expiration date.

- The protocol is exempt and no continuing review is needed.

- Minor changes as defined in HRP – 420 – SOP that do not impact risk or alter the exempt status may be made without prior IRB review. However, if any other changes are made to the protocol, a modification must be submitted to the NASA IRB for review.

  - If there are questions about whether IRB review is needed, please submit a modification by selecting "Create Modification / CR" within the study. The IRB will examine the modifications and determine if the proposed changes will alter the exempt status of the protocol.

- The Investigator must report any adverse events (AE) or unexpected problems (UPIRSOs) resulting from this study to the NASA IRB, sponsor/funding source, and the Safety Office (if applicable).

- Once all research activities are complete, a request for study closure should be made in the eIRB.

The Principal Investigator remains responsible for following all pertinent ethical and legal guidelines as well as NASA policies.

NASA Institutional Review Board (IRB)
2400 NASA Parkway
Houston, TX 77058
https://eirb.jsc.nasa.gov
https://irb.nasa.gov

The proposal was reviewed and determined to be exempt by the NASA IRB in accordance with ethical standards and the requirements of the Code of Federal Regulations on the Protection of Human Subjects (NASA 14CFR1230, HHS 45CFR46, and, if applicable, FDA 21CFR50 and 56).

Sincerely,

Jennifer Ensley Gorshe, CIP

IRB Coordinator, NASA IRB

APPENDIX D: RELIANCE AGREEMENT

Reliance Acknowledgement
Between

National Aeronautics and Space Administration (NASA)

And **Oklahoma State University**

For Institutional Review Board (IRB) Review

1. AUTHORITY AND PARTIES

1.1 **Name of Institution Providing IRB Review (IRB of Record): National Aeronautics and Space Administration (NASA)**

NASA IRB Registration Number	IORG0007525
NASA FWA Number	FWA00019876
Street Address	2101 E NASA Pkwy
City	Houston
State (if US)	TX
Zip/Postal Code	77058

Name of Individual Responsible for Administration of this Agreement	Mark Weyland, Institutional Official
Title of Individual	Director, Medical Policy and Ethics
Phone Number	832-671-5991
Email address	Mark.d.weyland@nasa.gov

1.2 **Name of Institution Relying on the Reviewing IRB (Relying Institution):**

Oklahoma State University

Institution's OHRP FWA #	00000493
Name of Institutional Official	Kenneth Sewell, PhD, Vice President for Research
Street Address	203 Whitehurst
City	Stillwater
State (if US)	Oklahoma
Zip/Postal Code	74078

Name of Individual Responsible for Administration of this Agreement	Beth Weichold, M.S.
Title of Individual	Manager, Institutional Review Board
Phone Number	405-744-5700
E-mail address	beth.weichold@okstate.edu

2. SCOPE OF THE ACKNOWLEDGEMENT

2.1 The Officials signing below agree that the Oklahoma State University IRB shall rely on the NASA IRB for review and continuing oversight of the following research protocol:

Title of Research Project*	Identifying environmental and forensic of human spaceflight mishaps through extreme case study analysis: Lessons for future spaceflight mishap Investigators and technical authorities
NASA eIRB Number	Study 458
Name of Principal Investigator (PI)	Dr. J.D. Polk
Name of Sponsor	National Aeronautics and Space Administration/Oklahoma State Univ
Name of Funding Agency	N/A
Award Number, if any	N/A

*If an RA for more than one research project is being completed at this time, attach an addendum for the additional projects to this form.

2.2 The review performed by NASA IRB will meet human subject protection requirements [14 CFR 1230, NPR 7100.1A, HHS 45 CFR 46, and FDA 21 CFR 50, 56, 312, and 812], as applicable. The NASA IRB will follow written procedures for reporting its findings and actions to the appropriate officials at the Oklahoma State University IRB.

2.3 The Oklahoma State University IRB remains responsible for ensuring compliance with the NASA IRB's determinations and with the terms of its OHRP-approved FWA. The Oklahoma State University IRB will notify the NASA IRB promptly, and in writing, of any suspension, restriction, termination, or expiration of its FWA.

2.4 This document must be kept on file by both parties and provided to the FDA, OHRP, and/or other applicable regulatory agencies upon request.

2.5 This acknowledgement is limited to the review and continuing administration of the protocol as outlined in the responsibilities located in the corresponding SOP.

3. RESPONSIBILITIES OF IRB OF RECORD: NASA IRB

3.1 Maintain an FWA;

3.2 Maintain a Board membership that satisfies the requirements of 14 CFR 1230.107, 45 CFR 46.107, and 21 CFR 56.107, as applicable.

3.3 Comply with all applicable Federal, State, and Local Laws and regulations;

3.4 Make available to Oklahoma State University the NASA IRB's Standard Operating Procedures;

3.4.1 Include any standardized language required for Informed Consent documents;

3.4.2 The Relying Institution shall confirm receipt and compliance with ***HRP – 100 – SOP Establishing Reliance Acknowledgements*** and ***HRP – 101 – SOP: NASA IRB Serving as the IRB of Record*** by checking the appropriate boxes and signing this document.

4. Responsibilities of the Relying Institution: Oklahoma State University

4.1 Maintain an FWA;

4.2 Comply with all applicable Federal, State, and Local laws and regulations and inform the IRB of Record when State and Local laws may affect the research and its oversight.

4.2.1 The Relying Institution must ensure organizational compliance with all HRPP. For example, if the Relying Institution requires approval by other internal review committees prior to IRB or EC approval (e.g. Institutional Biosafety, Radiation Safety), the Relying Institution must include that information and approval letters in the IRB application.

5 Liability

5.1 Each Party agrees to assume liability for its own risks arising from or related to activities conducted under the scope of this Acknowledgment.

6 Term of Agreement

6.1 The term of this Acknowledgement shall commence upon execution of this Acknowledgement by both parties, and shall continue until **18MAR2023** or until such time as either party gives 30 days written notice of termination, whichever comes first.

7 Points of Contact

The following personnel are designated as the Points of Contact between the Parties in the performance of this Acknowledgement and shall serve as the contacts for further communication.

Management Points of Contact:

IRB of Record, NASA IRB	**Relying Institution,** Oklahoma State University
Name: Jennifer Christensen, PharmD, CIP	Name: Beth Weichold, M.S
Title: Manager, NASA Office of Research Assurance	Title: Manager, Institutional Review Board
Email: Jennifer.l.christensen@nasa.gov	E-mail: beth.weichold@okstate.edu

Telephone:	Telephone: 405-744-5700
Cell: 713-997-0318	Cell: 209-923-7123
Fax:	Fax:
Mailing Address: 2400 NASA Parkway, Houston TX 77058	Mailing Address: 219 Scott Hall, Oklahoma State University, Stillwater, OK 74078

By checking the boxes below, confirm receipt* and compliance with:

1. ■ HRP – 100 – SOP: Establishing Reliance Acknowledgements
2. ■ HRP – 101 – SOP: NASA IRB Serving as the IRB of Record

** SOPs are available on the NASA IRB Website or can be provided upon request. Additionally, the NASA IRB will send updated versions of the SOPs to the reliance partners.*

IN WITNESS WHEREOF, each party accepts the terms herein as evidenced by their authorized signatures below.

The Relying Institution: Oklahoma State University		The IRB of Record: **NASA IRB**	
(Authorized Signature)		MARK WEYLAND — Digitally signed by MARK WEYLAND Date: 2022.03.18 14:39:11 -05'00' (Authorized Signature)	
Print Full Name:	Kenneth Sewell, PhD	Print Full Name:	Mark Weyland, Institutional Officer
Institutional Title:	Vice President for Research	Institutional Title:	Director, Medical Policy and Ethics
Date:		Date:	18-Mar-2022

VITA

Dr. James D. Polk

Candidate for the Degree of

Doctor of Education

Dissertation: IDENTIFYING ENVIRONMENTAL AND FORENSICS ASPECTS OF HUMAN SPACEFLIGHT MISHAPS THROUGH EXTREME CASE STUDY ANALYSIS: LESSONS FOR FUTURE HUMAN SPACEFLIGHT MISHAP INVESTIGATORS AND TECHNICAL AUTHORITIES

Major Field: Applied Educational Studies

Biographical:

Education:

Completed the requirements for the Doctor of Education in Applied Educational Studies at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

Completed the requirements for the Master of Medical Management at University of Southern California, Los Angeles, California in 2010.

Completed the requirements for the Master of Science in Space Studies at American Military University, Charles Town, West Virginia in 2005.

Completed the requirements for the Bachelor of Science in Liberal Arts as Excelsior College, Albany, New York in 2001.

Completed the requirements for the Doctor of Osteopathic Medicine at A.T. Still University, Kirksville, Missouri in 1993.

Experience:

Chief Health and Medical Officer, National Aeronautics and Space Administration
Dean of Medicine, College of Osteopathic Medicine, Des Moines University
Assistant Secretary (Acting), Health Affairs
Chief Medical Officer, U.S. Department of Homeland Security (DHS)
Principal Deputy Assistant Secretary, Health Affairs
Deputy Chief Medical Officer, U.S. Department of Homeland Security (DHS)
Chief of Space Medicine, NASA's Johnson Space Center in Houston, Texas
State Emergency Medical Services Medical Director, State of Ohio
Chief, Metro Life Flight in Cleveland, Ohio

Professional Memberships:

Fellow of the American College of Osteopathic Emergency Physicians
Fellow of the Aerospace Medicine Association
Fellow of Extreme and Wilderness Medicine