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A SYSTEMS APPROACH TO ASSESSING, INTERPRETING AND APPLYING HUMAN ERROR MISHAP DATA TO MITIGATE RISK OF FUTURE INCIDENTS IN A SPACE EXPLORATION GROUND PROCESSING OPERATIONS ENVIRONMENT

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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ABSTRACT

Research results have shown that more than half of aviation, aerospace and aeronautics mishaps/incidents are attributed to human error. Although many existing incident report systems have been beneficial for identifying engineering failures, most of them are not designed around a theoretical framework of human error, thus failing to address core issues and causes of the mishaps. Therefore, it is imperative to develop a human error assessment framework to identify these causes.

This research focused on identifying causes of human error and leading contributors to historical Launch Vehicle Ground Processing Operations mishaps based on past mishaps, near mishaps, and close calls. Three hypotheses were discussed. The first hypothesis addressed the impact Human Factor Analysis and Classification System (HFACS) contributing factors (unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences) have on human error events (i.e. mishaps, close calls, incident or accidents) in NASA Ground Processing Operations. The second hypothesis focused on determining if the HFACS framework conceptual model could be proven to be a viable analysis and classification system to help classify both latent and active underlying contributors and causes of human error in ground processing operations. Lastly, the third hypothesis focused on determining if the development of a model using the Human Error Assessment and Reduction Technique (HEART) could be used as a tool to help determine the probability of human error occurrence in ground processing operations.

A model to analyze and classify contributing factors to mishaps or incidents, and generate predicted Human Error Probabilities (HEPs) of future occurrence was developed using the HEART and HFACS tools. The research methodology was applied (retrospectively) to six Ground Processing Operations (GPO) Scenarios and 30 years of Launch Vehicle Related Mishap Data. Surveys were used to provide Subject Matter Experts' (SMEs) subjective assessments of the impact Error Producing Conditions (EPC) had on specific tasks.

In this research a Logistic Binary Regression model, which identified the four most significant contributing HFACS human error factors was generated. This model provided predicted probabilities of future occurrence of mishaps when these contributing factors are present.

The results showed that the HEART and HFACS methods, when modified, can be used as an analysis tool to identify contributing factors, their impact on human error events, and predict the potential probability of future human error occurrence. This methodology and framework was validated through consistency and comparison to other related research. A contribution methodology for other space operations and similar complex operations to follow was provided from this research. Future research should involve broadening the scope to explore and identify other existing models of human error management systems to integrate into complex space systems beyond what was conducted in this research.

This research is dedicated to my Family.

-My parents Dorothy and Willie Miller and my sister Lakaysha Miller.

Thank you for your love and support!

-To my phenomenal mother Dorothy, you are my biggest cheerleader and encourager.

Thank you for being an awesome example to me. I love you!

-To my incredible husband Ervin, you are my best friend.

Thank you for your love, patience, understanding and support. You are a constant encouragement to me and I love you for being you!

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TABLE OF CONTENTS

CHAPTER FIVE: RESULTS AND DISCUSSION 103

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS (or) ABBREVIATIONS

AOA	Assessed Proportion of Affect
CREAM	Cognitive Reliability and Error Analysis Method
EPC	Error Producing Conditions
FRANCIE	Framework Assessing Notorious Contributing Influences for Error
GEMS	Generic Error Model System
GO	Ground Operations
GPO	Ground Processing Operations
GSE	Ground Support Equipment
HEA	Human error analysis
HEART	Human Error Assessment and Reduction Technique
HEI	Human Error Identification
HEP	Human Error Probability
HERMES	Human Error Risk Management for Engineering Systems
HEROS	Human Error Rate Assessment and Optimizing System
HFACS	Human Factors Analysis and Classification System
HRA	Human Reliability Analysis
HRO	High Reliability Organization
IRB	Institutional Review Board
KSC	Kennedy Space Center

LC 39 A/B	Launch Complex 39
NARA	Nuclear Actions Reliability Assessment
NASA	National Aeronautics Space Administration
NMIS	NASA Mishap Information System
OPF	Orbiter Processing Facility
OSHA	Occupational Safety and Health Administration
PRA	Probabilistic Risk assessments
PSF	Performance shaping factors
RCAT	NASA Root Cause Analysis Tool
ROC	Republic of China
RPA	Remotely Piloted Aircraft
S&MA	Safety and Mission Assurance
SLS	Space Launch System
SME	Subject Matter Expert
SPAR-H	Standardized Plant Analysis Risk HRA
THEA	Tool for Human Error Analysis
THERP	Technique for Human Error Rate Prediction
VAB	Vehicle Assembly Building

CHAPTER ONE: INTRODUCTION

Background

In our world, we have unfortunately witnessed some disasters and incidents due to human error, such as the Space Shuttle Challenger Disaster on January 28, 1986 in which the United States lost the entire Space Shuttle Crew, the Chernobyl Nuclear Plant Disaster of April 26, 1986 where many lost their lives and thousands were impacted by a steam explosion and fires, resulting in radio activity released into the atmosphere, the Bhopal Industrial Disaster of December 1984, where at least 2,500 people were killed and more than 200,000 were injured due to a gas leak of a highly toxic chemical, methyl isocyanate (MIC) (Reason, 1990).

One of the identified main contributors to these incidents has been rooted back to Human latent errors. In this review, an overview of human error, the various types, approaches, models and methodologies that have been developed to help minimize these errors is discussed. An assessment of what has and hasn't been effective and a future potential work for determining the best types and approaches for Safety Critical domains is also discussed. In order to determine whether the current model and methods of minimizing human error is sufficient or identify where the gaps are, the current body of knowledge on this topic should be addressed. This review covers various aspects of this topic.

The Literature review covers many aspects of human error including some of the following areas: Human Error Defined, Understanding Human Error/The Nature of Error, Human Error Performance, Human Error - Two Main approaches, Active Failures and Latent Conditions, Reasons' Conceptual Model, Consequences of Human Error, Managing Human Error, Management Systems and Effective Risk Management.

Problem Statement

In 1993, NASA found that 78% of the incidents related to Space Shuttle Ground Processing Operations, since April 1991, was a result of human error (Perry et al., 1993). Unfortunately, most incident reports are not designed around a theoretical framework of human error. Even though these types of report systems have been beneficial for identifying engineering and mechanical failures, they have failed to address the core issues and causes of failure due to human error. This makes the intervention and integration of a strategy to reduce human error difficult, due to limited background and knowledge of human factors by the workers. In this research, it is important that human factor issues are addressed and a comparative analysis of existing databases be conducted to determine the human factors responsible for the failures, mishaps, etc. (Wiegmann and Shappell, 2001).

Research Objective

In this research the goal is to develop a model that can analyze and classify contributing factors to human error mishaps, close calls, or incidents during Launch Vehicle Ground Processing Operations and be used as a tool to accompany preexisting accident investigation and analysis systems in controlling and/or minimizing human error. NASA KSC was utilized as the core data for this research, due to its premises being America's major Spaceport.

The goal is also for the developed model to be sound from an ergonomic, mathematical and human factors standpoint. This research adds to the human factors body of knowledge in the area of human factors, by providing the ergonomic mathematical results from the Human Error Assessment and Reduction Technique (HEART) and Human Factors Analysis and Classification System (HFACS) tools.

Contribution to the Body of Knowledge

This research adds to the body of knowledge by developing an innovative approach to evaluating Aerospace Industry mishap data for the purpose of gaining additional insight that can be applicable in mitigating future risks. This involves modifying and validating a human error tool such as the Human Error Assessment and Reduction Technique (HEART) and Human Factors Analysis and Classification System (HFACS) model in order to assist in the identification and analysis of contributing factors to human error, resulting in mishaps, incident and close calls. There is a need to explore the use of HEART and HFACS as viable tools to use within the NASA Ground Processing Operations to effectively bridge the gap between theory and practice concerning the genesis of human error causation (Wiegmann, 2001).

Two underlying human error factors

According to James Reason, two underlying factors leading to accidents are: Active failures and Latent Conditions (Reason, 2000).

Active failures (also known active errors) effects are felt almost immediately and latent errors, whose adverse consequences may lie dormant within the system for a long time, only become evident when they combine with other factors to breach the systems' defenses (Rasmussen & Pedersen, 1984; as cited in Reason, 1990). Active failures are difficult to foresee and are directly created by the individual. Active failures include slips, mistakes, oversights or direct violation of procedural requirements. Latent conditions are considered "resident pathogens" that can produce a problem within the system.

This research adds to the body of knowledge by analyzing and gaining knowledge by means of better understanding the contributing latent errors that impact or influence human error during ground processing operations. System failures often occur when a combination of particular latent failures occur, thus causing a system to fail. When isolated, occurrences have less impact or importance, but when strategically combined, even the most extraordinary safety-oriented systems can experience catastrophic results, as in the case of the Shuttle Challenger incident (Cook, 1994).

As it relates to the Federal Aviation Administration (FAA) and the aviation industry, when describing errors in the cockpit, latent errors committed by officials within the management hierarchy are factors that directly influence the condition and decision of pilots (Reason 1990). This shows that latent errors can impact workers' decisions.

Significance of Research

The data in this research was used with the intent that other organizations may be able to use it for similar complex processes. The current processes used at NASA KSC is discussed further in the Literature Review chapter Research Gap discussion. This research can be beneficial to the NASA S&MA Directorate by providing methods and techniques that can be used to help assess and classify causes of human errors, which are identified with specific KSC Ground Processing Operation tasks, from an ergonomic, organizational and management perspective.

Research Question

With the objective of this research previously stated in this chapter, the specific research question is:

1. What are the identified leading human error causes and contributors to historical Launch Vehicle Ground Processing Operations mishaps and findings based on past mishaps, near mishaps, and close calls? Quantifying this data and identifying the leading cause is essential in the research analysis.

Research Hypotheses

Research Variables

Independent variable: Contributing Factors (i.e. unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes)).

Dependent Variable: Human error event (i.e. mishaps, close calls, incident or accidents).

Hypothesis 1

H_0: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do not have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in NASA ground processing operations.

H_1: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in NASA ground processing operations.

Hypothesis 2

H_0: The HFACS framework conceptual model can be proven to be a viable analysis and classification system to help classify both latent and active underlying contributors and causes of human error in NASA ground processing operations.

H_1: The HFACS framework conceptual model cannot be proven to be a viable analysis and classification system to help classify both latent and active underlying contributors and causes of human error in NASA ground processing operations.

Hypothesis 3

The HEART technique is a quantitative tool that analyzes ergonomic factors that have a substantial negative impact on human performance. This tool was used for KSC Ground Processing Operations and to help identify and calculate the human error probability.

H_0: The development of a model using the HEART assessment can be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

H_1: The development of a model using the HEART assessment cannot be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

Independent variable: Contributing Factors (identified by the SMEs for specific Scenarios of tasks performed for NASA KSC ground processing operations).

Dependent Variable: Probability of a Human error event (i.e. mishaps, close calls, incident or accidents).

Theoretical Framework

The Theoretical Framework is a conceptual model used to establish a structure for understanding research, identifying the variables that will be measured, understanding their relationship and their significance to the research problem. This guides the research, provides background support and justification for studying the research problem.

A theoretical framework can provide a diagram to display the relationship between the variables involved. What are the contributing factors that lead to human error mishaps? What is an effective way to classify, assess and categorize human error for future prediction and to reduce future human error mishaps? Table 1 and Figure 1 outlines the dynamics of the Generic Error Modeling System (GEMS) used to relating Reasons' three basic error types to Rasmussen's three performance levels (Reason, 1990).

Table 1: Reason's three Basic Error Types in relation to Rasmussen's three Performance Levels (Reason, 1990)

Performance Level	Error Type	Description
Skill-based level	Slips and lapses	Automated non-cognizant errors of automatic processing (attention/memory) during regular routine actions that are identified quickly (Reason, 1990).
Rule-based level	Rule-based mistakes	Errors of rule-based behavior. For example: applying the wrong rule for a given situation (often with a tendency to keep repeating the same wrong actions "strong but wrong").
Knowledge-based level	Knowledge-based mistakes	Errors of cognitive (knowledge-based) processing whereby a problem is not analyzed correctly (or not at all) and this results in an error (e.g. wrong response to a multitude of alarms based on an incomplete understanding of the actual problem).

GEMS is a broad framework used for recognizing the origins of the basic human error types (Reason, 1990). It is an effort to provide an integrated framework of the error types operating at all three levels of performance: Skill based, Rule based and Knowledge based. This is a hybrid of two sets of error theories proposed by Norman (1981) and Reason and Mycielska (1982) (Reason, 1987).

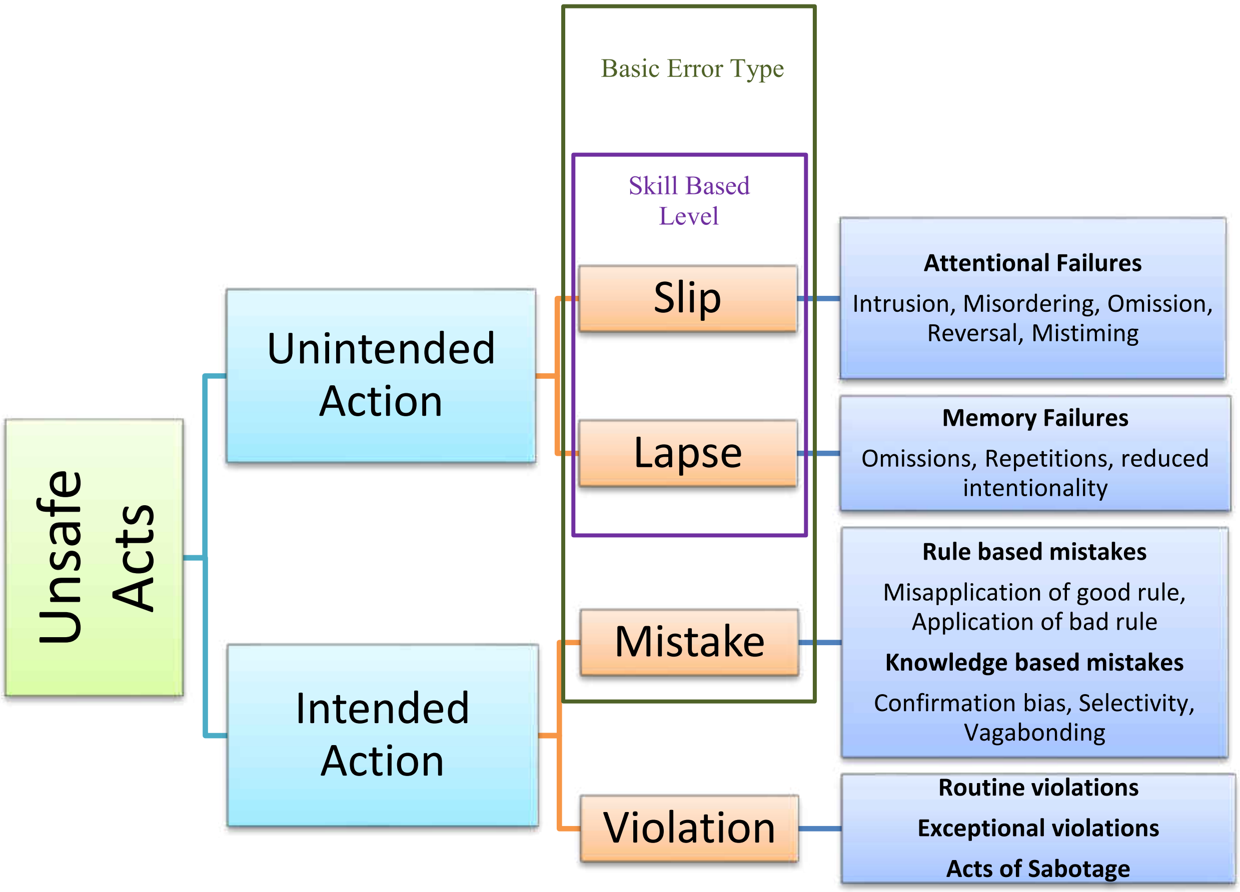


Figure 1: Generic Error Modeling System – GEMS (Reason, 1990)

CHAPTER TWO: LITERATURE REVIEW

Human Error

Human Error - According to Reason (2008), “Although there is no one universal agreed definition of error, most people accept that it involves some kind of deviation” (p. 29). So, as there are different definitions for human error, there can also be various classifications. These classifications can be based on intention, action, the outcome and contextual factors (Reason, 2008).

Erik Hollnagel prefers the term “erroneous action” instead of human error, which he defines as “an action which fails to produce the expected results and which therefore leads to an unwanted consequence” (Hollnagel, 1993). T.B. Sheridan defines it as “an action that fails to meet some arbitrary implicit or explicit criterion”. Despite the difference in specific definition, these both allude to the subjective element that the definition of human error must incorporate (Sheridan, 2008).

Understanding Human Error/The Nature of Error

Human error can typically be classified into four basic elements of error. These elements depend on intention, action, the outcome and contextual factors (Reason, 2008). Below are brief explanations of these classifications.

Intentions

When we look from the perspective of intention, there are some questions that must be considered. 1. Was the error planned, was it an authentic oversight or was it a neglection of following designated procedures? 2. If the action resulted in an unwanted resulted, then was the action a mistake of following directions? (Reason, 2008).

Actions

Errors in the action classification, deal with the behavior of the individual and the type of action that generated the error. Some examples of this would be, the act of omission (a step that is planned, but is not performed), repetition (unnecessarily repeating steps that have previously been performed), and misordering (the correct actions are performed, but in the wrong order) (Reason, 2008).

Contextual Factors

Errors based on contextual factors have to deal with the situation or environment in which the error is generated. Some of these situations or environments can be more prone to errors than others. Some contextual errors consist of: Interruptions and distractions (when an individual is following an individual, may believe they are ahead or behind in steps and could potentially repeat unnecessary or unwanted steps). Stress can be another factor, in which the environment or task can create stress, fear, noise or fatigue, which can increase the likelihood of an error (Reason, 2008). Another factor is when an individual is in a process or procedure and is then unexpectantly interrupted or distracted. When the individual returns to this process, they may not specifically be aware of where they were in the process. Joseph Sharit (2012) provides a basic human error framework. This framework consists of: human fallibility, context and barriers (Sharit, 2012).

Human Fallibility

The human fallibility component deals with the essential sensory, cognitive, and motor limitation of humans and an abundance of other behavioral tendencies that put humans in a position to generate an error.

Context

The context component deals with situational variables that can have an influence, shape, force, form or have some type of impact on the human's behavior and how their performance variability can lead to an error or unwanted consequences.

James Reason (2008) states, "We cannot easily change human cognition, but we can create contexts in which errors are less likely and, when they do occur, increase their likelihood of detection and corrections" (p. 32).

S.W. Dekker (2005) states that "Human actions are embedded in contexts and can only be described meaningfully in reference to the details of the context that accompanied and influenced them" (Dekker, 2005). Joseph Sharit, goes on to state, "The attribution and expression of human error will thus depend on the context in which task activities occur" (p. 737).

The barriers' component deals with the various ways in which human errors or performance failures can be contained and human error is typically viewed as being produced by some form of interplay between human fallibility and context (Sharit, 2012).

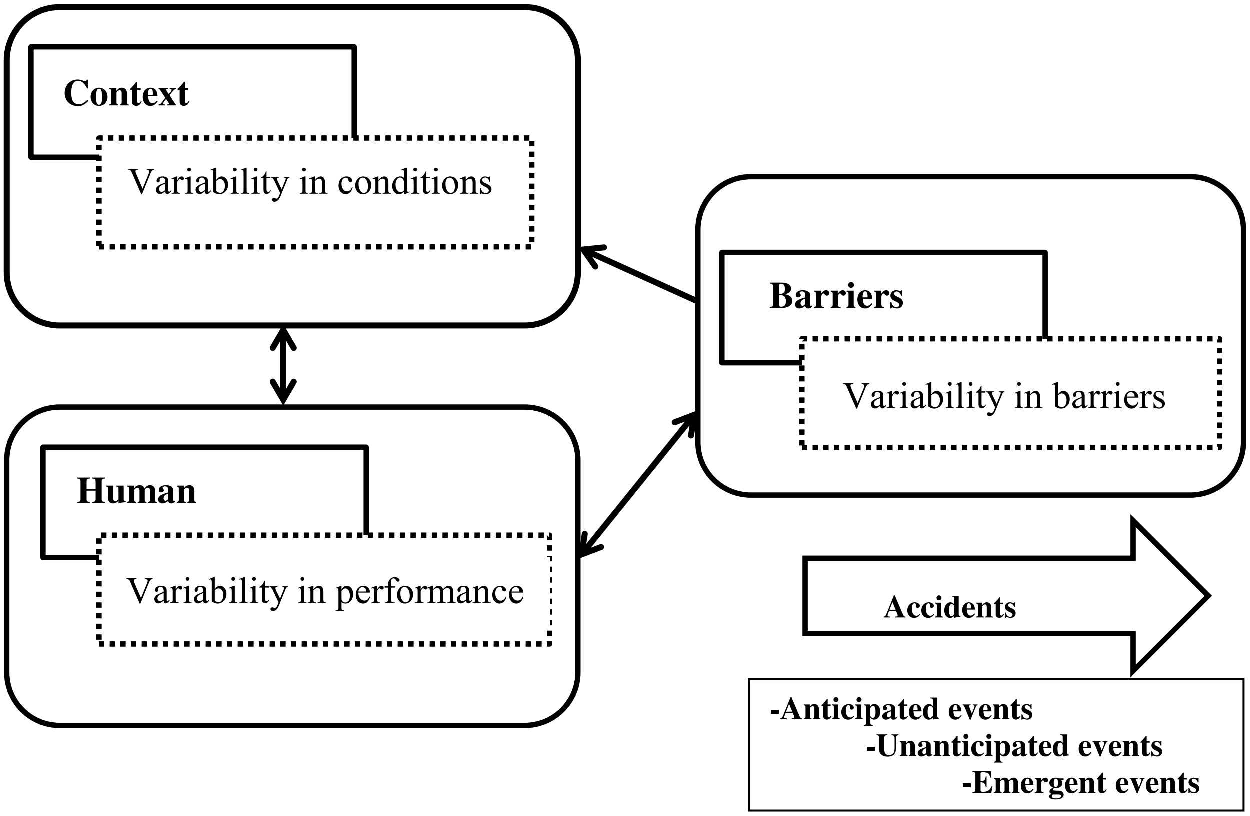


Figure 2: Framework for Understanding Human Error and its Potential for Adverse Consequences (Sharit, 2012)

Another aspect of human fallibility is the possibility for human error to be affected by personality traits. A submissive or compliant personality may be hesitant to interject, probe or question an outgoing worker concerning the information that is being communicated or aggressively pursue information from that person, particularly if that working person is perceived to have an aggressive temperament or assumes a high job status, which could lead to false assumptions (Sharit, 2012). Personality behaviors that reflect temperaments toward self-confidence, meticulousness, and insistence could also include the possibility for errors (Sharit, 2012).

An overconfident personality can lead to being a risk risker and this behavior can and has been implicated as a contributing factor in a number of accidents or even having the predisposition to taking risks (Sharit, 2012).

It is very important that we understand the types and aspects of human error or components that are related to human error. Design Error is one of those aspects and deals with the role of automation in human error, human error in maintenance operations, and the use of incident reporting systems (Sharit, 2012).

An example of design error can be illustrated in a case study presented by Cao and Taylor that dealt with the user's adaptation to new technologies. This case study focused on the effects of introducing a remote robotic surgical system for laparoscopic surgery on communication amongst the operating room team members (Cao and Taylor, 2004). In this research, communication was examined using a framework denoted as *common ground*, which characterizes a person's knowledge or expectations about what other people in the communication setting know (Clark and Schaefer, 1989). From this study Cao and Taylor suggested training to attain common ground, possibly through the use of rules or an information visualization system that could facilitate the development of a *shared mental model* among the team members (Stout et al., 1999). This was exemplified when a new technology was used such as a surgical robot and if issues arise if or when roles change and the use of the new technology are less familiar to particular team mates, which can compromise the expectations of communication from the team (Sharit, 2012).

Human Performance

In the big picture of human performance, James Reason states that it is divided into three levels: skill-based, rule-based and knowledge-based (Reason, 2008).

Skill-Based

Skill based performance is developed by the effort of practice and self-discipline. With the readjusting of our perceptions, we can gradually develop and obtain the fundamental principles or practices of a skill (Reason, 2008).

Rule-Based

Rule based is an intermediation between the skill-based and the knowledge-based, due to the need to break away from a sequence of largely habitual (skill-based) activity to interact with some form of a problem, or in which our actions needs to be adjusted or modified to accommodate some change of circumstances (Reason, 2008). According to James Reason, there are considered three basic forms of Rule-based mistakes (Reason, 2008):

1. We can misapply a normally good rule because we fail to spot the contra-indicators.
2. We can apply a bad rule.
3. We can fail to apply a good rule.

Knowledge-Based

Knowledge based is the knowledge that is considered the beginning level by which our actions are directed online by the slow, restricted, and arduous application of conscious attention.

This level is dependent upon conscious images or works to guide our actions, whether in the form of speech or the instructions of others. According to James Reason (2008), “knowledge-based mistakes occur in entirely novel situations when we have run out of pre-packed problem-solving rules and have to find a solution ‘on the hoof’” (p. 45).

Overall James Reason states that mistakes at both the rule-based and knowledge-based levels are shaped by a variety of biases that are listed below (Reason, 2008):

- Similarity bias – far from being random, errors tend to take forms that correspond to salient aspects of the problem configuration (Reason, 2008).
- Frequency bias – when cognitive operations are under-specified, they tend to take contextually appropriate, high frequency forms (Reason, 2008).
- Bounded rationality – the conscious workspace is extremely limited in its capacity (Reason, 2008).
- Reluctant rationality – The principle of “least effort” acts to minimize cognitive strain (Reason, 2008).
- Irrationality –Group dynamics can introduce genuine irrationality into the planning process. Willful suppression of knowledge indicating that a certain course of action leads to disaster (Reason, 2008).

Understanding the specification of the types of human errors are essential to understanding the types of errors, and their patterns which can help the organization move towards finding an effective tool to manage the human error. It is important to make sure the organization is on the same page and understanding of human error and their roles in the organization.

Human Error - Two Main approaches

According to James Reason, the human error problem can be observed in two ways: the person approach and the system approach with each model providing different causation and different philosophies of error management (Reason, 2000).

Of these two approaches they each have their difference in explained causation and methods of managing their perspective of human error. Understanding these approaches and properly identifying and applying the correct methodology to the operations systems will determine the impact and effect of the methodologies used to minimize human error. Identifying the cause of the error is essential to identifying and implementing the correct or best managing method to help minimize human error (Reason, 2000).

Person approach

The person approach focuses on unsafe acts, errors, and procedural violations of people on the sharp end (Reason, 2000). "At the sharp end" is defined as: involved in the area of any activity where there is most difficulty, competition, danger, etc. (English Dictionary, n.d.). The person approach views human unsafe acts as a result of the human abnormal mental processes, and focuses on errors of individuals, such as forgetfulness, inattention or moral weakness. In an attempt to counteract this behavior, tactics such as fearful poster campaigns, adding to procedures, disciplinary measures, retraining, naming, blaming and shaming are used (Reason, 2000).

Systems approach

The other approach is considered the System Approach in which errors are seen as consequences, rather than focusing on the human. Counteracting methods consist more of changing the conditions under which humans are working instead of the human condition we cannot change. The goal is to build defenses to avert errors or mitigate their effects (Reason, 2000).

Evaluation of the two approaches - James Reasons states “The pursuit of greater safety is seriously impeded by an approach that does not seek out and remove the error proving properties within the system at large” (Reason, 2000).

When evaluating these approaches, the “person approach” continues to be the prominent choice of viewing human error. With this approach, blaming the individual for the error or unsafe act is more convenient for the leadership than to blame or hold the organization responsible for making sure defenses are effectively in place to help minimize error. The individual is held with total responsibility for the error. However, one of the weaknesses in this approach is that directing total focus on the individual and the error can impede the attention or focus on the system as a whole. This creates an overlooking neglect of two important features of human error, which is that error is not the monopoly of the unfortunate few and mishaps tend to fall into recurrent patterns (Reason, 2000).

In the “systems approach”, defenses, barriers and safeguards occupy a key position. According to James Reasons’ “Swiss Cheese” Model, in an ideal world, the established defenses would be fully intact; however, reality is more like Swiss cheese, with unsafe actions continually opening, closing and shifting. As unsafe acts occur at various times, there are holes opening, closing and shifting in the Swiss cheese model. When and if these holes momentarily line up, this is where hazards and accidents occur. Two underlying factors creating the holes in the Swiss cheese model is: active failures and latent conditions (Reason, 2000).

Active Failures

The effects of active failures, also known as active errors, are felt almost immediately while latent errors, whose adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach the systems' defenses (Rasmussen & Pedersen, 1984; cited in Reason, (1990)). Active failures are difficult to foresee and are directly created by the individual. This could be a slip, mistake, oversight or direct violation of procedural requirements.

Latent Conditions

Latent conditions are considered "resident pathogens" that can produce a problem within the system. In the Swiss cheese model, latent conditions can cause long-lasting holes and weaknesses in the deficiencies, which can create untrustworthy alarms and indicators, unmanageable procedures and design deficiencies. Latent conditions can be identified and remedied before a hazard occurs. Unfortunately, these conditions can lie dormant for years before they combine with active failures to create a potential hazard (Reason, 2000). These conditions can be present from decisions by designers, builders, procedure developers, and leadership.

Fortunately, these conditions can be identified and rectified in the early stages, such as the design phase before any hazard effects or conditions arise.

Some holes due to active failures, others due to latent conditions.

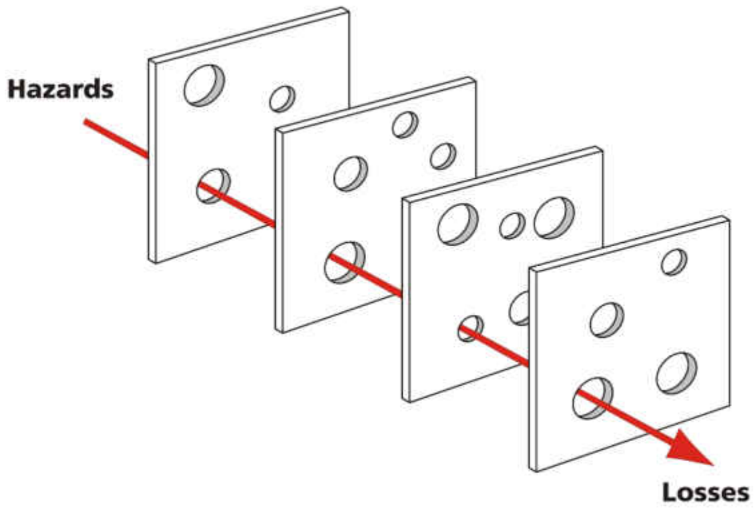


Figure 3: Cheese Model, Successive Layers of Defenses (Public Domain)

The system approach concentrates on the conditions under which the individuals work and tries to build defenses to avert errors or mitigate their effects.

Consequences of Human Error

One example of a consequence of human error is the Chernobyl Disaster - The Chernobyl Nuclear Disaster is known as the worst Nuclear Disaster in History. It occurred in April 26, 1986 at 1:24 a.m. in the morning in the Ukraine. Due to a defective reactor, the concrete cap ceiling blew off and released molten core fragmentation into the area and atmosphere. Thirty operators and firemen were killed within months of the disaster and thousands of others died in the months, and years to come due to cancer and other side effects of the event. This disaster is considered a man made one, due to the omission of procedure requirements and would fall into the category of a latent error (Reason, 1990).

Upon investigation there were obvious design defects to the reactor and based on failure analysis it is believed that the disaster components that created this was not new to the Soviet Union. It was determined that this was considered a system that was hazardous, complex, tightly-coupled, opaque and an operation outside normal conditions (Reason, 1990). According to James Reason (2000) "The complete absence of a reporting culture in the Soviet Union was the result of the Chernobyl Disaster" (p. 768). The Soviet Union's management structure was seen as weak, largely remote and slow to respond. Safety was considered ranking low in the light of their organizations goals and the operators possess only a limited understanding of the system (Reason, 1990).

Classification of Errors

When considering the classification of human error Reason (1990) explains that there are three levels of classification: behavioral, contextual and conceptual. The behavioral level is considered the least detailed level of the classifications. The observable aspect of this level can include the conventional characteristics of error, such as: omission, commission, repetition and misorders. This also includes considering the immediate consequences, such as: the nature and extend of the damage or injury (Reason, 1990). The second level is the contextual which deals with limited assumptions as it relates to the cause of the error. This level recognizes the crucial connection between the type of error generated and the situation or task in which the error appeared. However, there is no direct relation to how the same environment or situation does not always generate the same type of error. The third level is called the conceptual level. This level of classification relies on theoretical inferences than on observable characteristics of the error or its context (Reason, 1990).

Reason (1990) provides two distinctions on error: error type and error forms. “Error types” relate to the origin of an error within a category or stage, such as: the planning stage (goal and achieving a process), storage stage (framing the process actions) and execution stage (implementing the storage stage plan). Reason also describes that mistakes can be divided into two entities of "failure of expertise” and "lack of expertise.” Failure of expertise is when a plan or solution to a problem is inappropriately fulfilled. Lack of expertise is when a person does not have the routine or knowledge to appropriately fulfill the task and is forced to rely on previous knowledge. These two mistake categories are similar to the "rule" and "knowledge” based levels, described by Rasmussen (1983). “Error Forms” are forms of fallibility that appear across the board of cognitive activities, regardless of the error type. They can be apparent in types of errors such as mistakes, lapses and slips. Because the forms are extensive it is improbable that these error formed incidents are connected to the fault of a single cognitive item (Reason, 1990).

Table 2: Classification Error Types to Cognitive Stages at which they occur (Reason, 1990)

Cognitive Stage	Primary Error Type
Planning	Mistakes
Storage	Lapses
Execution	Slips

Approaches to Identifying and Assessing Human Error

Human Reliability Analysis (HRA) Methods/Models

Human Reliability Analysis is often referred to as "the probability of human failures", as it pertains to critical system interactions. Quantitative risk assessment, particularly known as Probabilistic Risk Assessment (PRA) is one of two common tools used for ensuring the safety of systems that have hazardous potential. PRAs are used as a safety analysis tool providing beneficial information for safety-related decision making (Salvendy, 2012).

Analysts learned early on that affecting realistic evaluation of system operations risks, required integrating human reliability with hardware/software analysis. As it relates to Human Reliability Analysts, the Probabilistic Risk Assessment (PRA) serves as a tool for determining the contribution to predetermined system failures, by identifying, presenting and quantifying (if identified) human errors and/or failures (Salvendy, 2012).

PRA human errors or actions typically considered in a Probabilistic Risk Assessment are frequently gathered into three categories: Pre-initiator human events, Initiator human events and Post-fault human events (Salvendy, 2012):

Pre-initiator human events – Events that occur within normal operations that can cause hardware or systems to become unavailable once needed.

Initiator human events – Events or actions that were originated on their own or in combination with other actions or failures that can initiate an event or occurrence.

Post-fault human events – human actions that, due to inadequate assessment of a situation, a strategic approach to resolve the issue, leads to an inadequate repair.

Despite the fact that a HRA is considered (and recognized) as an essential component of a Probabilistic Risk Assessment (PRA), it does not guarantee that this process will be integrated (effectively) into PRA analyses. With research revealing that human reliability accounts for 60-80% of total system risk, it is essentially imperative that the HRA analysis process be included and significantly involved in the PRA process (as cited in Salvendy, 2012).

Cognitive Reliability and Error Analysis Method (CREAM)

CREAM was proposed by Erik Hollnagel as a modified HRA tool to defining and analyzing human error causes (Yang, et al. 2007). Its theoretical context is centered on the classification of the error mode elements of human, technological and organizational factors (Konstandinidou, et al. 2006).

CREAM can be used by analysts for: recognizing tasks requiring human reasoning and hinge on cognitive reliability, determining the mental reliability state in which the reliability may be reduced, thus creating a reduced mental reliability and foundation of risk and lastly provide an assessment of the significant impact of human performance on system safety, which can be implemented in a Probabilistic Risk assessment (PRA) (Konstandinidou, et al. 2006). Three major benefits to using the CREAM method include: maximizing the capabilities of the human performance, minimizing the probabilities of human error and lastly maximizing the highest potential recovery from human error occurrences (Yang, et al. 2007).

The Technique for Human Error Rate Prediction (THERP)

The Technique for Human Error Rate Prediction (THERP) is considered one of the oldest and well-known HRA methods (Swain, 1990). THERP was developed and proposed by Swain and Guttman in 1961. The method's development was backed by the U.S. Nuclear Regulatory Commission (Swain and Guttmann, 1983).

THERP is a method used for predicting human error probabilities and their tendency to weaken a man-machine system due to isolated or a combination of human errors. This combination of errors can include machine functions, practices, operations processes or any other human factors (Swain and Guttmann, 1983). One of the major differences between the steps of THERP from other reliability analyses is the human events are replaced with machine outputs (Swain and Guttmann, 1983).

THERP Steps: 1) Describe the system failures, 2) Itemize and examine the associated human operations, 3) Calculate/determine the significant error probabilities, 4) Determine the human error effects on the system failure events, and 5) Discuss change considerations to the system and reevaluate the system failure.

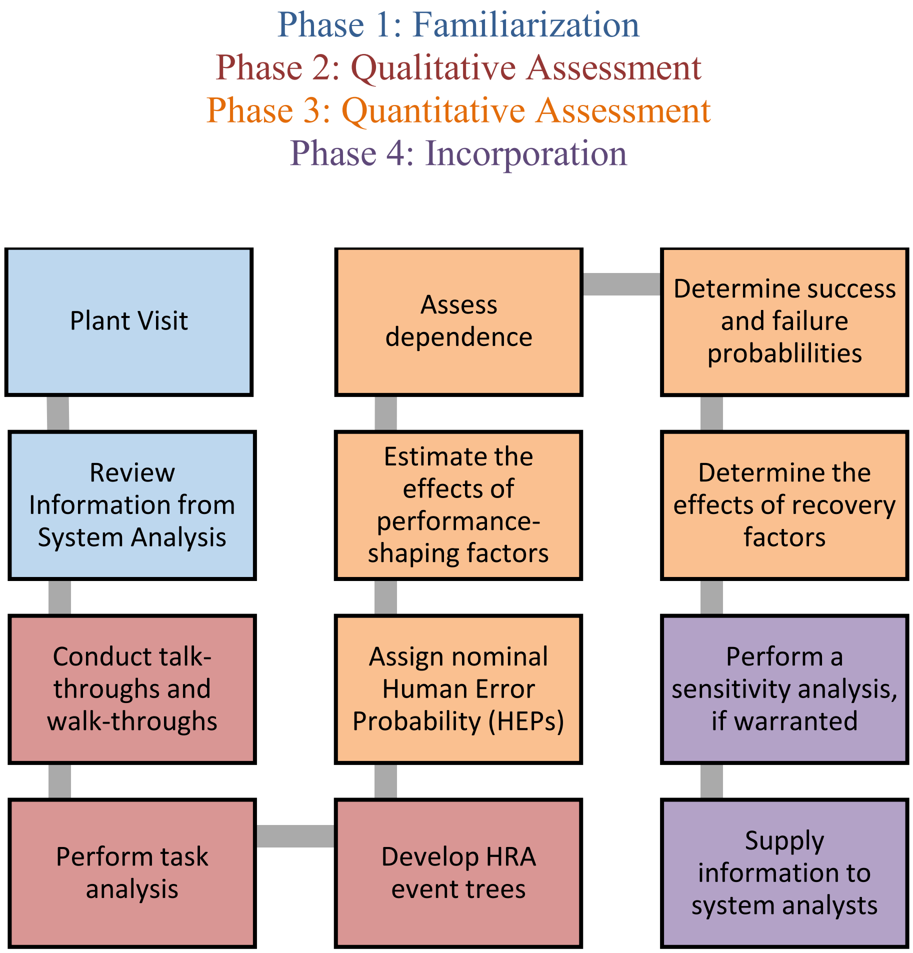


Figure 4: Example of Steps Encompassing THERP (Sharit, 2012).

Human Factors Analysis and Classification System (HFACS)

Human Factors Analysis and Classification System (HFACS) is primarily based on James Reason's Generic Error Modeling systems (GEMS) conceptual framework. The purpose of this framework is to identify the origin of basic human error types (Reason, 1990). Created from Reason's model, the HFACS lists human errors at each of the four levels of failure: 1) unsafe acts of operators, 2) precondition for unsafe acts, 3) unsafe supervision, and 4) organizational influences (which can be multiple causes) (Wiegmann, 2001). Nineteen (19) causal categories within the four categories of level of failures are also established for human failure.

HFACS was developed by Dr. Scott Shappell (Civil Aviation Medical Institute) and Dr. Doug Wiegmann (University of Illinois) as a response to data from the Navy and Marine Corp that identified human error as the leading primary cause for approximately 80% of all of their flight accidents. HFACS is used to categorize human causes of accidents and serves as a means to assist in the investigation of those causes. It also helps identify human causes of accidents, with the objective of establishing training and prevention efforts (Wiegmann and Shappell, 2001).

Below is a diagram (Figure 5) of the HFACS four levels of human failure and selected examples (Tables 3, 4, 5 and 6) from the Nineteen (19) causal categories within the four categories.

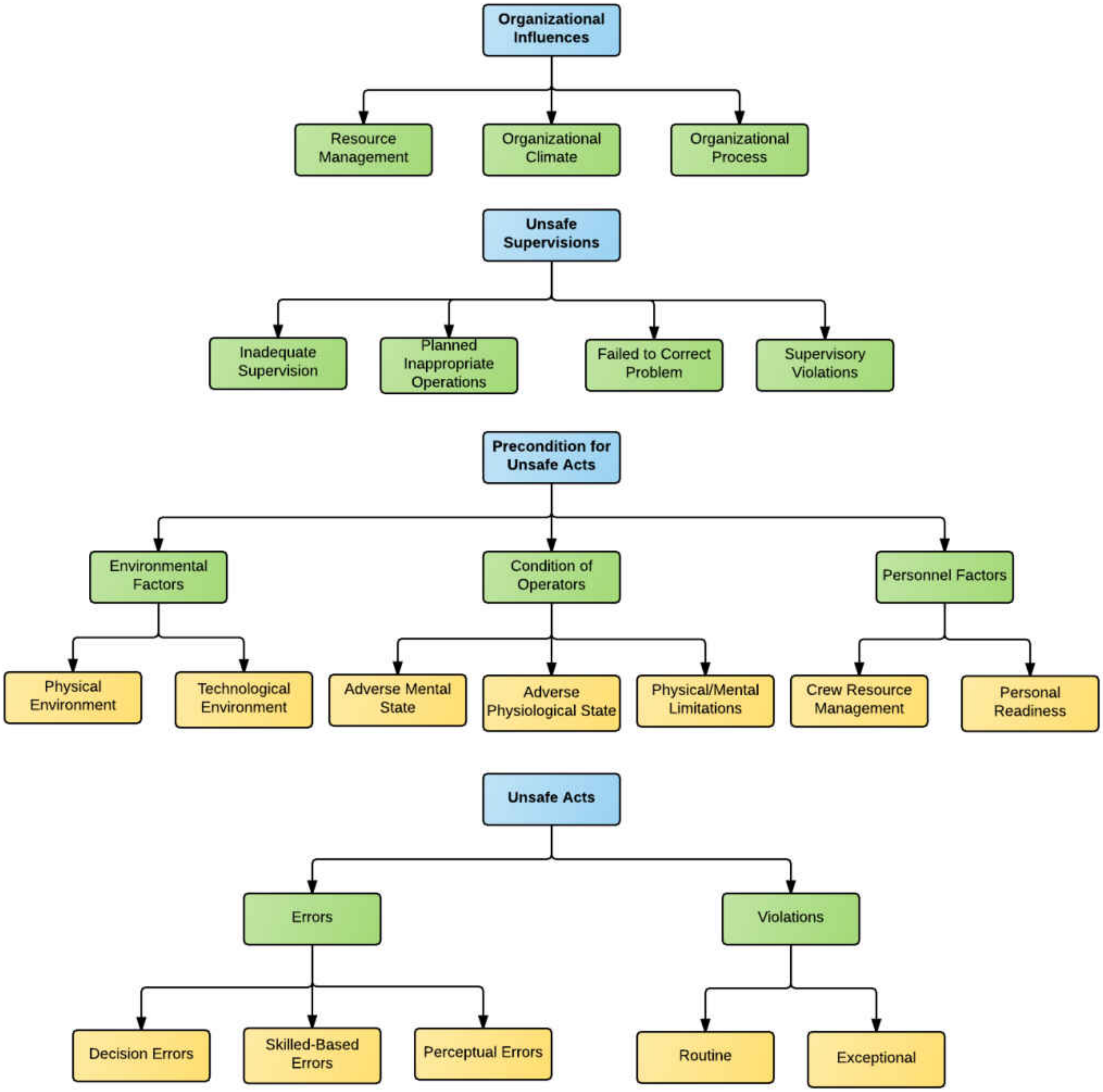


Figure 5: Human Factors Analysis and Classification System (HFACS) Overview (Shappell, 2012).

Table 3: Selected Examples of HFACS Preconditions of Unsafe Acts (not an exhaustive list) (Shappell, 2012)

Condition of Operators	Personnel Factors
Adverse Mental State	***Crew Resource Management***
Loss of situational awareness	Failed to conduct adequate brief
Complacency	Lack of teamwork
Stress	Lack of assertiveness
Overconfidence	Poor communication/coordination with and between aircraft, ATC, etc.
Poor flight vigilance	Misinterpretation of traffic calls
Task Saturation	Failure of Leadership
Alertness (Drowsiness)	***Personal Readiness***
Get-Home-Itis	Failure to adhere to crew rest requirements
Mental Fatigue	Inadequate training
Circadian dysrhythmia	Self-medication
Channelized attention	Overexertion while off duty
Distraction	Poor dietary practices
Adverse Physiological State	Pattern of poor risk judgment
Medical Illness	Environmental Factors
Hypoxia	***Physical Environment***
Physical fatigue	Weather
Intoxication	Altitude
Motion sickness	Terrain
Effects of Over the Counter (OTC) mediations	Lighting
Physical/Mental Limitations	Vibration
Visual Limitations	Toxins in the Cockpit
Insufficient reaction time	***Technological Environment***
Information overload	Equipment/controls design
Inadequate experience for complexity of situation	Checklist layout
Incompatible physical capabilities	Display/interface characteristics
Lack of aptitude to fly	Automation
Lack of sensory input	

Table 4: Selected Examples of Unsafe Acts (not an exhaustive list) (Shappell, 2012)

Errors	Violations
Skilled Based Errors	***Routine Violations***
Breakdown in visual scan	Inadequate briefing for flight
Inadvertent use of flight controls	Failed to use air traffic controls (ATC) radar advisories
Poor technique/airmanship	Flew an unauthorized approach
Over-controlled the aircraft	Violated training rules
Omitted checklist item	Failed Visual Flight Rules (VFR) in marginal weather conditions
Omitted step in procedure	Failed to comply with departmental manual
Over-reliance on automation	Violation of orders, regulations, Standard Operating Procedures
Failed to prioritize attention	Failed to inspect aircraft after in-flight caution light
Task overload	***Exceptional Violations***
Negative habit	Performed unauthorized acrobatic maneuver
Failure to see and avoid	Improper takeoff technique
Distraction	Failed to obtain valid weather brief
Decision Errors	Exceeded limits of aircraft
Inappropriate maneuver/procedure	Failed to complete performance computations for flight
Inadequate knowledge of systems, procedures	Accepted unnecessary hazard
Exceeded ability	Not current/qualified for flight
Wrong response to emergency	Unauthorized low-altitude canyon running
Perceptual Errors	
Due to visual illusion	
Due to spatial disorientation/vertigo	
Due to misjudged distance, altitude, airspeed, clearance	

Table 5: Selected examples of Preconditions of Unsafe Supervision (not an exhaustive list) (Shappell, 2012)

Inadequate Supervision	**Failed to Correct a Known Problem**
Failed to provide proper training	Failed to correct inappropriate behavior
Failed to provide professional guidance/oversight	Failed to identify risky behavior
Failed to provide current publication/adequate technical data and/or procedures	Failed to correct a safety hazard
Failed to provide adequate rest period	Failed to initiate corrective action
Lack of accountability	Failed to report unsafe tendencies
Perceived lack of authority	**Supervisory Violations**
Failed to track qualifications	Authorized unqualified crew for flight
Failed to provide operational doctrine	Failed to enforce rules and regulations
Failed to track performance	Fraudulent documentation
Over-tasked/untrained supervisor	Failed to enforce rules and regulations
Loss of supervisory situational awareness	Violated procedures
Planned Inappropriate Operations	Authorized unnecessary hazard
Poor crew pairing	Willful disregard for authority by supervisors
Failed to provide adequate brief time /supervision	Inadequate documentation
Risk outweighs benefit	
Failed to provide adequate opportunity for crew rest	
Excessive tasking/workload	

Table 6: Selected examples of Organization Influences (not an exhaustive list) (Shappell, 2012)

Resource Management	Organizational Process
Human resources	***Operations***
Selection	Operational tempo
Staffing/manning	Incentives
Training	Quotas
Background checks	Time pressure
Monetary/Budget Resources	Schedules
Excessive cost cutting	***Procedures***
Lack of funding	Performance standards
Equipment/Facility Resources	Clearly defined objectives
Poor aircraft/aircraft cockpit design	Procedures/instructions about procedures
Purchasing of unsuitable equipment	**Organizational Climate**
Failure to correct known design flaws	***Structure***
Organizational Process Oversight	Chain of command
Established safety programs/risk management programs	Communication
Management's monitoring and check of resources, climate and process at ensure a safe work environment.	Accessibility/visibility of supervisor
Organizations Climate Culture	Delegation of authority
Norms and rules	Formal accountability for actions
Organization customs	***Polices***
Values, beliefs, attitudes	Promotion
	Hiring, firing, retention
	Drugs and alcohol
	Accident investigations

Human Error Analysis Reduction Technique (HEART)

The Human Error Assessment and Reduction Technique (HEART) is a Human Reliability Analysis (HRA) developed by J. C. Williams in 1986, which uses a set of generic error probabilities that have been adjusted by Subject Matter Expert (SME) assessors along with controlled performance shaping factors to evaluate the likelihood of human errors that may occur within a system (Kirwan, 1996). Performance shaping factors (PSF) encompass a variety of factors that can directly or indirectly influence a human's performance. In the HEART tool the PSFs are called Error Producing Conditions (EPCs).

HEART has been suggested to be one of the most well-known HRA techniques used in the United Kingdom (Kirwan, 1996). Through a validation of three reliability quantification techniques performed by Kirwan (1996), HEART provides precise number estimates of the likelihood of failure founded on the practical use of the Quantification Process (Kirwan, 1996).

The HEART method also proposes remedial measures to combat or help minimize the likelihood of the error from occurring in a general sense (Williams, 1986).

HEART and HRA

The HRA process (see Figure 6) encompasses various risks, probability assessments and methods that follow a 10-step model process. This ranges from the first step of defining the problem to the final step of documentation, once the accepted human reliability is high (Sharit, 2012).

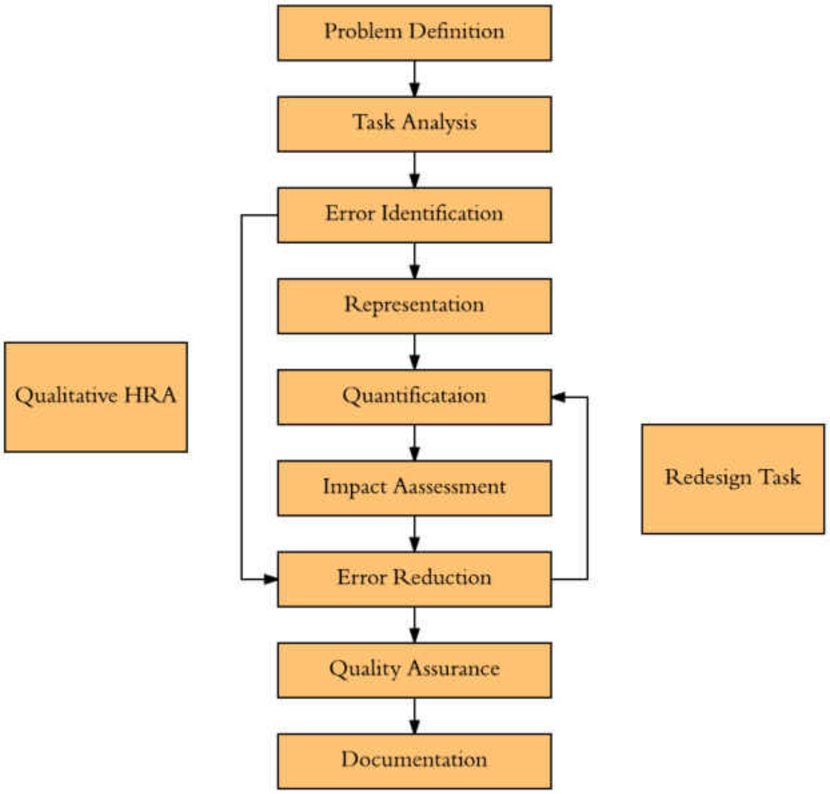


Figure 6: General HRA Process (Kirwan, 1994)

Amongst the various HRA methods for analyzing human error, the Human Error Assessment and Reduction Technique (HEART), created by J. C. Williams in 1986 evaluates the probability of human errors as it occurs throughout the completion of a specific task (Williams, 1988). This technique can be useful for assisting in reducing the likelihood of errors that may occur within a system, leading to an overall reduction of error, mishaps, and other safety aspects (Williams, 1988).

One of the benefits of using the HEART technique it that it is capable of answering both qualitative and quantitative questions, by identifying methods to reduce human error impact during risk analysis (qualitative) and then the reduced risk if such an error decreasing measure is implemented (quantitative) (Kirwan, 1997).

HEART was originally established for nuclear power and chemical process industries (Kirwan, 1994), but for this research it was modified to fit the needs of complex space operations, such as KSC ground processing operations.

With emphasis on more of a holistically appraisal of the reliability of human task performance, this method originally defined the limited set of "generic" tasks by describing nuclear power plane activities from which analysts can select. For this method, various resources were reviewed in order to develop a limited set of "generic" tasks performed by operators of various complex systems, including power plants. From this list the common factor tasks were generated (Sharit, 2012).

This HRA technique is based on human performance literature, with a central premise that when dealing with reliability and risk equations, ergonomic analysts are interested in the factors that have a large impact on performance. The HEART method concentrates on the factors that have a significant impact on this performance (Kirwan, 1994). This technique allows an ergonomist to assist engineers by identifying how important the ergonomic aspects are quantitatively (Kirwan, 1994).

This method is considered relatively easier to apply than the Technique for Human Error Rate Prediction (THERP) due to the fact that it is not forced to quantify large numbers of basic subtasks (Sharit, 2012).

Table 7: Kirwan's HEART Process (Yang, et al., 2007)

a.	Categorize tasks into one of the generic categories.
b.	Allocate a nominal Human Error Probability (HEP) to the task.
c.	Verify the Error Producing Conditions (EPCs: effectively PSFs) which will influence task reliability
d.	Decide the Assessed Proportion of Affect (AOA) for each EPC.
e.	Compute the task HEP.

HEART Human Error Probability (HEP)

The HEART assessment begins by taking a specific task or activity of interest performed by the human operator and assigning it a nominal human error probability by classifying it under a predefined generic task. This method is based on the standard that every time a task is performed, there is a potential for some probability of error, defined as the Error Producing Conditions (EPCs) (Kim, 2006).

The Human Error Probability (HEP) is the probability that an error will occur during the performance of a given task (Kim, 2006).

The HEP is defined as the ratio of committed errors to the number of opportunities that are available for errors to be made (Kim, 2006).

$$\text{HEP} = \frac{\text{Number of committed errors } (N_e)}{\text{Number of opportunities for errors to occur } (N_o)} \tag{1}$$

HEART classifies 9 generic task types, with projected nominal Human Error Probability (HEP) values (see Table 8) and their proposed bounding values along with 38 EPCs. An EPC can be: tiredness, noise, inexperience, stress, etc., all with varying degrees (Williams, 1988). Each of the 38 Error Producing Conditions (EPCs) have a maximum predicted value called the "nominal amount" that the nominal HEP can be multiplied by. This "EPC nominal amount" of how much the unreliability of the condition might change (going from "good" to "bad") was established on an wide-ranging analysis of human performance literature (Williams, 1998).

The generic tasks used for classification may be one or more of, but are not limited to, the 38 Error Producing Conditions (EPCs) defined by this technique (see Table 9). These EPCs are then specified for a given situation (as cited in Eastman, 2004).

The EPC(s) with the greatest negative impacts are of the greatest concern. Once the greatest impacting EPC(s) are identified, a final error chance can be calculated from the failure probability under the ideal condition (Williams, 1988).

Below (Table 8) are the Generic Task listed in the HEART process along with the Nominal Error Probabilities.

Table 8: **HEART Nominal Human Error Probabilities (HEPs) (Williams, 1986)**

Letter	Generic Task	Nominal HEP (5th-95th percentile)
A	Totally unfamiliar, performed at speed with no real idea of likely consequences.	0.55 (0.35-0.97)
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures.	0.26 (0.14-0.42)
C	Complex task requiring high level of comprehension and skill.	0.16 (0.12-0.28)
D	Fairly simple task performed rapidly or given scant attention.	0.09 (0.06-0.13)
E	Routine, highly-practiced, rapid task involving relatively low level of skill.	0.02 (0.007-0.045)
F	Restore or shift a system to original or new state following procedures with some checking.	0.003 (0.0008-0.007)
G	Completely familiar, well-designed, highly practiced routine task occurring several times per hour, performed to highest possible standards by highly-motivated, highly-trained and experienced person, totally aware of implication of failure, with time to correct potential error, but without the benefit of significant jobs aids.	0.0004 (0.0008-0.009)
H	Respond correctly to system command even when an augmented or automated supervisory system providing accurate interpretation of system state.	0.00002 (0.000006-0.0009)

Table 9: HEART Error Producing Conditions (EPCs) (Williams, 1986)

Number	Error Producing Condition (EPC)	Nominal amount by which unreliability might change
1	Unfamiliarity with a situation which is potentially important, but which only occurs infrequently, or which is novel.	X 17
2	A shortage of time available for error detection and correction.	X 11
3	A low signal to noise ratio.	X 10
4	A means of suppressing or overriding information or features which is too easily accessible.	X 9
5	No means of conveying spatial and functional information to operators in a form which they can readily assimilate. (e.g. Spatial and functional incompatibility)	X 9
6	A mismatch between an operator's model of the world and that imagined by a designer.	X 8
7	No obvious means of reversing an unintended action.	X 8
8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information.	X 6
9	A need to unlearn a technique and apply one which requires the application of an opposing philosophy. (e.g. Operation technique)	X 6

Number	Error Producing Condition (EPC)	Nominal amount by which unreliability might change
10	The need to transfer knowledge from task to task without loss.	X 5.5
11	Ambiguity in the required performance standards.	X 5
12	A mismatch between perceived and real risk. (e.g. Risk misperception)	X 4
13	Poor, ambiguous or ill matched system feedback.	X 4
14	No clear, direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted.	X 4
15	Operator inexperience. (e.g., a newly qualified tradesman, but not an expert)	X 3
16	An impoverished quality of information conveyed by procedures and person-person interaction.	X 3
17	Little or no independent checking or testing of output.	X 3
18	A conflict between immediate and long term objectives. (conflict of objectives)	X 2.5
19	No diversity of information input for veracity checks	X 2.5
20	A mismatch between the educational achievement level of an individual and the requirements of the task.	X 2

Number	Error Producing Condition (EPC)	Nominal amount by which unreliability might change
21	An incentive to use other more dangerous procedures.	X 2
22	Little opportunity to exercise mind and body outside the immediate confines of a job. (e.g. need for postural change)	X 1.8
23	Unreliable instrumentation (enough that it is noticed).	X 1.6
24	A need for absolute judgments which are beyond the capabilities or experience of an operator.	X 1.6
25	Unclear allocation of function and responsibility.	X 1.6
26	No obvious way to keep track or progress during an activity.	X 1.4
27	A danger that finite physical capabilities will be exceeded.	X 1.4
28	Little or no intrinsic meaning in a task.	X 1.4
29	High level emotional stress.	X 1.3
30	Evidence of ill-health amongst operatives especially fever.	X 1.2
31	Low workforce morale.	X 1.2
32	Inconsistency of meaning of displays and procedures.	X 1.2
33	A poor or hostile environment. (e.g. likely to impair performance)	X 1.15

Number	Error Producing Condition (EPC)	Nominal amount by which unreliability might change
34	Prolonged inactivity or highly repetitious cycling of low mental workload tasks (1st half hour)	X 1.1
34	(thereafter)	X 1.05
35	Disruption of normal work sleep cycles.	X 1.1
36	Task pacing caused by the intervention of others.	X 1.06
37	Additional team members over and above those necessary to perform task normally and satisfactorily (per additional team member).	X 1.03
38	Age of personnel performing perceptual tasks.	X 1.02

HEART Process (Williams, 1988)

1. Identify the complete range of sub-tasks that would be necessary for a human operator to complete within in a given task.
2. The tasks are then classified into the generic tasks provided within the HEART process with proposed nominal human unreliability for these tasks. These are the nominal Human Error Probability (HEP) scores for the particular task with calculated 5th – 95th percentage bounds (see Table 8).

3. The obvious EPCs that have high possibility or probability to have a negative effect on the particular situation are considered. The EPCs that show evidence of having a significant affect in this particular situation will be used by the assessor (Williams, 1988). To what extent each EPC applies to the given task of concern is then discussed and agreed upon again by local SMEs. EPCs should be considered as not beneficial to a work task.
4. The Assessed Proportion of Affect (AOA) for each tasks will be determined by consulting local subject matter experts (SMEs), in which the affect proportions range from 0 to 1. The AOA is a subjective assessment of the Error Producing Condition's (EPC) affect or impact on a specified Generic Task. The AOA range represents the percentage of this affect (e.g. 0.26 = 26% of the EPC maximum effect). This value will be a part of the assessed effect for each error producing condition of the given task.
5. A final HEP is then calculated, by multiplying the HEART nominal HEP of the task by each of the calculated assessed effects. The calculated effect is determined below:

(2)

$$\begin{aligned} &Calculated\ Assessed\ Factor\ Effect \\ &\qquad = \big((Max\ Effect - 1)\ \times Proportion\ of\ Affect\big) + 1 \end{aligned}$$

$$HEP = (Type\ of\ Task\ generic\ error\ probability) \times (Assessed\ Factor\ effect(s))$$

6. From here a HEP value can identify the EPCs that cause a higher probability for an error to occur and possible remedial or strategies to minimize the occurrence risk of future human errors can be developed.

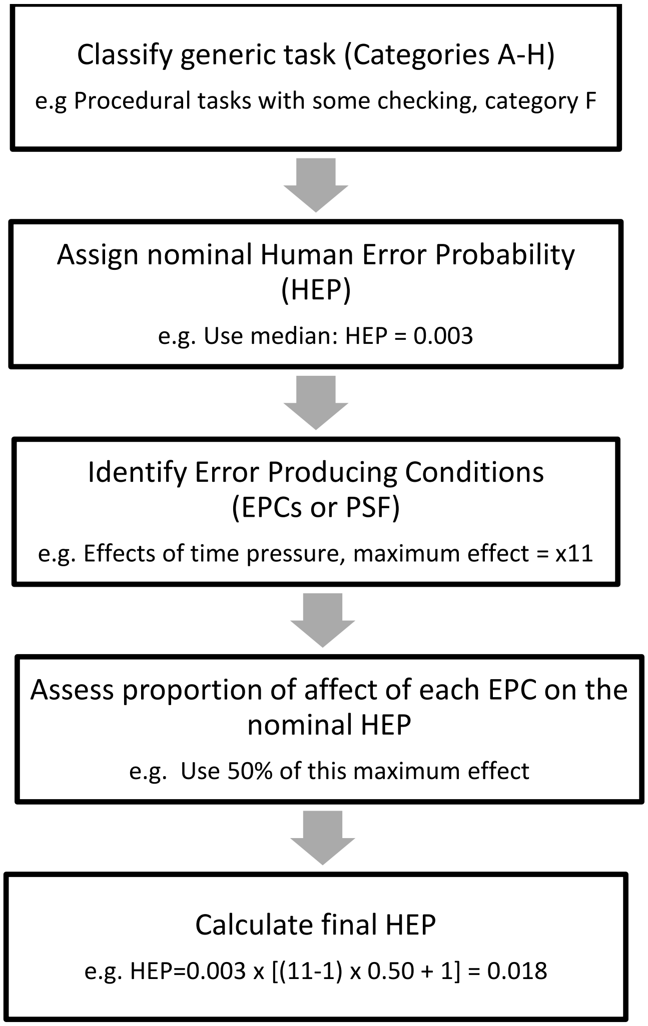


Figure 7: HEART Quantification Process, (Kirwan, 1996)

Human Error Risk Management for Engineering Systems (HERMES)

The Human Error Risk Management for Engineering Systems (HERMES) is a Human Factors methodology that provides a guide to applying pertinent human factors methods for a specific problem (Cacciabue, 2004). In its system's approach to applying correct Human Factors methods, it also provides a framework of methods, models and techniques to address the issues of

Human Risk Assessments (HRA), such as Human Error Management and the cognitive process (Cacciabue, 2004).

The steps for the HERMES method consists of:

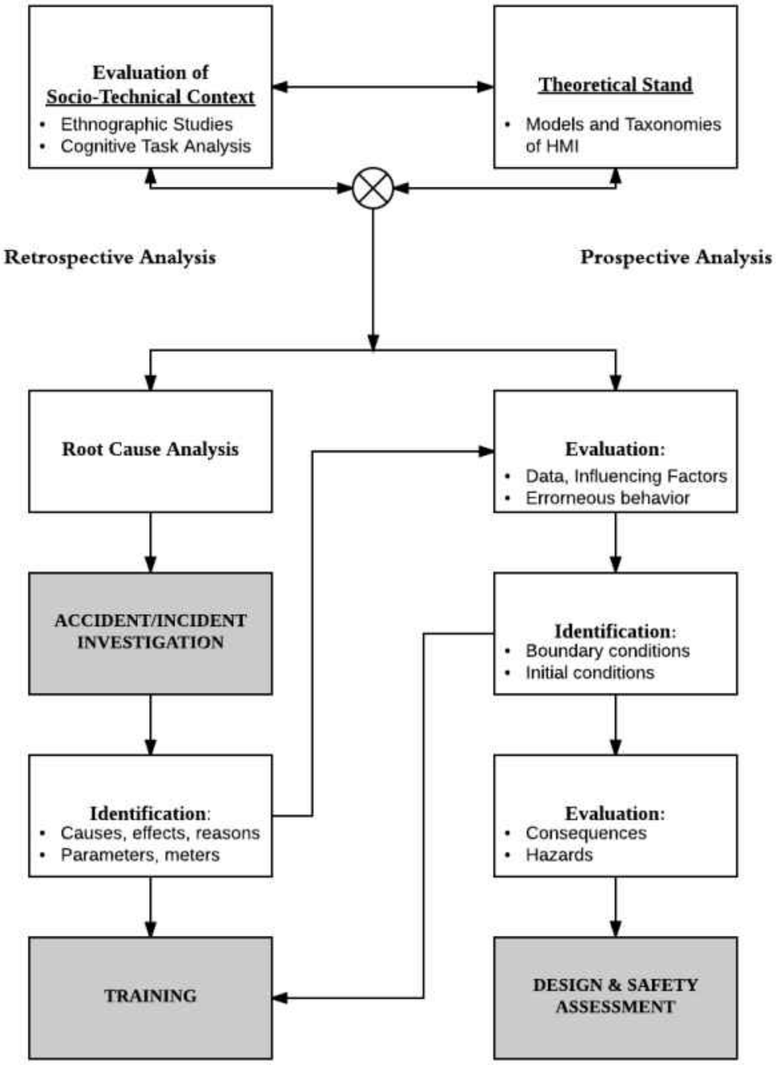


Figure 8: HERMES Methodology (Cacciabue, 2013).

Human Error Rate Assessment and Optimizing System (HEROS)

The Human Error Rate Assessment and Optimizing System (HEROS) is built on a fuzzy set concept that was developed to perform probabilistic assessments and optimization of man-machine systems (Richei, 2001). When using the HEROS method, the calculation of the probabilities of human error can be performed by the following processes.

Table 10: HEROS Process (Richei, 2001)

HEROS Processes
(a) Description of the present environment.
(b) Description of the objective action.
(c) Assessment of associated records.
(d) Description of active employees.
(e) Assessment of supervision leadership.
(f) Development of the order of steps for task analysis.
(g) Depiction by a fault tree.
(h) Assessment of PSFs. To identify the impacts of PSFs on assignment components can validate the impact on actions.
(j) Calculation of human error probabilities.

Below is an Advantage and Disadvantage Comparison Table of the seven HRAs discussed in this Literature Review.

Table 11: HRA Advantage and Disadvantage Comparison Table

Human Error Identification Methods	Advantages	Disadvantages
Humane Error Assessment and Reduction Technique (HEART)	Useful for prediction and quantifying human error likelihood or failure within complex systems; Easy to use; Minimal training required.	HEART Methodology is subjective to SME assessment, thus affecting the consistency.
The Cognitive Reliability and Error Analysis Method (CREAM)	Considered organized system approach to quantifiably identifying human error; very detailed.	Time consuming to implement; May be considered complicated to a novice analyst; appears complicated in application.
Human Factors Analysis and Classification System(HFACS)	Helps categorize and classify human error into four levels of failures.	Originally developed for Navy and Marine Corp. Will need to be modified for use in other fields.
Technique for Human Error Rate Prediction (THERP)	THERP can be used for task performance Prediction while designing the Human System Integration (HSI) interaction (Yang, et al. 2007).	THERP does not offer clear processes for performing error identification (Chandler, 2006).
Human Error Risk Management for Engineering Systems (HERMES)	The HERMES methodology has presented proficiency and usefulness in an actual and complex application (Yang, et al. 2007).	The application of HERMES is restricted to the identification of safety critical factors, or Indicators of Safety (IoS), and their dissemination into RSA-Matrices that serve the resolution of outlining the present level of safety within the organization and describing the position methods for audits in the future (Stanton, 2013).
Human Error Rate Assessment and Optimizing System (HEROS)	The importance of the Performance Shaping Factors (PSF) and Performance Influence Factor (PIF) values can be easy calculated for optimizing the man-machine system (Richei, 2001).	Even though is it minimized, there is still some level of subjectivity when vague linguistic statements on PSFs are selected and modified, then conveyed into expressions of fuzzy numbers or intervals to allow mathematical operations to be performed on them (Richei, 2001).

Human Error in Aerospace Industry

When considering human error in the Aerospace and Aeronautics Industry, it is imperative to define what the terms aerospace and aeronautics mean. Merriam Webster defines aerospace as "an industry that deals with travel in and above the Earth's atmosphere and with the production of vehicles used in such travel**:** space comprising of the earth's atmosphere and the space beyond" (Merriam-Webster, 2015). Aeronautics is defined as "a science that deals with airplanes and flying**:** a science dealing with the operation of aircraft" (Merriam-Webster, 2015).

In this research, various literature journals were reviewed in order to identify the leading contributing factors to human error in the aerospace and aeronautics industry. Unfortunately, from what was found, there was very limited research information from a space operations perspective; however, research information was provided for the aeronautical industry with considerable focus on pilot error. The aeronautical industry information found in this research review was used as a "closely related area" to "aerospace" science that deals with the earth's atmosphere and the manufacture of vehicles used in space. NASA KSC Ground Processing Operations deals with processing launch vehicles and space-craft used in the earth's atmosphere and beyond. This data was used as a reference benchmark for leading contributing factors, which was used in developing the categorization for the human errors listed in the KSC Mishap Data within the 30 year time span (October 1984 – May 2014).

Causes of Aviation Mishaps

To identify the most common human error causes as it relates to the casual categories of Human Error taxonomies, research of Aviation/aircraft operation Mishaps were reviewed. Mishap research shows that of the Human Error taxonomies related to operations (aeronautics industry), the Human Factors Analysis and Classification System (HFCAS) was found to be one of the prominent theoretical established instruments for evaluating and examining human error as it relates to accidents and incidents (Wiegmann et al., 2005).

A study of 523 accidents within the Republic of China (ROC) Air Force from 1978-2002 (24 years), revealed several significant associations between errors at the operation level and organization inadequacies. These were both found at the immediate HFACS adjacent level "Preconditions for unsafe acts" and higher levels of the "unsafe supervision and organizations influences." From the analysis, the greater frequencies and higher percentages of the frequency counts and inter-rater reliability status for each HFACS category were found in the following: Resource management (subcategories of organizational influence), Inadequate supervision (subcategories of Unsafe supervision), Crew resource management and adverse mental states (subcategories of Preconditions for unsafe acts), Violations, Perceptual errors, Skilled-based errors, and Decision errors (subcategories of Unsafe acts of operators) (Li, W., 2006).

Frequency counts for the Republic of China (ROC) Air Force's study were generated for each HFACS category for all 523 accidents. Of the four levels and subcategories, the sublevel errors that had the 10 highest frequency of occurrence (when ranking order of highest frequency) are in the table below, with "Unsafe Acts" and "Preconditions for unsafe acts" being the leading

HFACS Categories.

Level 1: Unsafe Acts (of Operators)
Level 2: Preconditions for unsafe acts (e.g. latent conditions)
Level 3: Unsafe supervision
Level 4: Organization Influences

Table 12: 10 Highest Frequency of Occurrence (in ranking order of highest frequency) (Li, W., 2006)

1. Skilled-based errors (Level 1) - Highest
2. Decision errors (Level 1)
3. Adverse mental state (Level 2)
4. Resource management (Level 2)
5. Inadequate supervision (Level 3)
6. Violations (Level 1)
7. Crew resource management (Level 2)
8. Perceptual errors (Level 1)
9. Organization process (Level 4)
10. Physical environment (Level 2) - Lowest

The HFACS tool was used in a research study concerning General Aviation accidents, in which the focus was on the unsafe acts of aircrew. When the research constrained the analysis to those causal categories, results indicated that Skill-based errors comprised the largest percentage of General Aviation accidents. Following Skilled-based errors, was Decision errors, Violations and Perceptual errors. Many of the identified accidents were linked with several HFACS causal categories. Thus an accident could have been linked with either a Decision, Skill-based, Perceptual error, Violation or a combination of errors. The identified accident may have also been linked with numerous occurrences of the same type of unsafe act. The results consisted of accidents that involved at least one occurrence of a particular unsafe act category (Wiegmann et al., 2005).

Managing Human Error

The primary goal of managing human error is to limit the incident of dangerous errors and producing systems that are able to endure occurrences of these errors and contain their destructive effects (Reason, 2000). When managing human error from the "person approach", efforts are made to direct management resources to make individuals less fallible. From the "systems approach" the effort is geared towards the management of several targets: the person, team, task, workplace and institution as a whole (Reasons, 2000).

When observing Human Reliability Analysis as it applies to aviation, William Nelson (Nelson at el., 1998) discussed an effective framework to apply human performance and human reliability methods to the full system development cycle, so that the full effectiveness of the methods to enhance design quality and system performance can be realized. Applying these human factor methods as early as possible within the system development, will help accomplish this effectiveness. This integrated design environment for human reliability analysis was developed at the Idaho National Engineering and Environmental Laboratory and its framework is comprised of five major elements (Nelson at el. 1998). Below are the elements and a brief explanation.

- Lessons Learned
- Functional Analysis
- Simulation
- Human Performance and Human error analysis
- Design engineering tools

Lessons Learned

Collecting and gathering lessons learned from relevant qualitative contextual information from operation experience can be used to learn more about the influences or contributions that lead to human error. This can also be effective in guiding the designs to help eliminate or mitigate any possibility of human error within those potential situations (Nelson at el. 1998).

Functional Analysis

This analysis is used to identify critical functions that must be realized and draws attention to the design phase and maintaining this during the operation phase in order to ensure the system objectives will be met. This system can identify the critical functions, maintenance of the performed tasks, the resources used to maintain these functions, and the required support systems for the operation of these resources. When a function model has been developed, system vulnerabilities can be identified as it relates to human error and the performance of the system can be explored in a variation of operation scenarios for various alternative designs from an either function or assess human performance in simulation or operation tests (Nelson at el. 1998).

Simulation

Nelson's (1998) research states that "Simulation should be viewed as a powerful tool with which to try our various design alternatives in a tightly-coupled feedback loop to investigate design options" (p. 211). Simulation allows the reenactment of various design alternatives and allows the investigation of the advantages and disadvantages of the varying design features as it relates to human performance and reliability (Nelson at el., 1998).

Human Performance and Human Error Analysis

This analysis can be used as a tool to help identify and predict potential human errors and how they interact with other errors and component failures which can lead to unwanted consequences, and provide potential counteractions to help prevent or mitigate the consequences of specific errors (Nelson at el., 1998).

Design Engineering Tools

This is considered the final element of the integrated design environment for human performance and human reliability analysis. These tools allow systematic application of the other design environment elements in the system development process (Nelson at el., 1998).

Of the management tools to manage and minimize human error, identifying and utilizing the correct tool is essential to minimizing human error. In this review, human error was discussed to help understand the current and proposed management methods and which principles of methods could be used help minimize human error in ground support operations for space operations at KSC. This study took a look into the various methods and if they could be used or modified for use in ground processing operations.

An essential part of effective risk management relies on creating a reporting culture. James Reasons (2000) states that "Without a detailed analysis of mishaps, incidents, near misses and lessons learned, we have no way of uncovering recurrent error traps or of knowing where the "edge" is until we fall over it" (p. 768).

Karl Weick observed that "reliability is a dynamic non-event" (Reason, 2008), which conveys that stable outcome is an expression of constant change rather than continuous repetition. To create this stability, a change in one system must be compensated by another change in another parameter (Reason, 1997). Reliability is considered dynamic because the process remains within boundaries due to constant moment by moment adjustments and compensations by the operator or individual. It is considered a “non-event” because safety nonevents typically draw little, if any, attention to them (Reason, 2008). Accidents are the events that are noticed and draw attention to them. The ongoing stable safety status is expected and although actions are generated in order to maintain it, the safe or stable act within itself is unnoticed.

The attributes of an organization’s reliability heavily depends on an unchanging consistency in the procedures and processes. Due to the structure, High Reliability Organizations (HROs) are able to cope with consistent performance and the ability to manage the unexpected. HROs are considered to have two distinguishing organization function aspects: cognition and activity (Reason, 2008). Research has shown that high reliability organizations provide an important model of what a resilient system consists of (Reason, 2000).

High Reliability Organizations, such as US Navy Nuclear aircraft carriers, Nuclear Power plants, and Air traffic control centers are models of HROs (Reason, 2000). All of these are serious jobs where depending on the type of error made, an error can be catastrophic. There are some similar distinct characteristics and challenges that were found within these organizations when these organizations were observed: Organization challenges, managing multifaceted challenging technologies to avoid major failures and sustaining the capacity for meeting periods of very high peak demands (Reason, 2000).

Organization defining characteristics consist of: Multifaceted, internally dynamic, sporadically, extremely collaborative, performing thorough tasks under extensive time pressure, fulfilling challenging activities with small incident rates and an almost near total absence of disastrous failures over several years (Reason, 2000).

High reliability organizations can reconfigure themselves. They have a repetitive mode (organized in orthodox ordered manner). During high temporary emergencies, the control shifts to the experts on the spot and then the organization reverts seamlessly back to repetitive controls once the disaster has passed (Reason, 2000). From James Reason's study, the value of High Reliability Organizations (HRO) can be summarized in the following four bullets:

- High reliability organizations are considered primary examples of the system approach, because they prepare for the worst and equip themselves to handle the situation at all levels of the organization (Reason, 2000).
- For these organizations, the quest of safety is about making the system as strong as possible in the mist of its human and operational hazards (Reason, 2000).
- HRO's have developed the skill of converting occasional setbacks into the improved flexibility of the system (Reason, 2000).
- High reliability organizations have a high awareness of the possibility of failure (Reason, 2000).

Paradox of High Reliability - With the study of high reliability there are some paradoxes. In research we typically gain knowledge and learn more about the negative outcomes or results of not having a high reliable system. For example, with medicine we understand more about the disease, than how it can be best avoided or in safety, more about unwanted events than the causes to avoid. These efforts have led some studies to learn more about the success in organizations, rather than the failures (Reasons, 2000).

When looking at how methodologies for managing error on the open road, Paul Salmon et al (2012) identified several forms of error management systems, methods that could be used to generate information regarding errors, their causation, their eradication, decrease or mitigation. These have been broadly broken down into the five methodological groups: incident reporting systems, accident investigation and analysis methods, human error identification methods, latent conditions identification methods and error databases (Salmon at el., 2010).

<u>Management Systems</u>

Incident reporting systems

This type of system collects near miss incidents, errors and safety concerns within the safety critical domain. These near misses can be indicators of potential hazards that are just waiting to happen. Evaluating and determining what the causes allow for preventative measures to be taken or incorporated into the system before a real accident occurs, is essential. Unfortunately, some workers are often reluctant to report near misses, due to the threat of personal consequences or retaliation (Salmon at el., 2010). This is an example of how the person approach may affect an individual's desire to feel comfortable with reporting close calls.

Accident investigation and analysis methods

By recreating the accident, these methods investigate the cause of the accidents, in an attempt to recognize the human and system contributors. Identifying the causes using this method can help mitigate future accidents from occurring. Applying the right system based accident analysis can assist in the development of system based counteracting measure to minimize or prevent future accidents from occurring (Salmon at el, 2010).

Human error identification methods (HEI)

This analysis tool serves as an error predictor to identify potential errors, in order to determine and provide a preemptive strategy for investing human error in complex sociotechnical systems and determine their contributing factors. One of the benefits of the HEI method is that in its predictions, it allows measures to be taken proactively before an accident occurs, allowing these counteractions to be in place earlier in the design process, before the development of the operational system (Salmon at el., 2010).

Human error analysis (HEA)

This analysis is similar to the HEI; however, its analysis is performed from a retrospective viewpoint. The analysis observes errors made by humans during accidents, both qualitatively and quantitatively (Salmon at el., 2010). One of the benefits of this analysis is that prior accidents can be thoroughly dissected and the causal factors determined for mitigating potential errors in future operations (Salmon at el., 2010).

Latent conditions identification methods

Inspired by James Reason, this method attempts to recognize and eradiate error-causing conditions and the scope to which latent or error-causing conditions are a problematic concern in the developed countermeasures created to remove latent conditions. The procedure generally involves safety leaders using failure checklists, error types and latent conditions to evaluate the risks related to a particular system. Once the areas of concern have been identified, remedial measures are then proposed and implemented (Salmon at el., 2010).

Error databases

This database type contains data related to various errors that have transpired within a particular system, their related causal factors and consequences. These databases can be used for in-depth study, error trending, development of domain specific error taxonomies, quantitative error analysis, and the development of error counter measures (Salmon at el., 2010).

Effective Risk Management

James Reason (2000) says "Effective risk management depends crucially on establishing a reporting culture. Without a detailed analysis of mishaps, incidents, near misses, and "free lessons," we have no way of uncovering recurrent error traps or knowing where the "edge" is until we fall over it" (p. 768). Free lessons are considered inconsequential unsafe actions that could result in an unwanted outcome in other circumstances. Lessons like these provide opportunities to learn from near misses and help the individual and organization (Reason, 2008).

In recent studies concerning managing error in the transport domain, it was determined that in comparison to other safety critical domains, where human error is a problem, systems based error methodologies and managing tools have not been widely used (Salmon at el., 2010).

Amongst the various human error models that have been developed and been around for over 20 years, a study of selected error management approaches, as it pertains to road transportation, was performed (Salmon et al., 2010). As a part of this study, three questions were asked in an effort to determine if any of the human error models previously mentioned (Incident Reporting systems, Accident Investigations systems, Human Error Identification methods, Human Error analysis, Latent Conditions and Error Databases) have made any significance to the transportation domain when considered amongst other safety critical domains (Salmon et al., 2010).

1. What contributions have human error models and methods provided within road transport?
2. Do the current models and methods deliver adequate knowledge and tools to take action and fight the problem within the road transportation system?
3. In consideration of technology advancement, policy and system design, what are the potential error models and method contributions for the future?

After a Driver Behavior questionnaire was given to 520 drivers asking about their frequency of committing various errors and violations while driving, an assessment of the human error manage methods and their application in safety critical domains was performed. The development of a Driver error causation factor chart was created and the answers to the previous three questions were determined (Salmon et al., 2010).

Answers to the three questions to define whether valuable safety advances have been, and can continue to be made through the application of current error models and methods are below:

1. Compared to other fields in which human error has been recognized as an issue, there has only been restricted systems based human error related research directed within the road transport field (Salmon et al., 2010).
2. The degree to which practitioners are adequately prepared to approach an issue, is the research's view that the prevailing models and methods described offer adequate information and resources to combat an error issue within road transport. Error administration methods are significantly underutilized within road transport, and so the question remains why is this so? (Salmon et al., 2010).
3. The probable influence of the error management methods defined within road transport is substantial. Incident reporting systems, in which drivers report errors and error related near miss incidents, could produce significant insights into various types of errors that road users make. This also included the environments that encourage errors and regaining approaches used in the event of occurring errors (Salmon et al., 2010).

KSC Mishap Data

Mishap report data can be useful for exploring the important correlations between a human error event and its contributing factors, as well as the development of a hypothesis (Rouse, 1983). It is significant to get in-depth of knowledge of human error for analyzing valuable information leading up to the actual human error event. It also is important to collect data from as many sources available (including historical data) to assist in effectively analyzing the human error and its contributing factors (Rouse, 1983). This section provides a brief overview of KSC Mishap Data procedural requirements, types and tools used to assess mishaps.

Per the NPR 8621.1 "NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping", a NASA Mishap is defined as "an unplanned event that results in an injury to non-NASA personnel, caused by NASA operations, damage to public/private property, occupation injury/illness to NASA personnel, NASA mission failures prior to scheduled completion of missions, and destruction of or damage to NASA property" (NASA, 2013).

The NASA Procedural Requirements (NPR) provide the requirements for reporting, investigating and documenting mishaps, close calls, and previously unknown severe workplace hazards to preclude the repetition of related accidents (NASA, 2013).

Mishaps Types

There are six (6) NASA mishap types. These terms are defined from the NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping.

Mishap Types

Type A Mishap

A mishap event causing either death or total permanent disability as a result of a job related damage or sickness, a complete cost of a failed mission and asset damage equivalent to or greater than $2 Million, exterior loss of an aircraft with a crew inside, and/or an unanticipated aircraft with a crew inside parting from a controlled flight (NASA, 2013).

Type B Mishap

A mishap event causing either partial permanent disability as a result of a job related damage or sickness or requiring admission into a hospital for 3 or more people within 30 work days of the occurrence, or a complete cost of a failed mission and asset damage equivalent to or greater than $500,000 but less than $2 Million (NASA, 2013).

Type C Mishap

A mishap event resulting a nonfatal job related damage or sickness, that caused days missed from work, with the exception of the day or shift of occurrence, limited work of relocation to another job with the exception of the day or shift of occurrence, requiring admission into a hospital for 1 or 2 people within 30 work days of the occurrence, or a complete cost of a failed mission and asset damage equivalent to or greater than $50,000 but less than $500,000 (NASA, 2013).

Type D Mishap

A mishap event resulting in any nonfatal Occupational Safety and Health Administration (OSHA) documentable job related damage and/or sickness that doesn't satisfy the definition of a Type C or a complete cost of a failed mission and asset damage equivalent to or greater than $20,000 but less than $50,000 (NASA, 2013).

Incident

A mishap or close call event.

Close Call

An event resulting in no physical damage or only insignificant damage that required first aid, no asset damage or insignificant asset damage of less than $20,000, no physical and/or only insignificant physical damage requiring first aid, but has a potential to result in a Mishap (NASA, 2013). Anything that does not fall under the Occupational Safety and Health Administration (OSHA) recordable Injury category is considered a Close call.

Per Occupational Safety and Health Administration (OSHA) recordable injury reporting requirements, the following events must be reported to OSHA by employers. All occupation related fatalities, all occupation related injuries resulting in "in-patient" hospitalization for a minimum of one (or more) employee(s), all occupation related injuries that result in amputation and all occupation related injuries that result in a loss of an eye (OSHA, 2014). Fatalities must be reported within 8 hours of incident awareness and within 24 hours of incident awareness for the remaining requirements (OSHA, 2001). According to OSHA requirements (2001): "If any injury results in any of the following, it must also be reported: death, days away from work, restricted work or transfer to another job, medical treatment beyond first aid, or loss of consciousness. It must also be considered a case to meet the general recording criteria if the injury involves a significant injury or illness diagnosed by a physician or other licensed health care professional, even if it does not result in death, days away from work, restricted work or job transfer, medical treatment beyond first aid, or loss of consciousness" (29 CFR Part 1904).

NASA Root Cause Analysis Tool (RCAT)

The NASA Root Cause Analysis Tool (RCAT) is used by NASA to assess Mishaps. It was created to assist in the analysis of anomalies, close calls, and accidents along with identifying the necessary corrective actions to help avoid future occurrences (NASA Safety Center).

The RCAT uses a repeatable method that is quick, simple, precise to execute and document root cause analysis, develop trending data, identify needed corrective actions and produce data that is usable in the beginning stages of analyzing and risk assessments from a probabilistic perspective (NASA Safety Center).

The RCAT was developed after a widespread review of tools and methods that were commercially available was found unable to support a complete root cause analysis of the unique NASA environment and complications it deals with on Earth, in space, in the oceans, in the air, on the moon and on planetary forms. NASA found that the prevailing current tools were developed based on special areas such as aviation or a particular type of active or human error type, with inadequate causal codes. This tool is a paper-based tool that works with software to deal with the inadequacies recognized in the current exiting tools (NASA Safety Center).

The RCAT was developed to consider the entire system, in order to address all possible types of activities and accident causes, regardless if they originated by: the environment, wonders of nature, software, hardware, weather, human or outside event, or could be integrated into a timeline, a fault tree and event/causal factor tree (NASA Safety Center).

Research Gap Discussion

During this research, questions were asked in order to identify the research gaps concerning retrospectively analyzing Mishaps relating to complex space systems such as NASA Ground Processing Operations. The research questions were in areas of: Human Reliability Analysis, Human Error Taxonomies and Human Error Frameworks.

The following questions were asked:

Human Reliability Analysis

1. What techniques are capable of answering both qualitative and quantitative questions, by classifying human error producing conditions (qualitative) and calculating future probability of human error occurrence (quantitative)?
2. What techniques are easy to use and can be performed by novice analysts?
3. What developed Human Reliability Analysis (HRA) methodologies classify human error contributing factors and error producing conditions to human error related mishaps?
4. What HRA methods provide a quantitative ergonomic approach through analysis of ergonomic factors that may have substantial, negative effects on human performance for Mishaps?

5. What are the identified leading human error causes and contributors to historical Launch Vehicle Ground Processing Operations mishaps and findings based on past mishaps, near mishaps, and close calls?
6. What methodologies have the ability to determine quantifiable human error probability (HEP)?
7. What methodologies have specific performance shaping factors (PSF) or Error Producing Conditions (EPC) that are in line with complex space operations, such as Space Ground Processing Operations?
8. What HRA method(s) are not more resource intensive than others, have low application time and are an ease in its application?
9. Is there a Human Error probability methodology modified specifically for aerospace complex operations, such as NASA KSC Ground Processing Operations?

Taxonomy

10. Is there a Human Error Classification system modified specifically for aerospace complex operations, such as NASA KSC Ground Processing Operations?
11. Is there a taxonomy that provides a comprehensive human error analysis that considers multiple causes of human failure (Wiegmann and Shappell, 2001)?
12. What Aerospace industry methodology can ergonomically and cognitively, classify mishap data for complex operations, such as NASA KSC Ground Processing Operations?

Framework

13. What framework conceptual model can be proven to be a viable analysis and classification system to help identify both latent and active underlying contributors and causes of human error in complex operations, such as KSC ground processing operations?
14. Is there a Framework developed for retrospective Mishap analysis and the prediction of potential future human error related mishaps for complex operations, such as KSC ground processing operations?
15. What Framework covers ergonomic, cognitive and organizational factors in human error related mishaps?

Table 13: Literature Review Gap Questions

Research Questions	Human Reliability Analysis	Human Error Taxonomy	Human Error Framework
1. What techniques are capable of answering both qualitative and quantitative questions, by classifying human error producing conditions (qualitative) and calculating future probability of human error occurrence (quantitative)?	X	X	
2. What techniques are easy to use and can be performed by novice analysts?	X		
3. What developed HRA methodologies classify human error contributing factors and error producing conditions to human error related mishaps?	X		
4. What HRA methods provide a quantitative ergonomic approach through analysis of ergonomic factors that may have substantial, negative effects on human performance, for mishaps?	X		
5. What are the identified leading human error causes and contributors to historical Launch Vehicle Ground Processing Operations mishaps and findings based on past mishaps, near mishaps, and close calls?	X		
6. What methodologies have the ability to determine quantifiable human error probability (HEP)?	X		
7. What methodology has specific performance shaping factors (PSF) or Error Producing Conditions that are in line with complex operations, such as Space Ground Processing Operations?	X		
8. What HRA methods are not more resource intensive than others, have low application time and are an ease in application.	X		
9. Is there a Human Error probability methodology modified specifically for aerospace complex operations, such as NASA KSC Ground Processing Operations?	X		

Research Questions	Human Reliability Analysis	Human Error Taxonomy	Human Error Framework
10. Is there a Human Error Classification system modified specifically for aerospace complex operations, such as NASA KSC Ground Processing Operations?		X	
11. Is there a taxonomy that provides a comprehensive human error analysis that considers multiple causes of human failure (Wiegmann and Shappell, 2001)?		X	
12. What Aerospace industry methodology can ergonomically and cognitively, classify mishap data for complex operations, such as NASA KSC Ground Processing Operations?		X	
13. What framework conceptual model can be proven to be a viable analysis and classification system to help identify both latent and active underlying contributors and causes of human error in complex operations, such as KSC ground processing operations?			X
14. Is there a Framework developed for retrospective Mishap analysis and the prediction of potential future human error related mishaps for complex operations, such as KSC ground processing operations?			X
15. What Framework covers ergonomic, cognitive and organizational factors in human error related mishaps?			X

Table 14 provides a summary of the Literature Review and Research Gap. The table shows the Literature Review researchers and the human error areas that are expected to provide answers to the questions in this research.

Table 14: Literature Review Gap

Researchers	Human Reliability Analysis	Human Error Taxonomy	Human Error Framework
Cacciabue, P. C. (2004)	X		X
Cacciabue, P. C. (2013)	X		X
Cao, C. G., & Taylor, H. (2004)	X		X
Chandler, F., Chang, Y., et al. (2006).	X		
Clark, H. H., & Schaefer, E. F. (1989)	X		
Hollnagel, E. (1993).	X		X
Kirwan, B. (1994).	X		X
Kirwan, B., Scannali, S., & Robinson, L. (1996)	X		X
Kirwan, B. (1996)	X		X
Kirwan, B. (1997)	X		X
Kim, B., & Bishu, R. R. (2006)	X		
Konstandinidou, M., Nivolianitou, Z., et al. (2006).	X		X
Li, W., & Harris, D. (2006)		X	
Nelson, W. R., Haney, L. N., et al. (1998)	X		X
Norman, D. A. (1981)	X		X
Rasmussen, J. (1983)	X		
Reason, J. (1990)			X
Reason, J. T. (1997)			X
Reason, J. (1987)			X

Researchers	Human Reliability Analysis	Human Error Taxonomy	Human Error Framework
Reason, J. (2000)			X
Reason, J. T. (2008)			X
Reason, J. T. & Mycielska, K (1982)			X
Reinach, S., & Viale, A. (2006)		X	
Richei, A., Hauptmanns, U., & Unger, H. (2001)	X		X
Rouse, W. B., & Rouse, S. H. (1983)		X	
Salmon, P. M., Lenne, M. G., Stanton, et al. (2010)	X		X
Salvendy, G. (2012)	X		
Shappell, S., Detwiler, C et al. (2007)		X	
Shappell, S. A., & Wiegmann, D. A. (2012)		X	
Sharit, J. (2012)	X		X
Stanton, N. A. (2013)	X		X
Swain, A. D. (1990)	X		X
Swain, A. D. & Guttman, H. E. (1983)	X		X
Wiegmann, D., Faaborg, T., et al. (2005)		X	
Wiegmann, D. A., & Shappell, S. A. (2001)		X	
Williams, J. (1986, April)	X		X
Williams, J. C. (1988, June)	X		X
Yang, C., Lin, C. J., Jou, Y., et al. (2007)	X		X

Researchers	Human Reliability Analysis	Human Error Taxonomy	Human Error Framework
Alexander, T. (2016)	X	X	X

Summary

In 2006, a study was conducted by the NASA Office of Safety and Mission Assurance to assess current Human Risk Assessments (HRA) methods and their applicability in the aerospace industry for potential use and adaptation for current and future NASA systems and missions (Chandler, 2006). Even though the study evaluated the various HRA methods and their applicability to human interfacing for hardware preservation activities, such as ground processing and flight operations, launch, mission control and space flight teams, its primary focus was to offer recommendations for the "quantitative analysis of space flight crew human performance in the support of Probabilistic Risk Assessments (PRAs)" (Chandler, 2006).

The HRA methods identified from this research as suitable for aerospace application when conducting NASA PRAs were: THERP, CREAM, Nuclear Actions Reliability Assessment (NARA) and Standardized Plant Analysis Risk HRA Method (SPAR-H) (Chandler, 2006). However, these methods were identified for PRAs performed on new space flight vehicles system designs and not ground processing hardware and operations that support the vehicle maintenance and processing (Chandler, 2006).

Research shows that organizations such as the Federal Aviation Administration (FAA) and NASA have studied and examined the use of HFACS as a complement to preexisting accident investigation and analysis systems. Results of the HFACS framework have demonstrated that it can be a viable tool for use within the civil aviation arena. However, there are still few system efforts that have examined whether HFACS is a viable tool with the civil aviation industry (Wiegmann and Shappell, 2001).

To date, no documented research has specifically used the HFACS as a model to verify if it is a viable tool for assessing human error within NASA Launch Vehicle Ground Processing Operations. This research will bridge the gap of using this analysis to verify its validity in classifying, assisting, investigating and analyzing human causes of accidents. This works as a part of a larger process to help minimize risks and human error in NASA Ground Processing Operations (Wiegmann, 2001).

In 1998, the Idaho National Engineering and Environmental Laboratory showed that the NASA Ames Research Center and the Boeing Commercial Airline Group developed a human error framework (Framework Assessing Notorious Contributing Influences for Error (FRANCIE)) and a software tool (Tool for Human Error Analysis (THEA)), that were used in analyzing human error in respect to the design of commercial air transportation (Nelson at el., 1998). These methods and tools were recommended for future NASA ground processing operations, but were not applied to Launch Vehicle Program Ground Processing Operations, the new Space Launch System (SLS), International Space Station or any manned or unmanned space missions.

In my thorough research on Human Reliability Analysis and the Human Error assessments and reduction technique (HEART), no documented research to date shows that this technique has been used specifically for assessing human error for NASA Ground Processing Operations.

Justification for HEART and HFACS Methods

For this research, two Human Factor tools were used to classify and assess human error: The Human Error Assessment and Reduction Technique (HEART) (which is a part the Human Reliability Analysis (HRA)) and the Human Factor Analysis Classification System (HFACS).

HEART was chosen for this research because of its quantitative ergonomic approach through analysis of ergonomic factors that may have substantial, negative effects on human performance. This technique can provide human factor specialists with quantitative supported data for design and other recommendations for overall improvement (as cited in Eastman, 2004).

HFACS was chosen for this research because it is considered a comprehensive analysis of human error that takes into account multiple causes of human failure (Wiegmann and Shappell, 2001). One of the advantages to using HFACS is that the generic terms and descriptors allow it to be used for a range of industries and activities (Reinach, 2006). Both methods are explained in further detail in the Methodology chapter.

This introductory chapter provides the background, research gaps, objectives of this study and research variables. The literature review provides a more detailed analysis of the human error performance levels and approaches to identifying and assessing human error.

CHAPTER THREE: PRELIMINARY ANALYSIS

Informal SME Discussions

HEART

Subsequent to the Literature Review and prior to the Experimental procedure, informal Subject Matter Experts (SMEs) discussions were conducted to help identify and categorize examples of historical Launch Vehicle specific ground processing operations tasks generally performed during Ground Processing Operations, with the Generic Tasks listed in the HEART Nominal Human Error Probabilities (HEPs) (Table 8) found in the Literature Review chapter. These specific tasks will match the associated HEART proposed nominal human unreliability probability, which includes their 5th – 95th percentile boundaries. At the same time that we are calculating the HEP, we are also using the EPCs to match with the HFACS conditions to see what umbrella it falls under: unsafe acts, preconditions, etc.

Three (3) KSC Launch Vehicle Ground Processing Operations SMEs, with 34 years, 31 years and 30 years of NASA KSC Ground Processing Operations experience, reviewed the HEART Generic Tasks and provided examples of equivalent related tasks to the 8 HEART Generic Tasks. This modified table is provided in the Methodology chapter (Table 21).

The specific ground processing operation tasks are based on a select number of Scenarios/Locations that have been identified from the greatest frequency of generated mishaps (recorded from the NASA KSC Mishap Data) located within the Launch Complex 39 Ground Processing Operations area.

Launch Vehicle Ground Processing Operation Areas found in the Mishap Data with the highest frequency of occurrence were: Vehicle Assembly Building (VAB), Launch Complex Pad A/B (LC39 A/B) and Orbiter Processing Facilities (OPFs) 1, 2 or 3. These locations were also independently validated by Subject Matter Experts as the locations where the majority of Launch Vehicle Ground Processing Operations work was performed and was used as locations of occurrence for this research's human error related Mishaps.

The Mishap Data includes both NASA and Contractor employees and encompasses, Type B, C, D, and Close Calls Incidents.

The SMEs contributed to the development of the Scenarios' Tasks, Subtasks, and Error Producing Conditions and was used for the subjective AOA assessment of the Error Producing Condition's (EPCs) impact on the Scenario's Ground Processing Operations Tasks. The SMEs also identified corresponding Error Producing Conditions for each Scenario subtask. Some Tasks received more than one Error Producing Condition (EPC). These are identified in Tables 15-20 below.

Table 15: HEART Survey VAB Scenario 1

Task: Performing Booster Hold Down Posts

Subtasks	**Error Producing Conditions**	**HEART Generic Task (Table 21)**	**HEART EPC(s) (Table 9)**
Arming the Booster	Tiredness – Long hours – 3rd Shift	C	35
Connecting the Booster Segments	Accessibility limitations	C	22
Installing Safety Wires	Poor lighting	C	33

Table 16: HEART Survey VAB Scenario 2

Task: Orbiter lift and mate to stack

Subtasks	Error Producing Conditions	HEART Generic Task (Table 21)	HEART EPC(s) (Table 9)
Attaching sling and cranes	Heat (Orbiter lifting required doors to be closed and coveralls worn)	C	27
Lifting and lowering Orbiter into position for mate	Heights, climbing ladders to access platforms	C	27
Install and attaching hardware	Tripping hazards	C	33

Table 17: HEART Survey OPF Scenario 1

Task: Wire Inspections inside the Vehicle, Cargo Bay, under the Floor Board

Subtasks	Error Producing Conditions	HEART Generic Task (Table 21)	HEART EPC(s) (Table 9)
Performing electrical tests	Accessibility limitations – Crawling around on wires bundle	E	22, 27
Repairing/replacing wiring	Physical Stress - twisting and turning	E	27
Installing/removing protective tubing	Confined working space - breakable parts in or on way to/from work area (air ducts, phenolic brackets, tubing)	E	5, 22, 38

Table 18: HEART Survey OPF Scenario 2

Task: Wing Closeouts

Subtasks	Error Producing Conditions	HEART Generic Task (Table 21)	HEART EPC(s) (Table 9)
Elevon actuator servicing	Claustrophobic	F	27
Scheduled inspections	Physical Stress - twisting and turning	F	27
Modifications and repairs	Confined working space - Accessing and backing out of small tight areas with; wire harnesses, tubing, and struts.	F	5, 22, 38

Table 19: HEART Survey Pad A/B Scenario 1

Task: Pad Aft Closeouts

Subtasks	**Error Producing Conditions**	**HEART Generic Task (Table 21)**	**HEART EPC(s) (Table 9)**
Removing access platforms and nonflight items	Confined working space - accessibility limitations; crawling and climbing around/near; wiring bundles/connectors, hydraulic/pneumatic lines, air ducts, etc. Physical stress - twisting and turning	F	5, 22, 27
Inspections, repairs	Noise (air purge)	F	3
Repairs	Poor lighting	F	13, 27, 33

Table 20: HEART Survey Pad A/B Scenario 2

Task: Installing Engines at Pad

Subtasks	**Error Producing Conditions**	**HEART Generic Task (Table 21)**	**HEART EPC(s) (Table 9)**
Installing and torqueing hardware	Accessibility limitations –when open below, required to wear safety harness and lanyard	C	22
Connecting lines (inspect, clean, install seals, hardware install and torque)	Physical stress due to installing vertically	C	22, 27
Electrical connects	Tiredness – 3rd Shift Work	C	35

HFACS

SME discussions were also conducted for identifying possible contributing factors, based off of their expertise and experience in Launch Vehicle Ground Processing Operations. Three SMEs independently reviewed and analyzed the HFACS four levels of human error selected examples of “unsafe acts”, “preconditions of unsafe acts”, “unsafe supervision”, and “Organizational Influences” provided in the literature review of this research. Then their results were discussed and validated collectively. From their assessments, the SMEs determined that the list of selected examples were closely related to the possible Error Producing Conditions that can influence and be a factor is human error generated mishaps. The SMEs also determined that the direct references to aircraft and flight should be omitted and replaced with standards, processes, and procedures which reflect Ground Processing Operations (GPO) historically performed at the Kennedy Space Center. Interestingly, the SMEs stated they felt one of the biggest potential influences to human error mishaps in GPO is confined spaces.

The modified HFACS four levels of human failure and selected examples from the nineteen (19) HFACS causal categories, is provided in the Methodology chapter.

Below is a NASA KSC Ground Processing Operations Human Error Framework of the three (3) Scenarios in this research, the Ground Processing Operations (GPO) Tasks performed at the Kennedy Space Center, the HFACS four levels of human error categories and their relation to the common errors, HFACS sublevels and specific Error Producing Conditions that lead to Human Error mishaps at NASA.

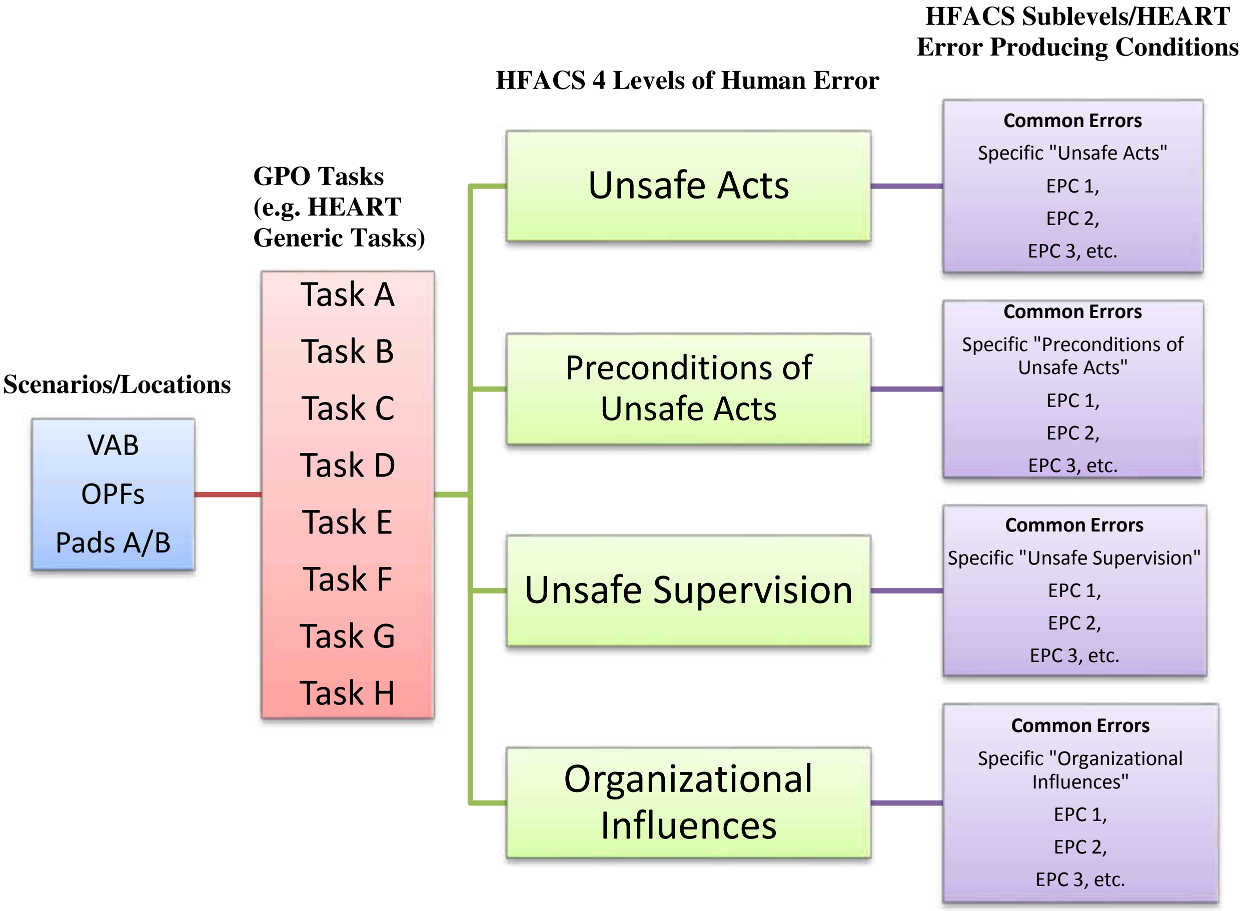


Figure 9: NASA KSC Ground Processing Operations Human Error Framework

CHAPTER FOUR: METHODOLOGY

Research Objective

The purpose of this experiment was to develop a model that can analyze and classify contributing factors to human error mishaps, close calls, or incidents during Launch Vehicle ground processing operations and be used as a tool to accompany preexisting accident investigation and analysis systems in controlling and/or minimizing human error.

For this research, historical data was retrieved from NASA KSC mishaps, close calls, incidents, or accidents and was used to identify contributing factors associated with NASA Ground Processing Operations.

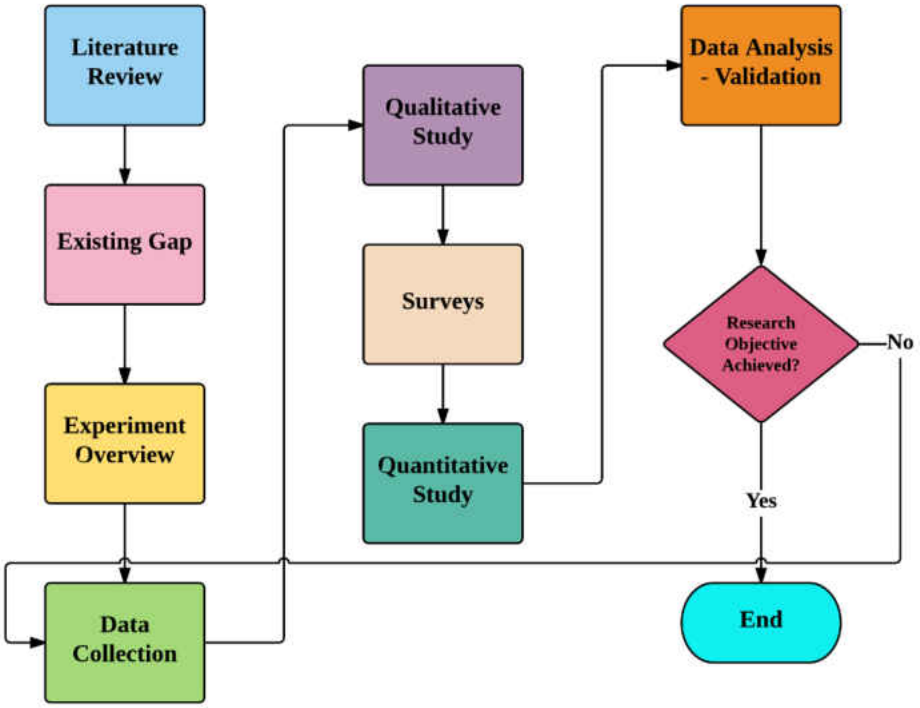


Figure 10: Research Methodology

Literature Review

The literature review in Chapter Two provides a comprehensive review of human error literature, detailed analysis of the human error performance levels, approaches to identifying and assessing human error and a review of existing models of human error and mitigation.

To this date, no documented research has specifically used a standalone or hybrid form of the Human Factor Analysis Classification System (HFACS) and the Human Error Assessments and Reduction Technique (HEART) as a model to verify whether it is a viable tool for assessing human error within NASA Ground Processing Operations (Wiegmann and Shappell, 2001).

Existing Gap

In the Literature Review chapter of this research, questions were asked in order to identify the research gaps concerning retrospectively analyzing mishaps relating to complex space systems such as NASA KSC Ground Processing Operations. The research questions were in the areas of: Human Reliability Analysis, Human Error Taxonomies and Human Error Frameworks. These questions recognized a weakness within the current literature which lacks a proven analysis framework for classifying, assessing, investigating and analyzing human causes of accidents in complex space systems such as NASA KSC Ground Processing Operations.

Experiment Overview

Assessment Approach

Statistically, 70-80% of all aviation mishaps and near mishaps involve human factors (Strauch, 2004), and a study by the U.S. Bureau of Mines also found that nearly 85% of all mining accidents identified human error as a causal factor (Rushworth et al., 1999). For this reason, it is essential to have good assessment approaches and tools to effectively analyze human error research data. For this research, both the Human Error Assessment and Reduction Technique (HEART) (which is a part the Human Reliability Analysis (HRA)) and the Human Factor Analysis Classification System (HFACS) was used as the assessment approaches.

The proposed methodology developed a model to represent the relationship between human error events (i.e. mishaps, incidents, or close calls) and its contributing factors. An experimental design using a modified hybrid HEART and HFACS model to address human error producing conditions during NASA Ground Processing Operations was generated to identify significant contributing factors, and determine Human Error Probabilities and Predicted Probabilities.

The HEART proposed remedial measures, to combat or assist in minimizing the likelihood of the error from occurring, will not be used for this research (Williams, 1986).

The primary focus of this research was to use the HEART method to calculate the Human Error Probability (HEP) and the HFACS method to categorize historical launch vehicle mishap data and build a regression model to predict the probability of future mishaps.

A binary logistics regression was the regression model used to predict the probability of future mishaps based on retrospective historical Launch Vehicle Ground Operation Mishap Data. The human error potential contributing factors were coded from the HFACS four (4) levels of human error and selected examples of human error causes.

Data Collection

Mishap Data

The data was collected from past NASA Launch Vehicle Mishap Reports (from October 1984 – May 2014) entered into the Incident Reporting Information System (IRIS), which is now known as the NASA Mishap Information System (NMIS). This data was used for determining significant contributing factors and predicted probabilities.

Launch Vehicle related Ground Processing Operations data performed in the Vehicle Assembly Building (VAB), Launch Complex Pad A/B (LC39 A/B) and Orbiter Processing Facilities (OPFs) 1, 2 or 3 was identified and pulled from this data. Human error related data was isolated from these data entries to identify the leading occurrence of specific types of human errors at NASA.

Identifying the human error causes that led to the Mishaps recorded in the NASA Mishap Information System (NMIS) is only identifiable by the detail of the data provided in the “Detail Description” portion of the NMIS system. Therefore, each Mishap was individually read and categorized by the “human error” information provided in the description. The qualification of what is considered a “human error” was provided by the HFACS “human error” types. From this data, the occurrences of “human error” identified was the focus of this Dissertation.

Survey Participant Data

To assist with objective data and subjective data for this research’s qualitative study, SME surveys were conducted, collected and used for analysis (Rouse, 1983). The survey requested participants’ subjective Assessed Proportion of Affect (AOA) values for Human Error Probability calculations.

The survey participants (aka subjects) were strategically selected from their years of experience in NASA KSC Ground Processing Operations, Human Factors background and Mishap Control Board experience. This includes engineering, safety and mission assurance personnel and “on the floor” technicians. This will help ensure a balanced response to properly represent the workforce.

Qualitative Study

HEART Method

As previously stated, the survey data collected from Launch Vehicle Ground Processing Operations subjects was used with the HEART method to determine the Human Error Probability of select Ground Processing Operations.

Scenarios/Locations

As stated in the Preliminary Analysis chapter, Scenarios from the Vehicle Assembly Building (VAB), Launch Complex Pad A/B (LC39 A/B) and Orbiter Processing Facilities (OPFs) 1, 2 or 3, was used for this research.

SME Preliminary Analysis

Subject Matter Expert discussions performed in the previous Preliminary Analysis chapter provided examples of specific Ground Processing Operation tasks which were categorized within the eight (8) HEART generic tasks and their associated proposed nominal Human Error Probability (nominal human unreliability) 5th – 95th percentile range. When determining the categorized tasks, the tasks were identified in relation to the three (3) ground processing operations scenarios (VAB, OPFs and Pads A/B).

Below, (Table 21) represents the NASA KSC specific modified examples (in bold, underlined and italicized) provided by the three (3) SMEs from the Preliminary Analysis chapter. This modified table was used with the HEART Error Producing Conditions (Table 9) to calculate the Human Error Probability of the specific KSC Ground Processing Operations tasks.

Table 21: *NASA KSC Specific Modified* *Examples for* HEART Nominal Human Error Probabilities (HEPs) (Williams, 1986)

Letter	Generic Task	Nominal HEP (5th-95th percentile)
A	Totally unfamiliar, performed at speed with no real idea of likely consequences. ***NASA KSC: OJT Trainee working with experienced Technician*** ***NASA KSC: Startracker Removal and Replacement***	0.55 (0.35-0.97)
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures. ***NASA KSC: Operating Procedure Special Instructions allowing flexibility or rework.***	0.26 (0.14-0.42)
C	Complex task requiring high level of comprehension and skill. ***NASA KSC: Launch Vehicle Main Engine bolt stretching*** ***NASA KSC: LH2/LO2 Monoball Installations*** ***NASA KSC: Certified Turbo Pump Operations***	0.16 (0.12-0.28)
D	Fairly simple task performed rapidly or given scant attention. ***NASA KSC: Housekeeping, area cleaning*** ***NASA KSC: Bonding Tile Cleaning*** ***NASA KSC: Thermal Blanket Installation***	0.09 (0.06-0.13)
E	Routine, highly-practiced, rapid task involving relatively low level of skill. ***NASA KSC: Cleaning a GSE cover or panel*** ***NASA KSC: Torque or tighten GSE cover*** ***NASA KSC: GSE connector mates****	0.02 (0.007-0.045)

Letter	Generic Task	Nominal HEP (5th-95th percentile)
F	Restore or shift a system to original or new state following procedures with some checking. ***NASA KSC: Return to print Problem Report (PR), Material Review (MR) Repair, and Non-conformance (N/C) repair.*** ***NASA KSC: Ordnance installation, requiring electrical check prior to installation***	0.003 (0.0008-0.007)
G	Completely familiar, well-designed, highly practiced routine task occurring several times per hour, performed to highest possible standards by highly-motivated, highly-trained and experienced person, totally aware of implication of failure, with time to correct potential error, but without the benefit of significant jobs aids. ***NASA KSC: Area access Monitor for confined space.*** ***NASA KSC: Physical aid, payload blanket installations****	0.0004 (0.0008-0.009)
H	Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system stage. ***NASA KSC: System State Alarm or Alert*** ***NASA KSC: Automated Alarm for improper switch activation***	0.00002 (0.000006-0.0009)

HFACS Method

The SME modified NASA KSC HFACS examples of Human Error Contributing Factors for all four levels of the HFACS are provided in Tables 22, 23 24 and 25.

The SMEs independently reviewed, analyzed and modified the HFACS four levels of human error selected examples of “Unsafe acts”, “Preconditions of unsafe acts”, “Unsafe supervision”, and “Organizational Influences” provided in the Literature Review of this research.

These modified levels were used to categorize the historical KSC Ground Processing Operations Mishaps.

Table 22: ***NASA KSC SME Modified*** **Selected examples of HFACS Preconditions of Unsafe Acts (not an exhaustive list) (Shappell, 2012)**

Condition of Operators	Personnel Factors
Adverse Mental State	**Crew Resource Management**
Loss of situational awareness	Failed to conduct adequate brief
Complacency	Lack of teamwork
Stress	Lack of assertiveness
Overconfidence	Poor communication/coordination with and between ***tasks.***
Poor ***situational awareness***	Misinterpretation of ***procedures and processes***
Task Saturation	Failure of Leadership
Alertness (Drowsiness)	**Personal Readiness**
Get-Home-Itis	Failure to adhere to crew rest requirements
Mental fatigue	Inadequate training
Circadian dysrhythmia	Self-medication
Channelized attention	Overexertion while off duty
Distraction	Poor dietary practices
Adverse Physiological State	Pattern of poor risk judgment
Medical Illness	Environmental Factors
Acrophobia	**Physical Environment**
Physical fatigue	Weather
Intoxication	Altitude
Effects of Over the Counter (OTC)	Terrain
Physical/Mental Limitations	Lighting
Visual Limitations	Vibration
Insufficient reaction time	***Confined Space***
Information overload	Toxins in the ***Hazardous Areas***
Inadequate experience for complexity of situation	**Technological Environment**
Incompatible physical capabilities	Equipment/controls design

Lack of sensory input	Checklist layout
	Display/interface characteristics

Table 23: *NASA KSC SME Modified* Selected Examples of Unsafe Acts of Operators (not an exhaustive list) (Shappell, 2012)

Errors	**Violations**
Skilled Based Errors	**Routine Violations**
Breakdown in visual scan	Inadequate briefing for ***operations***
Inadvertent ***action***	Failed to use ***area access control***
Poor technique/***preparation***	Flew an unauthorized approach
Inadvertent switch management	Violated rules
Bypass checklist item	Failed Visual Flight Rules (VFR) in marginal weather conditions
Omitted step in procedure	Failed to comply with ***procedures and processes***
Over-reliance on automation	Violation of orders, regulations, Standard Operating Procedures
Failed to prioritize attention	Failed to inspect ***vehicle after in flight anomalies***
Task overload	**Exceptional Violations**
Negative habit	Performed unauthorized acrobatic maneuver
Failure to see and avoid	Improper ***task*** technique
Distraction	Failed to obtain valid weather brief
Decision Errors	Exceeded ***specified*** limits
Inappropriate ***action***/***not per*** procedure	Failed to complete ***procedure steps***
Inadequate knowledge of systems, procedures	Accepted unnecessary hazard
Exceeded ability	Not current/qualified for ***task***
Wrong response to emergency	
Perceptual Errors	
Due to visual illusion	
Due to spatial disorientation/vertigo	
Due to misjudged distance, altitude, airspeed, clearance	

Table 24: *NASA KSC SME Modified* Selected examples of Preconditions of Unsafe Supervision (not an exhaustive list) (Shappell, 2012)

Inadequate Supervision	**Failed to Correct a Known Problem**
Failed to provide proper training	Failed to correct inappropriate behavior
Failed to provide professional guidance/oversight	Failed to identify risky behavior
Failed to provide current publication/adequate technical data and/or procedures	Failed to correct a safety hazard
Failed to provide adequate rest period	Failed to initiate corrective action
Lack of accountability	***Failed to stop work due to safety/hazard concern***
Perceived lack of authority	Failed to report unsafe tendencies
Failed to track qualifications	**Supervisory Violations**
Failed to provide operational doctrine	***Failed to ensure qualified crew task (e.g. repair, inspection)***
Failed to track performance	Failed to enforce rules and regulations
Over-tasked/untrained supervisor	Fraudulent documentation
Loss of supervisory situational awareness	Failed to enforce rules and regulations
Planned Inappropriate Operations	Violated procedures
Poor crew pairing	Authorized unnecessary hazard
Failed to provide adequate brief time /supervision	Willful disregard for authority by supervisors
Risk outweighs benefit	Inadequate documentation
Failed to provide adequate opportunity for crew rest	
Excessive tasking/workload	

Table 25: *NASA KSC SME Modified* Selected examples of Organization Influences (not an exhaustive list) (Shappell, 2012)

Resource Management	Organizational Process
Human resources	**Operations**
Selection	Operational tempo
Staffing/manning	Incentives
Training	Quotas
Background checks	Time pressure
Monetary/Budget Resources	Schedules
Excessive cost cutting	**Procedures**
Lack of funding	Performance standards
Equipment/Facility Resources	Clearly defined objectives
Poor ***access***	Procedures/instructions about procedures
Purchasing of unsuitable equipment	**Organizational Climate**
Failure to correct known design flaws ***(e.g. Operational Procedure workaround, EOs to follow that never get updated, etc.)***	**Structure**
Organizational Process Oversight	Chain of command
Established safety programs/risk management programs	Communication
Management's monitoring and check of resources, climate and process at ensure a safe work environment.	Accessibility/visibility of supervisor
Organizations Climate Culture	Delegation of authority
Excessive Task Loading	Formal accountability for actions
Organization customs	**Polices**
Values, beliefs, attitudes	Promotion
Norms and rules	Hiring, firing, retention
	Drugs and alcohol
	Accident investigations

Surveys

Survey subjects were asked to evaluate three (3) NASA KSC Ground Processing Operations Scenarios involving the VAB, OPFs and Pads A/B. The table below (Table 26) was used as a Likert survey scale for the subjects to provide an Assessment of Affect (AOA) value based on the Error Producing Conditions identified for the Scenarios.

Table 26 is a modified Aggregate Risk Value table from a previous study. The table was modified for the Assessment of Affect (AOA) percentage range, proportions of affect and their descriptions (McCauley-Bell and Baiduru, 1996).

The subjects' assessment was based on the level of affect an Error Producing Condition (EPC) has on a specific Ground Processing Operations task (very low, low, moderate, high, and very high). The values were used to determine the Human Error Probability of those tasks.

Survey data for this research was collected on the NASA KSC site via hard copies. The pool of employee candidates were strategically selected from their years of experience in NASA Launch Vehicle Ground Processing Operations, Human Factors background, Mishap Control Board experience, Engineering, Safety and Mission Assurance, and "on the floor" Technicians

A power and sample size for a Paired t Test was used for the survey sample size determination. Due to the fact that there are no past research studies with HEART Assessment proportion of Affects (AOA) for complex systems, a conventional statistical significance value of $\alpha = .05$, power of .80 (Cohen,1992), and a standard deviation 0.5 was used for this research.

The result of the Power curve for Paired t test, indicated a minimum sample size of eighteen (18) participants.

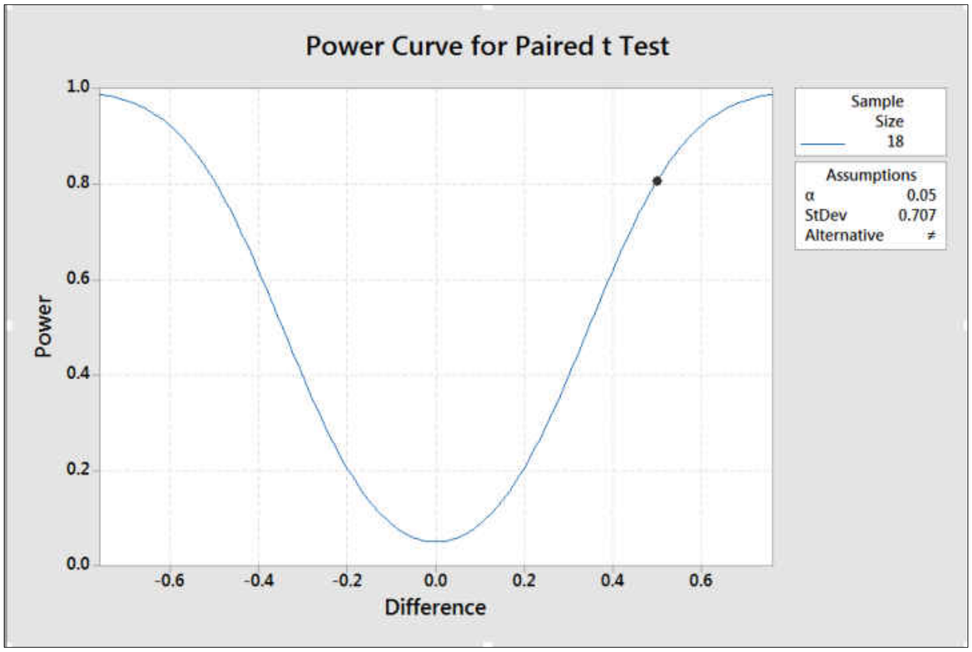


Figure 11: Power Curve for Paired t Test

Table 26: Assessment of Affect (AOA) Range Table (McCauley-Bell & Baiduru, 1996)

Percentage Range (Median)	Proportions of Affect	Description
(.10) 0.00 – 0.20	Very Low Affect	Human error is very unlikely to occur. Strong Controls may be in place.
(.305) 0.21 – 0.40	Low Affect	Human Error is not likely to occur. Controls have minor limitations and uncertainties.
(0.510) 0.41 - 0.60	Moderate Affect	Human Error may occur. Controls exist with some uncertainties.
(0.7) 0.61 - 0.80	High Affect	Human Error is highly likely to occur. Controls have significant uncertainties.
(0.9) 0.81 – 1.00	Very High Affect	Human Error is certain to occur. Controls have little to no affect.

Quantitative Study

Human Error Assessment and Reduction Technique (HEART) Data Analysis

As stated in the Preliminary Analysis chapter, Survey subjects will provide their subjective Assessed Proportion of Affect (AOA) to help determine the negative affect each Error Producing Condition (EPC) has on the tasks performed during the three (3) Scenarios. This data was collected and used to calculate the Human Error Probability for each Scenario question.

Determining the AOA involves providing a percentage rating between 0 and 1 (0.0 representing 0% of the maximum EPC effect and 1 representing 100% of the maximum EPC effect) for each EPC. The ratings offered are based upon the subjective judgment of the SMEs and survey subjects involved (Stanton, 2013).

To determine if there is a statistical difference between the AOA values generated by the SMEs, an ANOVA test on the mean values for the AOAs was used. This test was performed to compare the mean values of the Assessed Proportion of Affect (AOA) values generated by the Survey Subjects.

The null hypothesis is that all AOA means are equal and the null alternative is that at least 1 mean is not equal.

H_0: $\mu_{\text{AOA 1}} = \mu_{\text{AOA 2}} = \mu_{\text{AOA 3}} = \mu_{\text{AOA 4}}$, etc.

H_1: At least 1 not equal.

Calculating the Human Error Probability for GPO Tasks using the HEART method

HEART Process for Experiment (Williams, 1988)

1. The full range of sub-tasks that a human operator would be required to complete within in a given task were identified. During the Preliminary process, tasks were identified from the three (3) scenarios (VAB, OPFs and Pad A/B).
2. The tasks were then classified into the generic tasks provided within the HEART process with proposed nominal human unreliability for these tasks. These are the nominal Human Error Probability (HEP) scores for the particular task with calculated 5th – 95th percentage bounds (see Table 21). Specific details to these generic task categories were determined by consulting local subject matter experts (SMEs).
3. The obvious EPCs that had a high possibility or probability to have a negative effect on a particular situation was considered. This indicated that the EPCs with the greatest negative impact are the EPCs that need to be addressed for risk reduction and mitigation. The EPCs identified was also compared to the equivalent HFACS conditions.
4. The Assessed Proportion of Affect (AOA) for each task was determined by SME Survey Participants (aka subjects), in which the affect proportions ranged from 0 to 1. The AOA is a subjective assessment of the Error Producing Condition's (EPC) affect or impact on a specified Generic Task. The AOA Table range (Table 26) represents the percentage of this affect (e.g. 0.1 = 10% of the EPC maximum effect). This value

was a part of the assessed effect for each error producing condition of the given task. This was established in the survey given to the SMEs.

5. A final HEP was then calculated, by multiplying the HEART nominal HEP of the task by each of the calculated assessed effects. The calculated effect was determined below:

$$\begin{aligned} &Calculated\ Assessed\ Factor\ Effect \\ &\qquad = \big((Max\ Effect - 1)\ \times Proportion\ of\ Affect\big) + 1 \\ &HEP = (Type\ of\ Task\ generic\ error\ probability) \\ &\qquad \times (Assessed\ Factor\ effect(s)) \end{aligned} \tag{3}$$

6. From here a HEP value can identified the EPCs that cause a higher probability for an error to occur and possible remedial strategies to minimize the risk of future human error occurrence.

HEART HEP Calculation Example

Below is an example of calculating the HEP using the HEART method. The AOA is what affect EPCs #1 and #2 (Unfamiliarity and Time Pressure) have on Generic Task F (Restore/Shift to original/new state following procedures, with some checking). The AOA ranges from 0.0 to 1.0, in which the 0.0 represents a 0% affect and the 1.0 represents a 100% affect.

Table 27: HEART Calculation Example (Kirwan, 1996)

EPC	Maximum Effect	Assessed Proportion of Affect	Assessed Factor – Calculation
Unfamiliarity	X 17	0.1	((17-1)0.1) + 1 = 2.6
Time Pressure	X 11	0.3	((11-1)0.3) +1 = 4.0
HEP = 0.003 (Task type F probability) x 2.6 x 4.0 = 0.03			

$$Calculated\ Assessed\ Factor\ Effect = \left((Max\ Effect - 1)\ \times Proportion\ of\ Affect\right) + 1 \tag{4}$$

$$HEP = (Type\ of\ Task\ generic\ error\ probability) \times (Assessed\ Factor\ effect(s))$$

Human Factors Analysis and Classification System (HFACS) Data Analysis

Binary Logistics Regression

To identify the significant factors that contributed to human error related Ground Processing Operations mishaps, a binary logistic regression was used for the statistical analysis approach. From the binary logistics regression method, significant factors were identified and a regression model created and evaluated in order to determine its validity. The regression model was be analyzed to determine if the model is adequate.

The binary logistics regression dependent variable was the Mishap, with Mishaps (Type B, C, D or incident) equaling a value of 1 and Close Calls equaling a value of 0.

Y, was the binary response variable, presence or absence of a mishap

$Y = 1$ if a Mishap/Incident occurred

$Y = 0$ if a Close Call occurred

$X = (X_1, X_2, X_3, \ldots..X_k)$

The p value results (less than 0.05) from the binary logistic regression results was analyzed to determine the significant factors contributing to the human error mishaps during ground processing operations. The Goodness-of-Fit test was assessed to determine how effective the model is.

Simple Linear Regression (Probabilistic) Model

(5)

$$y = \beta_0 + \beta_1 x + \varepsilon$$

y: dependent variable
β_0: interception at y axis
β_1: Line gradient
x: Predictor variable, independent variable
ε: Error
x predicts y

Mean value of y, for a given value of x

(6)

$$E(Y \backslash x) = \beta_0 + \beta_1 x$$

In this equation, the Y represents the outcome variable, the x represents the value of the independent variable, and the β represents the model parameters.

Binary Logistic Regression Model equations

The equation below is probability the outcome will occur (e.g. mishaps) is:

(7)

$$\ln\left(\frac{\hat{p}}{1-\hat{p}}\right) = \beta_0 + \beta_1 x$$

Or

(8)

$$\widehat{p} = \frac{\exp(\beta_0 + \beta_1 x)}{1 + \exp(\beta_0 + \beta_1 x)} = \frac{e^{\beta_0 + \beta_1 x}}{1 + e^{\beta_0 + \beta_1 x}}$$

The probability of the outcome not occurring is:

$$1 - \hat{p} = \frac{1}{1 + \exp(\beta_0 + \beta_1 x)} \tag{9}$$

Once the various HFACS sub-preconditions were classified, a binary logistics table was generated for the year and the occurrence of the error producing conditions. Below is an example chart of the collected data.

<u>Binary Logistics Table</u> (**Example only**)

$Y = 1$ or 0

X_1 = Physical Environment (Lighting)

X_2 = Adverse Mental State (Get Home It-is)

X_3 = Adverse Physiological States (Physical Fatigue)

X_4 = Skilled Based Error (Distraction)

X_5 = Skilled Based Error (Task Overload)

X_6 = Failure to Correct a Known Problem (Failed to initiate corrective action)

X_7 = Failure to Correct a Known Problem (Failure to correct safety hazard)

X_8 = Supervisory Violation (Failed to enforce rules and regulations)

X_9 = Planned Inappropriate Operations (Poor Crew Planning)

X_{10} = Equipment/Facility Resources (Poor Access)

X_{11} = Organizational Process (Time Pressure)

X_{12} = Resource Management (Staffing/Manning)

Table 28: Example of Binary Logistics Table for Statistical Analysis

	Unsafe Acts		Preconditions of Unsafe Acts			Unsafe Supervision				Organizational Influences			MISHAP/ CLOSE CALL
Year	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	Y
1985	1	0	0	1	0	0	0	1	0	0	1	1	1
1986	0	1	0	1	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	1	1
1988	0	0	1	0	0	0	0	1	0	0	1	0	1
1989	0	0	0	1	1	0	0	0	0	0	0	1	0
1990	0	0	0	1	0	1	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	1	0	0	0	0	0	1
1992	0	0	0	0	0	0	0	1	1	0	1	0	1
1993	0	0	0	0	0	0	0	0	0	1	1	1	1
2013	0	0	1	1	0	0	0	1	1	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0	1	1

Data Analysis - Validation

Triangulation

Triangulation, which is defined as “cross checking” information and conclusions through multiple procedures of sources, data and research methods (Johnson, 1997), was used for model validation.

The binary logistics regression model was used to analyze contributing factors to Mishap occurrence and was compared to the results of the Human Error Probability (HEP) values calculated from the HEART methodology.

As a secondary comparison for the HEART Human Error Probability (HEP) values, an ANOVA One-Way test and repeated measures of data was performed to compare the mean values of the Assessed Proportion of Affect (AOA) values generated by the SMEs.

The binary logistic regression model “Goodness-to-Fit” tests, “Odds Ratios” and “Binary Fitted plots” was analyzed to determine if the model is adequate.

CHAPTER FIVE: RESULTS AND DISCUSSION

Summary

This chapter provides an overview of the research question, hypothesis and discusses the research findings and results.

Using the HFACS tool to categorize the Ground Processing Operations (GPO) human error related mishaps from October 1984 – May 2014, two binary logistics regression models were generated. The first binary logistics regression model with eight (8) categorized human error contributing factors, identified two (2) as significant factors (perceptual error and decision based error). To simplify the model, the binary logistics regression analysis was performed again with stepwise backward elimination. As a result, four (4) human error contributing factors were identified as statistically significant (skilled based error, perceptual error, decision based error, and exceptional violation).

The Goodness-to-Fit tests, Odds Ratios, and Main Effect Plots in both Regression models, all indicated that they were good models. Predicted probabilities were calculated from both generated binary logistics regression model equations. The predicted probabilities calculated the probability of a mishap for each contributing factor's occurrence, in which a "1" indicated an occurrence and a "0" indicated a nonoccurrence of that event.

These predicted values were compared and confirmed as consistent with related Mishap literature reviews and research performed in similar fields, such as the Aviation and Aeronautics industry. Generated Binary Fitted Plots from the regression analysis also confirmed and validated the predicted probabilities.

The HEART Method was also used to calculate predicted Human Error Probabilities (HEP). The HEART HEP values generated from the survey data identified “Physical Limitations” related Error Producing Conditions (EPCs) as the contributors to the highest Human Error Probabilities (22% - 26%). In comparison, this is also in line with the predicted probably of 33% from the HFACS binary logistics regression model (see Table 29) for “Physical Environment” Contributing Factors (e.g. Confined Space).

Together these two methods were used to determine predicted human error probability within NASA Ground Processing Operations (GPOs), in order to identify areas that need attention for mitigating future potential Mishap occurrences.

The remainder of this chapter will explain the process and predicated probabilities that were generated, provide information on the survey results and demographics of the survey participants.

HFACS Human Error Probability Results and Analysis

Binary Logistics Regression Model Results

In this research, binary logistics regression was used to analyze contributing factors to Mishap occurrence.

The p value results from the binary logistic regression results were analyzed to determine the significant factors contributing to the human error mishaps during ground processing operations. The Goodness-to-Fit tests were assessed to determine how good the model was.

When performing the binary logistics regression analysis, the occurrence of a Mishap (represented by and “0” or “1”) was identified as the “response” and “response event.” Each of the HFACS sub level categories from the HFACS four levels of human failure were selected as categorical (non-continuous) predictors. However, when entering all 19 categorical predictors into Minitab for the binary logistic regression model, an error was generated, due to the requirement that the categorical predictors must have more than one distinct value. Subsequently, eleven (11) sublevel categories were removed from the binary regression analysis and classified as having no significant impact on human error related mishaps during Launch Vehicle ground processing operations during the recorded data time period. This was due to the fact that there were no events for eleven (11) of the HFACS factors.

Performing the regression analysis generated a model in which the predicted probability of each occurrence was calculated. Below are the HFACS regression model values. Three Goodness-of-Fit tests were performed in this analysis: Deviance, Pearson and Hosmer-Lemeshow.

The Deviance and Pearson Goodness-of-Fit models assess the discrepancy between the current model and full model. The Hosmer-Lemeshow Goodness-of-Fit test compares the observed expected frequencies of events and non-events to assess how well the model fits the data. For this analysis the Deviance p value is 0.723, Pearson p value is 0.380 and the Hosmer-Lemeshow p value is 0.897. For all three Goodness-to-Fit tests the p values are greater than 0.05, indicating there is no significant deviation and the model fits the data.

Table 29: Identified HFACS Regression Model Values

HFACS Human Error Factor	Fitted Probability	P value	Odds Ratio	Beta Coefficient (N=414) $\beta_0 = -3.31$
Skilled Based	**27%**	0.070	10.15	$\beta_1 = 2.32$
Decision Based	**41%**	0.037	18.72	$\beta_2 = 2.93$
Perceptual Errors	**47%**	0.009	24.25	$\beta_3 = 3.20$
Routine Violation	**9%**	0.444	2.67	$\beta_4 = 0.98$
Exceptional Violation	**36%**	0.052	15.67	$\beta_5 = 2.75$
Crew Resource Management	**14%**	0.283	4.38	$\beta_6 = 1.48$
Physical Environment	**33%**	0.138	13.72	$\beta_7 = 2.62$
Supervisory Violation	**24%**	0.226	8.61	$\beta_8 = 2.15$

Binary Logistics Regression Model with Stepwise Backward Elimination

For the original binary logistics expression in this research all factors with events were used. In an effort to simplify the model, Stepwise Backward elimination was used. Backward elimination, is a process that begins with all candidate variables, then tests the deletion of each variable using a selected model comparison criterion. This deleting process is repeated, until no further improvement is possible (Fox, 2015). Below are the results from the backward elimination process.

For the Beta coefficients of the regression model, the constant (which is the β_0) is -2.242 and the HFACS Human Error factor Beta coefficients (β_x) are: Skill Based $\beta_1 = 1.264$, Decision Based $\beta_2 = 1.887$, Perceptual Errors $\beta_3 = 2.335$, Exceptional Violation $\beta_4 = 1.682$.

For the factors in this regression model, the p values are: Skilled Based p = 0.000, Decision Based p = 0.005, Perceptual Errors p = 0.000, Exceptional Violation p = 0.013. From the p values, the Skilled Based Error, Decision Based Error, Perceptual Error and Exceptional Violation p values are < 0.05, thus all statistically significant.

Table 30: Identified HFACS Regression Model with Backward Elimination P Values and Beta Coefficients

HFACS Human Error Factor	**P value**	**Beta Coefficient** (N=414) $\beta_0 = -2.242$
Skilled Based	0.000	$\beta_1 = 1.264$
Decision Based	0.005	$\beta_2 = 1.887$
Perceptual Error	0.000	$\beta_3 = 2.335$
Exceptional Violation	0.013	$\beta_4 = 1.682$

For the Odds Ratio, each Human Error Factor Beta coefficient indicates that for each additional occurrence of a HFACS Human Error factor, the odds of this measurement falling into the "1" category (which represents a Mishap/Incident Occurrence), increases by that value. This value is derived by calculating the exponential of the Beta Coefficient. So, for the Skilled Based Error β_1, the additional occurrence on this factor increases the odds of a mishap/incident occurrence by 3.54 ($e^{1.264} = 3.54$). The odds ratios for β_1 through β_4 are: Skilled Based 3.54, Decision Based 6.60, Perceptual Errors 10.33, and Exceptional Violation 5.38.

Table 31: HFACS Regression Model with Backward Elimination Odds Ratio

HFACS Human Error Factor	**Odds Ratio**
Perceptual Errors	10.33
Decision Based	6.60
Exceptional Violation	5.38
Skilled Based	3.54

Of these odds ratios, the highest values rank from Perceptual Errors at 10.33, followed by Decision Based Errors at 6.60, Exceptional Violations at 5.38, and Skilled Based at 3.54, in which they are all statistically significant.

Goodness-of-Fit Tests

For all three Goodness-to-Fit tests, the p value was greater than 0.05, indicating that we want to reject the null hypotheses (H_0), which states H_0: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do not have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in NASA ground processing operations. This indicates that there is no significant deviation and the model fits the data.

Table 32: HFACS Goodness-of-Fit Tests with Backward Elimination P Values

Goodness-of-Fit tests	P value
Deviance	0.725
Pearson	0.458
Hosmer-Lemeshow	0.795

Binary Fitted Plots

The Binary Fitted Line Plots for each Human Error Factor are listed below. From the plot observations, the x axis displays the impact of error an occurrence (either “0” indicating no occurrence, or “1” indicating an occurrence). The Y-axis displays the Probability of a Mishap Event occurrence. All of the observations (which are represented by the blue dots) have a probability of either a “1” indicating a Mishap occurred or “0” a Mishaps did not occur. The burgundy line on the graph reveals the probability that a mishap will occur based on the type of human error factor manifested. From the Skilled Based Error Binary Fitted Plot it is observed that when a Skilled Based Error occurs (1), there is about a 25% probability of a Mishap occurrence, around 40% for Decision Based, 50% for Perceptual Errors and 35% for Exceptional Violation.

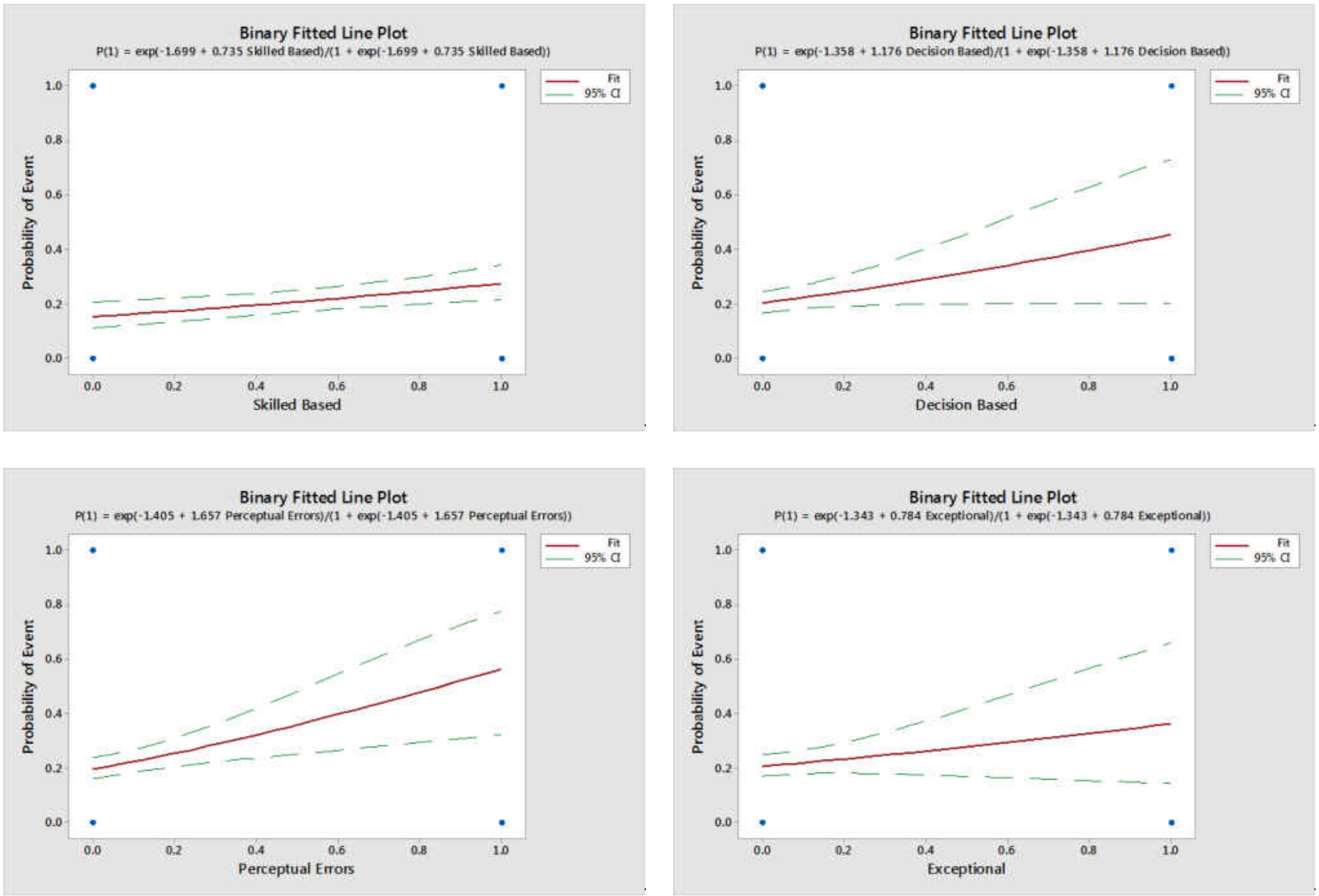


Figure 12: Binary Fitted Line Plots

Prediction from the Regression Model

The Binary Logistic Regression Expression for this Model is P (1) = e $^{(Y')}$ / (1 + e $^{(Y')}$), with the Y′ equal to: **(10)**

$$Y' = -2.242 + 1.264\,\beta_1\,(skilled\ based) + 1.887\,\beta_2\,(decision\ based)$$
$$+\,2.335\,\beta_3\,(perceptual\ errors) + 1.682\,\beta_4\,(exceptional\ errors)$$

In order to use this model for probability prediction, the occurrence of human error events are entered into the equation. Using the model equation, which is the same as Equation 8 for calculating the binary regression model probability we have:

(11)

$$\hat{p} = \frac{\exp(\beta_0 + \beta_1 x)}{1 + \exp(\beta_0 + \beta_1 x)} = \frac{e^{\beta_0 + \beta_1 x}}{1 + e^{\beta_0 + \beta_1 x}}$$

$$= \frac{e^{-2.242 + 1.264\,Skilled\ Based + 1.887\,Decision\ Based + \cdots + 1.682\,Exceptional}}{1 + e^{-2.242 + 1.264\,Skilled\ Based + 1.887\,Decision\ Based + \cdots + 1.682\,Exceptional}}$$

To predict the probability of a Mishap occurrence based on the HFACS Human Error Factor "Skilled Based" occurrence (1), the following values were entered into the Equation.

Table 33: HFACS Factor with Backward Elimination Binary X Values

HFACS Factor	X Values			
Skilled Based	1	0	0	0
Decision Based	0	1	0	0
Perceptual Errors	0	0	1	0
Exceptional Violation	0	0	0	1

Table 34: Binary Logistics Regression with Backward Elimination Prediction Y for given X value

Logistic Regression with Backward Elimination Prediction Y for given X Value				
X-Variables	*Coefficients*	*X-values (For: **Skilled Based**)*	*Product*	
Intercept	-2.242	1	-2.242	
Skilled Based	1.264	1	1.264	
Decision Based	1.887	0	0	
Perceptual Errors	2.335	0	0	
Exceptional Violation	1.682	0	0	
			-0.978	log(p/(1-p)) = Sum of products in column
			0.273288808	Probability Formula = exp(-0.978)/(1+exp(-0.978))
			27%	

The Remaining Probability Values were calculated and are in Table 35 below. When comparing the calculated Fitted Probability, the values are consistent with the Binary Fitted Line Plots.

Table 35: Identified HFACS Regression Model Fitted Probability with Backward Elimination Values

HFACS Factor	**Fitted Probability**	SE (Standard Error) Fit	Lower 95% Confidence Interval	Higher 95% Confidence Interval
Skilled Based	**27%**	3%	21%	34%
Decision Based	**41%**	15%	17%	71%
Perceptual Errors	**52%**	13%	29%	75%
Exceptional Violation	**36%**	15%	14%	66%

HFACS Factorial Plots

Figure 13 displays the main effects plots for this research's mishaps/incidents data. When analyzing the slopes of the main effects plots, the slope indicates the presence and significance of a main effect. The more the slope line is non horizontal, the more of a main effect is present. The greater the difference in the positions of the plotted point, indicates the greater the significance of the main effect. The Skilled based, Decision based, Perceptual and Exceptional Errors have strong (non-parallel to the x axis) slopes, low p values and a range of 27% - 52% probability of mishap occurrence when present, etc. This indicates that as the Human Error event increases, the probability of the mishap event increases.

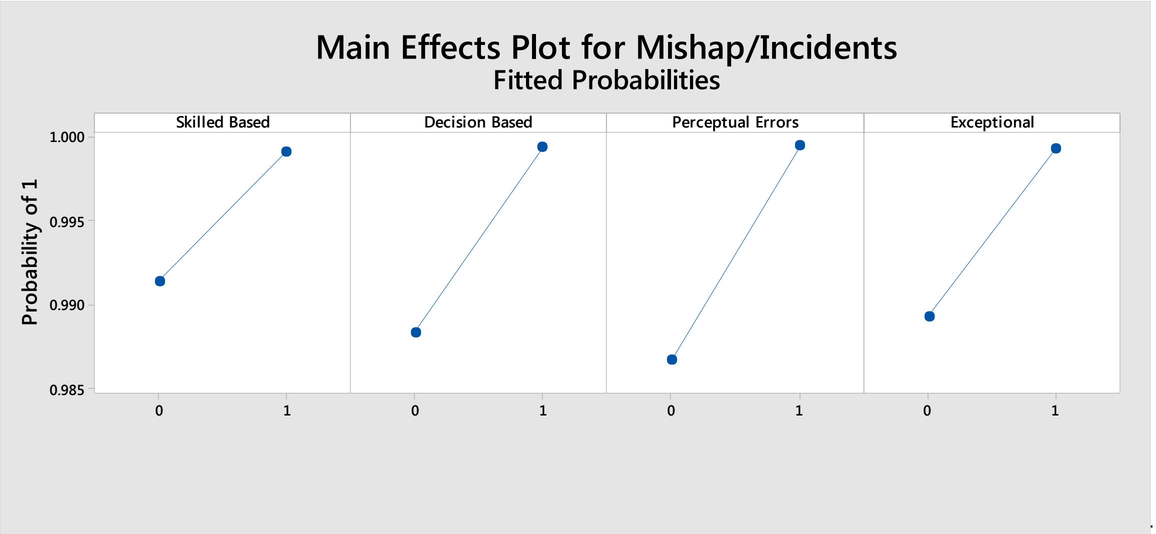


Figure 13: Main Effects Plot for Mishap/Incidents with Backward Elimination

Participant Survey Results

For this research survey, the subjects were asked to answer a total of 21 questions. Of the 21 questions, they were asked to evaluate and answer 18 questions from 3 NASA Launch Vehicle Ground Processing Operations Scenarios involving the VAB, OPFs and Pads A/B. There were a total of 41 survey participants. Table 26 was used as a survey scale for the subjects to provide an Assessment of Affect (AOA) value based on the Error Producing Conditions identified for the Scenarios. The subjects were asked to provide their assessment based on the level of affect an Error Producing Condition (EPC) may have on a specific Ground Processing Operations task (very low, low, moderate, high, and very high).

Below are graphs depicting the survey participants' job function titles, years/experience working at the Kennedy Space Center, and their years/experience working in Ground Processing Operations (GPO). Survey participant #39 did not record their demographic data on their survey, so it was removed from the years at KSC and in GPO line graphs. The survey participants' average years working at KSC is 23.9875 years and their average years working at KSC supporting Ground Processing Operations is: 19.8125 years.

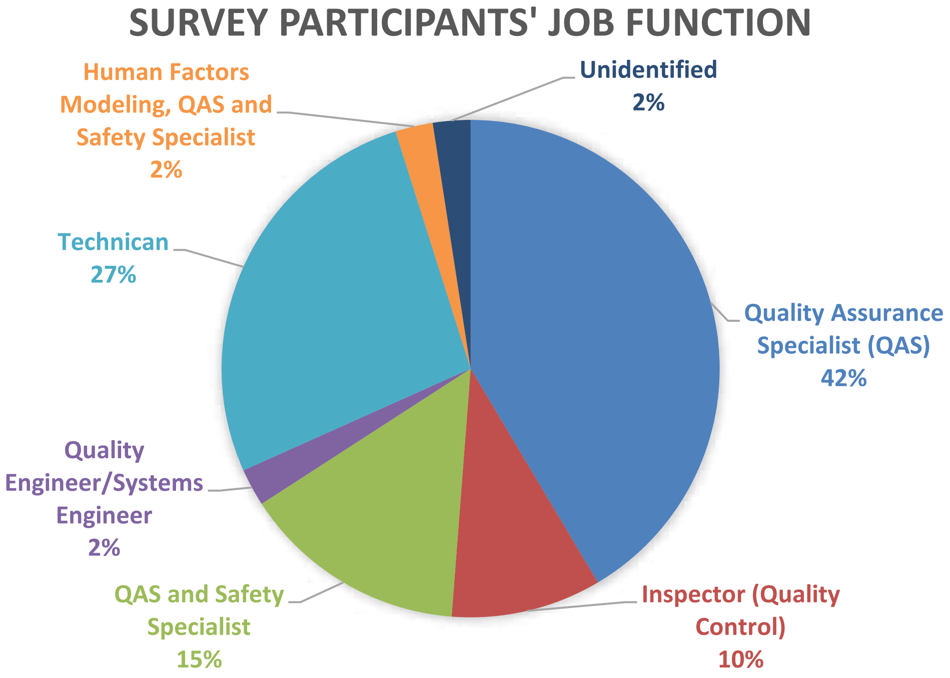


Figure 14: Survey Participants' Job Function

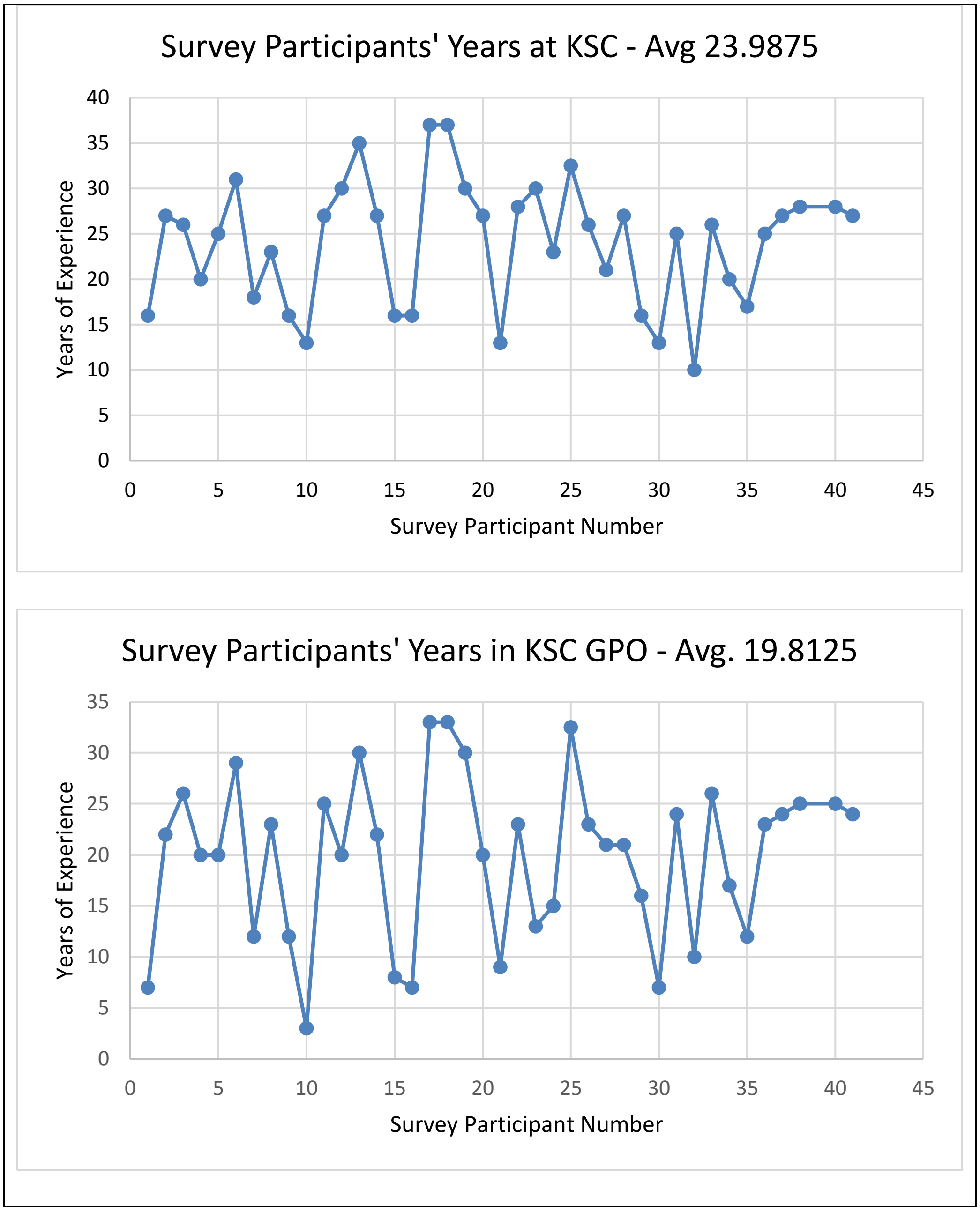


Figure 15: Survey Participants' Years at NASA KSC and KSC GPO

HEART Human Error Probability (HEP) Results

Below in Table 36 are the values and Assessed Proportion of Affects (AOA) generated by the survey participants to calculate the Human Error Probability (HEP).

Table 36: HEART Survey Participants Assessed Proportion of Affect (AOA)

Survey Question Number	Scenarios	Generic Task, HEART Nominal HEPs (Table 21)	Error Producing Conditions	HEART EPC(s) (Table 9)	Survey Participant's Average Assessment (AOA)
4	VAB - Scenario 1	C	Tiredness – Long hours – 3rd Shift.	35	**0.55641026**
5	VAB - Scenario 1	C	Accessibility limitations.	22	**0.495**
6	VAB - Scenario 1	C	Poor lighting.	33	**0.529872**
7	VAB - Scenario 2	C	Heat (Orbiter lifting required doors to be closed and coveralls worn).	27	**0.421711**
8	VAB - Scenario 2	C	Heights, climbing ladders to access platforms.	27	**0.397179**
9	VAB - Scenario 2	C	Tripping hazards.	33	**0.463077**
10	OPF - Scenario 1	E	Accessibility limitations – Crawling around on wires bundle.	22, 27	**0.62561**
11	OPF - Scenario 1	E	Physical Stress - twisting and turning.	27	**0.538902**
12	OPF - Scenario 1	E	Confined working space - breakable parts in or on way to/from work area (air ducts, phenolic brackets, tubing).	5, 22, 38	**0.597195**
13	OPF - Scenario 2	F	Claustrophobia.	27	**0.603125**

Survey Question Number	Scenarios	Generic Task, HEART Nominal HEPs (Table 21)	Error Producing Conditions	HEART EPC(s) (Table 9)	Survey Participant's Average Assessment (AOA)
14	OPF - Scenario 2	F	Physical Stress - twisting and turning.	27	**0.529**
15	OPF - Scenario 2	F	Confined working space - Accessing and backing out of small tight areas with; wire harnesses, tubing, and struts.	5, 22, 38	**0.58475**
16	Pad A/B - Scenario 1	F	Confined working space - accessibility limitations; crawling and climbing around/near; wiring bundles/connectors, hydraulic/pneumatic lines, air ducts, etc. Physical stress - twisting and turning.	5, 22, 27	**0.529146**
17	Pad A/B - Scenario 1	F	Noise (air purge).	3	**0.412683**
18	Pad A/B - Scenario 1	F	Poor lighting.	13, 27, 33	**0.552439**
19	Pad A/B - Scenario 2	C	Accessibility limitations – when open below, required to wear safety harness and lanyard.	22	**0.47622**
20	Pad A/B - Scenario 2	C	Physical stress due to installing vertically.	22, 27	**0.448205**
21	Pad A/B - Scenario 2	C	Tiredness – 3rd Shift Work.	35	**0.573415**

Of the Human Error Probability (HEP) values calculated from the surveys, there were three values that had the highest probability. The HEP values were from survey questions 5, 19, and 20, which all had a probability above 20%. These three questions and their scenario are below.

VAB Scenario 1

Task: Performing Booster Hold-down Posts

Subtasks	Error Producing Conditions
Arming the Booster	Tiredness – Long hours – 3rd Shift.
Connecting the Booster Segments	Accessibility limitations.
Installing Safety Wires	Poor lighting.

Question 5: What proportion of affect would "Accessibility Limitations" affect performing Booster Hold-down Posts and any of its Subtasks?

Pad A/B - Scenario 2

Task: Installing Engines at Pad

Subtasks	Error Producing Conditions
Installing and torqueing hardware	Accessibility limitations –when open below, required to wear safety harness and lanyard.
Connecting lines (inspect, clean, install seals, hardware install and torque)	Physical stress due to installing vertically.
Electrical connects	Tiredness – 3rd Shift Work.

Question 19: What proportion of affect would "Accessibility limitations –when open below, required to wear safety harness and lanyard" affect performing the Installation of Engines at the Pad and any of its Subtasks?

Question 20: What proportion of affect would "Physical stress due to installing vertically" affect performing the Installation of Engines at the Pad and any of its Subtasks?

Figure 16: HEART Survey Questions with Highest Human Error Probabilities (HEPs)

Within these three questions with the highest HEP value, there is a commonality between them. Each of the questions have error producing conditions that deal with accessibility limitations, physical stress and tiredness. Poor lighting deals with the physical environment contributing factor.

Table 37: HEART Survey Calculated Human Error Probabilities (HEPs)

Survey Question	EPC(s) (Table 9)	Max. Effect #1	Max. Effect #2	Max. Effect #3	Assessed Proportion of Affect (average)	Assessed Factor – Calc. #1	Assessed Factor – Calc. #2	Assessed Factor – Calc. #3	Generic Task, HEART Nominal Human Error Prob. (HEPs) (Table 21)	Generic Task, HEART Nominal Human Error Prob. Value (HEPs) (Table 21)	HEP %
4	35	1.1			0.556410	1.055641			C	0.16	17%
5	22	1.8			0.495	1.396			C	0.16	22%
6	33	1.15			0.529872	1.079481			C	0.16	17%
7	27	1.4			0.421711	1.168684			C	0.16	19%
8	27	1.4			0.397179	1.158872			C	0.16	19%
9	33	1.15			0.463077	1.069462			C	0.16	17%
10	22, 27	1.8	1.4		0.62561	1.500488	1.250244		E	0.02	4%
11	27	1.4			0.538902	1.2155608			E	0.02	2%
12	5, 22, 38	9			0.597195	5.77756			E	0.02	12%
13	27	1.4			0.603125	1.24125			F	0.003	0%
14	27	1.4			0.529	1.2116			F	0.003	0%
15	5, 22, 38	9	1.8		0.58475	5.678	1.4678		F	0.003	3%
16	5, 22, 27	9	1.8	1.4	0.529146	5.233168	1.423317	1.211658	F	0.003	3%
17	3	10			0.412683	4.714147			F	0.003	1%
18	13, 27, 33	4	1.4	1.15	0.552439	2.657317	1.220976	1.082866	F	0.003	1%
19	22	1.8			0.47622	1.380976			C	0.16	22%
20	22, 27	1.8	1.4		0.448205	1.358564	1.179282		C	0.16	26%
21	35	1.1			0.573415	1.057342			C	0.16	17%

Model Validation

HFACS Model

The HFACS model was verified by consistency and comparison to other research conducted with the HFACS Classification system and data in the aeronautics field.

Research performed on Human Factors in Remotely Piloted Aircraft (RPA) Operations, conducted a HFACS analysis on 221 Mishaps over a 10 year period (Tvaryanas, 2006). In this study, the HFACS model was modified specifically for the Department of Defense and was used to code their mishaps. A binary regression model was created and used for predicting Operator Error (Tvaryanas, 2006).

Within the Human Factors Remote Pilots Aircraft (RPA) study's summary of prior RPA mishap studies, 3 of the 5 studies' largest percentage of mishaps fell into the "Unsafe Acts" (Skilled Based, Decision Based, Routine Violation, Exceptional and Perceptual) Category (Tvaryanas, 2006). This is consistent with the overall percentage levels of HFACS Factor Events in this study. Figure 17 below shows the percentages of the eight categories that the Ground Processing Operations Mishaps fell into. The "Unsafe Acts" HFACS categories (Skilled Based, Decision Based, Routine Violation, Exceptional and Perceptual) comprise the majority of the Ground Processing Operations Mishaps.

Overall, of the 221 Mishaps reviewed in the RPA Study, 60.2% of the mishaps were associated with operations-related human causal factors (Tvaryanas, 2006).

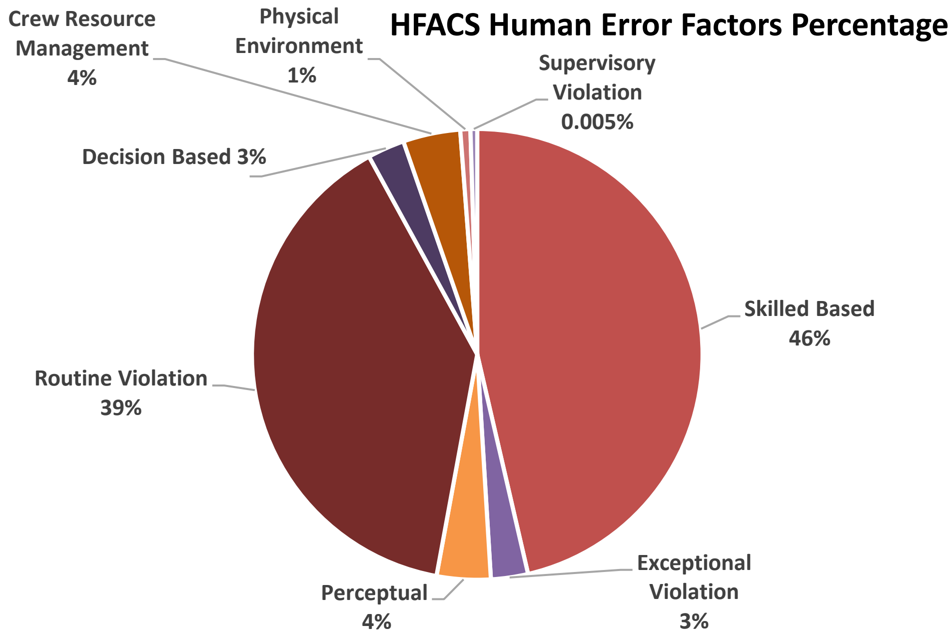


Figure 17: HFACS Human Error Factors Percentages for KSC GPO

As discussed in the Literature Review chapter, a study of 523 accidents within the Republic of China (ROC) Air Force from 1978-2002 (24 years), revealed several significant associations between errors at the operation level and organization inadequacies (Li, W., 2006).

The frequency counts and inter-rater reliability statistics for the Republic of China (ROC) Air Force's study were generated for all 523 accidents. Of the four categories and subcategories, the sublevel errors that had the ten (10) highest frequencies of occurrence (when ranking order of highest frequency) are in the graphs below, with "Unsafe Acts (Level 1)" and "Preconditions for unsafe acts (Level 2)" being the leading HFACS Categories.

When comparing the highest frequency of occurrences between the Republic of China (ROC) Air Force study and the KSC Ground Processing Operations (GPO) study, the highest frequencies of occurrence are consistent, due to the majority of human error occurrence falling within the "Unsafe Acts (Level 1)" and "Preconditions for unsafe acts (Level 2)" HFACS Categories. Two graphs comparing the studies are presented below.

Level 1: Unsafe Acts (of Operators)
Level 2: Preconditions for unsafe acts (e.g. latent conditions)
Level 3: Unsafe supervision
Level 4: Organization Influences

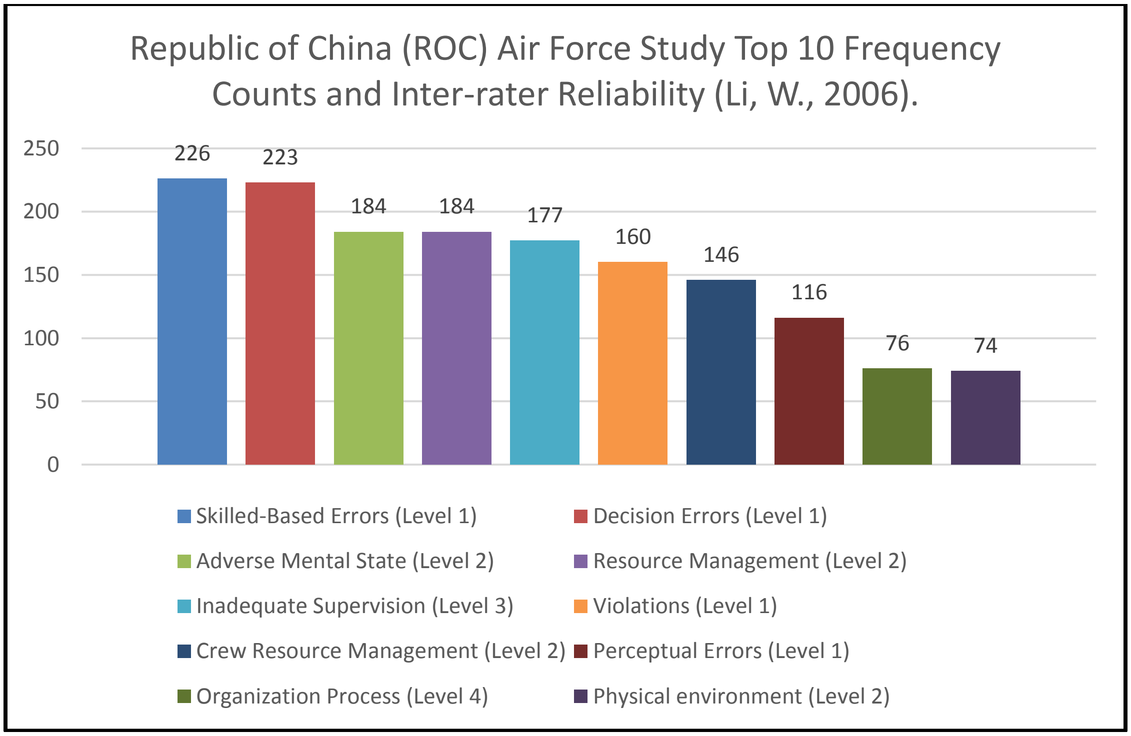


Figure 18: Republic of China (ROC) Air Force Study Top 10 Frequency Counts and Inter-rater Reliability

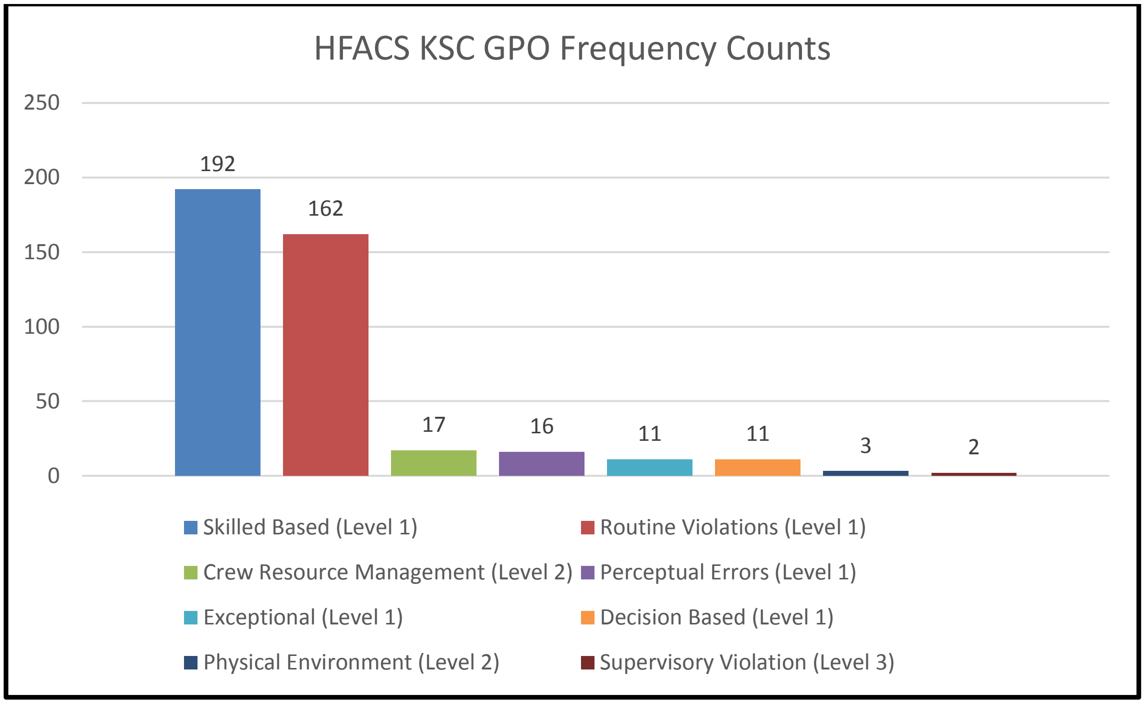


Figure 19: HFACS KSC GPO Frequency Counts

In another research study on recurrent error pathways in HFACS Data, the research focused on an analysis of 95 Remotely Piloted Aircraft Mishaps. In this research, the Perceptional and Skilled Based Error pathways, which both fall under the HFACS "Unsafe Acts" Level 1, had common latent failures associated with each other and together were accountable for the majority of crewmember related mishaps (Tvaryanas, 2008). This result is consistent with the four factors in this study's binary logistics regression Stepwise Backward Elimination Model (Skilled Based, Perceptual Error, Decision Based and Exceptional Violation) in which Skilled Based and Perceptual Error were the two most statistically significant with a p value of 0.000 (reference Table 36) and with the majority of human error factors identified, which fall under the HFACS "Unsafe Acts" Level 1.

Binary Logistics Regression Model

The Goodness-to-Fit tests were within acceptable range for fitting the data. For both the binary logistics regression equation and equation with backward elimination all Goodness-to-Fit p values were greater than 0.05. This indicates that there is no significant deviation and the model fits the data, and indicates to us that we should reject the null hypotheses (H_0), which states Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do not have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in KSC ground processing operations.

Survey One-Way ANOVA

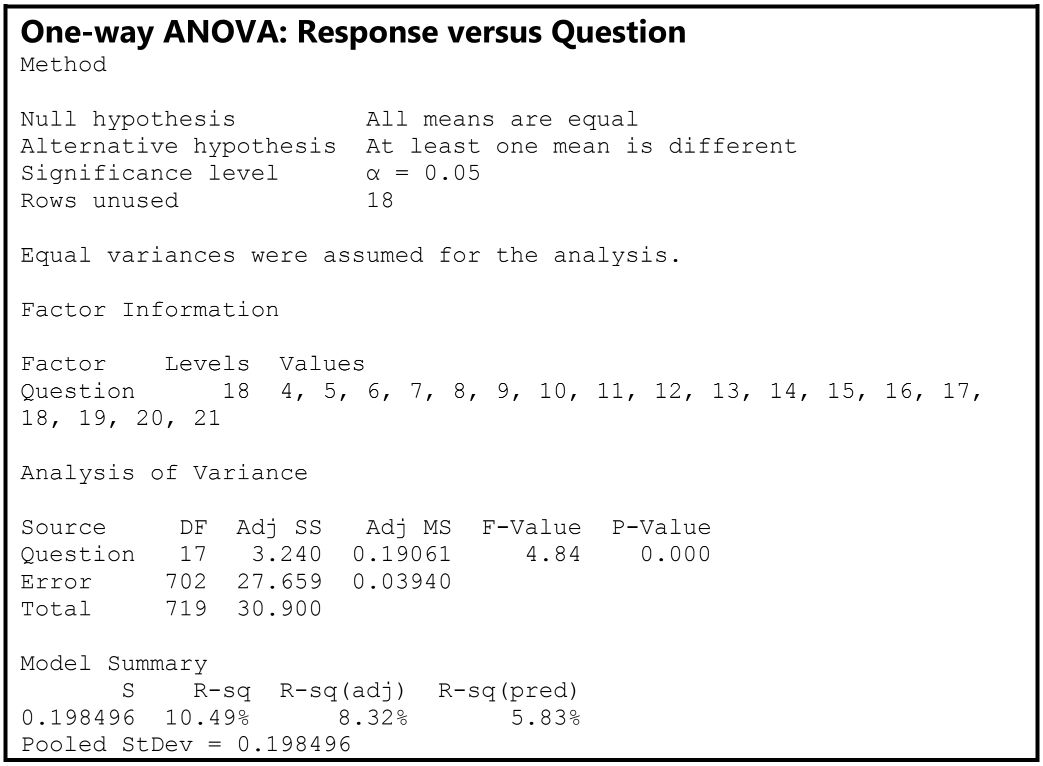
In order to determine if there is a statistical difference between the Assessed Proportion of Affect (AOA) values generated by the survey participants, an ANOVA on the mean values for the AOAs was used. A One-Way ANOVA was performed to compare the mean values of the Assessed Proportion of Affect (AOA) values generated by the SMEs.

The null hypothesis is that all AOA means are equal and the null alternative is that at least 1 mean is not equal.

H_0: $\mu_{\text{AOA 1}} = \mu_{\text{AOA 2}} = \mu_{\text{AOA 3}} = \mu_{\text{AOA 4}}$, etc.

H_1: At least 1 not equal.

Based on the One-Way ANOVA performed on the survey data, the p value of 0.00 indicates that there is a statistically significant difference between the SME's response to the survey questions. With a p value of 0.000, which is less than the 0.05 significance level, the null hypothesis, which reads: H_0: $\mu_{\text{AOA 1}} = \mu_{\text{AOA 2}} = \mu_{\text{AOA 3}} = \mu_{\text{AOA 4}}$, etc., is rejected.



```
One-way ANOVA: Response versus Question
Method

Null hypothesis         All means are equal
Alternative hypothesis  At least one mean is different
Significance level      α = 0.05
Rows unused             18

Equal variances were assumed for the analysis.

Factor Information

Factor    Levels  Values
Question      18  4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17,
18, 19, 20, 21

Analysis of Variance

Source     DF  Adj SS   Adj MS  F-Value  P-Value
Question   17   3.240  0.19061     4.84    0.000
Error     702  27.659  0.03940
Total     719  30.900

Model Summary
       S    R-sq  R-sq(adj)  R-sq(pred)
0.198496  10.49%      8.32%       5.83%
Pooled StDev = 0.198496
```

Figure 20: One-Way ANOVA - Minitab

HEART Human Error Probability (HEP) Validation

The three highest HEP values from the survey data had an “Accessibility Limitations”, “Physical Stress” and “Tiredness” Error Producing Condition as commonalities between them.

When comparing the EPCs of the HEART method to the NASA KSC Modified Levels of the HFACS, the HEART EPCs “Accessibility Limitations,” “Physical Stress” and “Tiredness” are best matched with HFACS Preconditions of Unsafe Acts sublevels "Physical Environment Confined Space" and "Adverse Physiological States - Physical Fatigue."

When reviewing the result values of the Binary Logistics Model (prior to the backward elimination) Predicted Human Error Probabilities, the "Physical Environment" had a Fitted Probability of 33%.

There is no correlation between all of the calculated HEART HEP values to all of the HFACS predicted binary logistics regression values. However, there is some correlation between the 3 highest HEP values (22%, 22%, and 26%) from the survey data to the Physical Environment Fitted Probability of 33% from the binary logistics regression (before Backward Elimination) to draw statistically valid conclusions. Due to survey participants providing their subjective Assessed Proportion of Affect (AOA) for each EPC, it is difficult to directly compare remaining HEART HEP values to the remaining HFACS binary logistic regression signification factors.

It can be noted that all of the SMEs contributions to the developed Scenarios, tasks, subtasks and identified EPCs developed all fall under the HFACS Preconditions of Unsafe Acts Levels (Physical Environment Factor and Adverse Physiological States). In the Preliminary Analysis of this study, it was also noted that many of the SMEs stated that they felt one of the biggest influences to human error mishaps in Ground Processing Operations (GPO) is confined spaces, which is a physical environment limitation.

Research Question and Hypothesis Tests/Results

The Research Question and Hypotheses and results are below.

Question 1: What are the identified leading human error causes and contributors to historical Launch Vehicle Ground Processing Operations mishaps and findings based on past mishaps, near mishaps, and close calls? Quantifying this data and identifying the leading cause is essential in the research analysis.

Question 1

Both binary regression logistics equations in this study identified leading human error causes and contributors to the historical Launch Vehicle Ground Processing Operations mishaps and findings based on past mishaps, near mishaps, and close calls.

The binary logistics regression equation with stepwise backward elimination (simplified) equation identified the significant causes and contributors as: Skilled Based Errors, Decision Based Errors, Perceptual Errors, and Exceptional Violations.

Hypothesis 1

H_0: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do not have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in NASA ground processing operations.

H_1: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in NASA ground processing operations.

Hypothesis 1

Results of the Binary Logistics Model provides support that when mishaps are categorized using the modified NASA KSC HFACS Model, the model does show there are significant contributing factors to KSC Ground Processing Operations (GPO) Human Error.

The fact that KSC's GPO related Mishaps were able to be sorted into the HFACS Levels and sub-categories support the idea that the HFACS tool could be used for complex operations such as KSC GPOs. Of the four (4) HFACS Levels, the only level that did not have any KSC GPO mishaps was "Organizational Influences." This may be due to the difficulty of identifying latent conditions, which are considered "resident pathogens" that can produce a problem within the system, and can lie dormant for years before they combine with active failure to create a potential hazard (Reason, 2000).

The binary logistics regression model Goodness-to-Fit Tests all met the criteria for validity. For all three Goodness-to-Fit tests the p value was greater than 0.05, indicating that we should reject the null hypotheses (H_0), which states H_0: Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) do not have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in KSC ground processing operations. This indicates that there is no significant deviation and the model fits the data.

When comparing the HFACS Fitted Probability values to the HEART Human Error Probability values, there is a similar probability concerning physical limitations (confined space) for the HFACS Factors and HEART EPCs.

Therefore, the H_0 null Hypothesis is **<u>REJECTED</u>**. Contributing factors: unsafe acts of operators, preconditions for unsafe acts, unsafe supervision, and/or organizational influences (multiple causes) **DO** have an impact on human error events (i.e. mishaps, close calls, incident or accidents) in KSC ground processing operations.

Hypothesis 2

H_0: The HFACS framework conceptual model can be proven to be a viable analysis and classification system to help classify both latent and active underlying contributors and causes of human error in NASA ground processing operations.

H_1: The HFACS framework conceptual model cannot be proven to be a viable analysis and classification system to help classify both latent and active underlying contributors and causes of human error in NASA ground processing operations.

Hypothesis 2

The HFACS framework conceptual model used in this research revealed both active and latent failures. The majority of the significant contributing factors were from HFACS Levels 1 and 2, which encompass both active and latent failures. Figure 19 shows the frequency count of KSC Ground Processing Operations Mishaps that were categorized into the HFACS framework.

Tables 29 and 35 show the Human Error underlying contributors and causes based on the HFACS framework identified with the binary logistics regression equations.

In the model validation of this chapter, the HFACS model was verified by consistency and comparison to other research conducted with the HFACS Classification system and data in the aeronautics field.

Therefore, the H_0 null Hypothesis is **ACCEPTED**. The HFACS framework conceptual model **CAN** be proven to be a viable analysis and classification system to help identify both latent and active underlying contributors and causes of human error in KSC ground processing operations.

Hypothesis 3

H_0: The development of a model using the HEART assessment can be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

H_1: The development of a model using the HEART assessment cannot be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

Hypothesis 3

A NASA KSC Specific Modified HEART assessment tool was used to calculate the Human Error Probability (HEP) based on Assessment of Affect (AOA) values provided by survey participants with years of experience and a background with NASA KSC Ground Processing Operations.

Based on the Model Validation section of this research, when comparing the Error Producing Conditions (EPCs) of the HEART method to the NASA KSC Modified Levels of the HFACS, the HEART EPCs “Accessibility Limitations,” “Physical Stress” and “Tiredness” are best matched with HFACS Preconditions of Unsafe Acts sublevels “Physical Environment - Confined Space” and “Adverse Physiological States - Physical Fatigue.”

There is no correlation between all of the calculated HEART HEP values to all of the

HFACS predicted binary logistics regression values. However, between the 3 highest HEART HEP values (22%, 22% and 26%) from the survey, there is a correlation with the HFACS data for the Physical Environment Fitted Probability of 33% (which was generated from the binary logistics regression, before stepwise backward elimination).

It can be noted that from the Preliminary chapter of this Research, the developed Scenarios, tasks, subtasks and identified EPCs all fall under the HFACS Preconditions of Unsafe Acts Levels ("Physical Environment" and "Adverse Physiological States" contributing factors). It is also noted from the Preliminary Analysis of this study that many of the SMEs stated they felt one of the biggest influences to human error mishaps in Ground Processing Operations (GPO) is confined spaces, which is a "Physical Environment" limitation.

As a part of the statistical approach, one of the goals of this research was to use the HEART model to compare the HEP generated values from survey participants' data to the HFACS significant factors and predicted probability values. After the surveys were completed and the HEART HEPs were calculated, there was no correlation to all of the significant factors and predicted probabilities identified with the HFACS binary logistics regression model, except for the "Physical Environment" significant factor and its fitted probability of 33%.

There was also no sufficient HEART Human Error Probability (HEP) calculated research data conducted in relation to the aeronautics or aerospace field for verification through consistency or comparison.

However, the fact that all of the SME generated HEART Survey Scenarios, tasks, subtasks and EPCs all fell under the HFACS Preconditions of Unsafe Acts Levels, is consistent with previous studies discussed in this research identifying the highest frequency of occurrences and the majority of human error occurrences falling within the "Unsafe Acts (Level 1)" and "Preconditions for unsafe acts (Level 2)" HFACS Categories.

The 3rd hypothesis for this research is to determine if the development of a model using the HEART assessment can be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

After conducting the survey, gathering the data, and calculating the HEART Human Error Probabilities (HEP), the HEART tool was successful in determining the probability of human error occurrence from the generated Scenarios.

Therefore the H_0 null hypothesis is **ACCEPTED** due to consistency with related HFACS aerospace studies identifying the majority of human error occurrences falling with the "Unsafe Acts" and "Preconditions of Unsafe Acts" categories. The development of a model using the HEART assessment **CAN** be used as a tool to help determine the probability of human error occurrence in NASA ground processing operations.

CHAPTER SIX: CONCLUSION

Research Summary

Chapter 1: This established the context and motivation for this research.

The goal was to also develop a sound model from an ergonomic, mathematical and human factors standpoint and to add to the body of knowledge in the area of human factors, by providing ergonomic and mathematical results from the Human Error Assessment and Reduction Technique (HEART) and Human Factors Analysis and Classification System (HFACS) tools.

Chapter 2: Research shows through a literature review that statistically human error is identified as the leading primary cause of aviation, mining and other mishaps. Unfortunately, most incident reports are not designed around a theoretical framework of human error. In this research, it was important that human factor issues were addressed and a comparative analysis of existing databases be conducted to determine the human factors responsible for the failures, mishaps, etc. (Wiegmann and Shappell, 2001).

Chapter 3: A preliminary analysis was performed by SMEs to modify the HEART Generic Tasks and the HFACS four levels of human error to be more in line with NASA KSC Ground Processing Operations. The SMEs also played a significant role in the development of the six (6) scenarios that were used for the HEART Survey, which identified the Tasks, Sub-tasks and Error Producing Conditions (EPCs) used for assessing the EPCs' affect on NASA Ground Processing Operations tasks.

Chapter 4: Initial data was collected from recorded NASA KSC Mishap Data from October 1984 – May 2014. Launch Vehicle related Ground Processing Operations (GPO) mishaps from the OPF, VAB and Pad A/B were identified and pulled from this data. These mishap data entries were read one by one and categorized by the HFACS Human Error Levels and sublevels. Any ambiguous mishap data entries were reviewed and consulted by Subject Matter Experts to assist in appropriately assigning the mishaps to the best fitting HFACS Level or subcategory.

Survey participants were asked to evaluate 3 NASA KSC Ground Processing Operations Scenarios involving the VAB, OPFs and Pads A/B. The participants were given a survey scale to provide their Assessed Proportion of Affect (AOA) of the Error Producing Conditions identified for the Scenarios. These values were recorded and calculated using the Human Error Assessment and Reduction Technique (HEART) Human Error Probability (HEP) Formula.

From the experiment process, a binary logistics regression model was generated. Fitted probabilities of future mishap occurrences based on the regression model and Human Error Probabilities were calculated based on the survey participants' assessed values. The binary logistics regression model was also performed a second time with Stepwise Backward Elimination to simplify the equation.

Chapter 5: The results of the binary regression equation identified several significant contributors to NASA GPOs. These significant contributors were consistent with the literature review and research performed in similar fields, such as Aviation and Aeronautics.

Results from the HEART Human Error Probability (HEP) values, did not directly compare with all of the HFACS binary logistics regression identified significant contributors, but there was a comparable probability of occurrence as it relates to the Physical Environment and Confined Spaces.

Chapter 6: Based on the HFACS and HEART results and validation, the KSC Ground Processing Operations Framework is confirmed as a valid approach for mishap analysis. The Framework is flexible in that it allows modification for various unique operations that it will be used for. In this research, the Scenarios can be changed and/or selected from diverse Operations and locations. Due to the fact that the HEART tool has Generic Tasks, this can be modified to specific tasks performed in the Operation.

Although all of the HEART HEP values did not have a direct correlation to all of the HFACS binary logistic regression signification factors, the framework still encompasses the HEART Generic Tasks that can be modified to meet unique job functions. The final stage of the framework encompasses both HFACS human error levels and HEART Error Producing Conditions, which from previous studies mentioned in the Model Validation section of Chapter 5, indicate that the majority of human error related incidents fall under the “Unsafe Acts (Level 1)” and “Preconditions for unsafe acts (Level 2)” HFACS Categories.

The literature review also reveals that from historical and research data the HFACS four (4) Levels of Human Error encompasses the common categories that most mishaps fall into. Lastly, the HFACS Sublevels, Common Errors and HEART Error Producing Conditions cover a broad scope of errors that can occur during complex Operations. All of the error producing conditions in the final stage of the NASA KSC GPO framework (Figure 9), cover contributing factors for both models.

Research Limitations

One of the limitations of this research framework is the subjectivity of the Assessed Proportion of Affect (AOA). The Calculated Human Error Probability (HEP) can vary, due to its dependency on the survey participants. The modification of the HEART and HFACS model is also subject to the Subject Matter Experts' recommendations for the models' modification, in order to make it more in line with NASA KSC Operations.

Identifying the human error related causes that led to the Mishap is limited by the detail of the data provided in the "Detail Description" portion of the Mishap Data entry system. Therefore, if a person entering the data leaves out any pertinent human error related information, this affects the categorization of the Mishap. There is also a potential opportunity for "latent error" related information to not be entered into the database, due to the fact that latent errors can be hidden and may lay dormant within a system, in comparison to active errors, which effects are sensed almost immediately, and are more visible and identifiable.

In this research general slips, trips and falls (e.g. someone tripping and falling as they are getting out of a vehicle) annotated in the Mishap reports were not included in the categorization. Only slips, trips and falls that occurred or were related to the execution of Ground Processing Operations tasks were included.

Research Contributions

The central contribution of this research is a unique complex operations framework that incorporates three aspects: Human Reliability Analysis, Human Error Taxonomy and Human Error Framework.

In the Literature Review chapter, questions were asked in order to identify the research gaps concerning retrospectively analyzing mishaps relating to complex space systems such as NASA KSC Ground Processing Operations. The research questions were in areas of: Human Reliability Analysis, Human Error Taxonomies and Human Error Frameworks. This research addressed all three areas.

Human Reliability Analysis

From the literature review we learned that Human Reliability Analysis is often referred to as "the Probability of human failures," as it pertains to critical system interactions (Salvendy, 2012). Literature research reveals that human reliability accounts for 60-80% of total system risk, which makes it imperative that the HRA process be included and significantly involved in the Probabilistic Risk Assessments (PRA) process (as cited in Salvendy, 2012).

In this research, two HRA tools were used: HFACS and HEART. The HFACS was used to categorize retrospective Ground Processing Operations (GPO) Human Error related mishaps. A binary logistics regression model was used for the statistical approach and a regression equation was generated, which identified the significant factors to the occurrence of the human error related Mishaps. This equation was then used to perform a Probability prediction of future Mishaps based on the presence of a specific contributing factors.

The HEART tool was used to generate a Human Error Probability based on survey participants providing their Assessment of Affect that select Error Producing Conditions had on select Ground Processing Operations Scenarios.

The contribution of this Human Reliability Analysis methodology, utilized both HRAs that can be modified and used on other organizations and their retrospective historic mishap occurrences.

Human Error Taxonomies

The HFACS was used to classify the Launch Vehicle Ground Processing Operations Mishap Data. With the help of experienced Subject Matter Experts, the HFACS Taxonomy level examples were modified to match the complex operations of NASA Ground Processing. The four levels were kept the same; however, the sublevel examples were modified to match KSC Ground Processing Operations. This model was used to categorize all of the Mishap data that corresponded to Human Error. From this categorization, a binary logistics regression model was used to identify the significant contributing factors.

Human Error Framework

The NASA KSC Ground Processing Operations Human Error Framework was developed for the three (3) Scenarios that were the focus of this research. The Framework was built from the first stage of the Scenarios, then to the Ground Processing Operations (GPO) Tasks performed at the Kennedy Space Center, next the HFACS four levels of human error categories and their relation to the common errors, and finally the HFACS sublevels and specific Error Producing Conditions that lead to Human Error mishaps at NASA. This framework was created specifically for KSC Ground Processing Operations; however, it can be modified and used for complex operations, such as other Space Operations and Space Programs on an International Level.

The advantage of this framework is that this study's literature review found no known framework that covers all three Human Reliability Analysis, Human Error Taxonomies and Human Error Frameworks aspects, as it relates to Space Operations. This research study contributes to the Human Error body of knowledge by developing a model/framework that can be used to address all three aspects. The framework uses a Human Reliability Analysis process (HRA), that can classify and categorize human error causes (Human Error Taxonomy), generate a binary logistics regression equation and provide generic tasks and common EPCs that can be used and modified for other complex operations (Human Error Framework).

Research Methodology

This research also provides a methodology contribution. The following set of steps is a research methodology approach that Space Operations and other complex organizations may use to modify and apply to their unique processes.

1. Data Collection
    a. Gather and/or collect Mishap data. Once the Mishap data is collected, determine if all recorded mishaps will be included in the study or if mishaps during a specific time frame, specific location, etc. will be included. This information will be used for HFACS categorization.

2. Qualitative Study
    a. Using the HEART Methodology, develop specific modified examples of the HEART “Generic Tasks” (From Table 8: Nominal Error Probability Table Generic Tasks). This can be done by identifying equivalent specific tasks for the Operations identified for the study. Modified examples may also be developed for the HEART Error Producing Conditions (EPCs) (Table 9). **Note:** This was not implemented for this research, but it is recommended for future research.
    b. HEART Survey Development
        i. Develop “operations related” scenarios in which Subject Matter Experts (SMEs) can provide their subjective Assessment of Affect (AOA) (e.g. Tables 15-20). This will be used to calculate Human Error Probabilities (HEPs) based on SMEs’ experience.
        ii. Develop SME survey questions to gather data for Assessment of Affect (AOA) values (e.g. Appendix E: Survey/Voting Instrument). This is a requirement for the HEART Method. Assign corresponding Error Producing Conditions (EPCs) and HEART Generic Tasks to the Survey questions.
        iii. Develop a Range Table/Chart scale (e.g. Table 26) for SMEs to provide their AOA. The range of values must be in percentage form (e.g. 0.1 = 10% of the EPC maximum effect) values.

    iv. Strategically select survey participants from "operations related" experience. Determine statistical sample size for sufficient data (e.g. Figure 11).
    v. Prior to conducting surveys, obtain appropriate Institutional Review Board (IRB) approval. Once approved, conduct surveys and gather data results.
    vi. Perform Survey One-Way ANOVA to determine statistical difference between the SME AOA responses. If no difference, then go back and verify survey data.
  c. HFACS
    i. Take the HFACS method's four (4) Levels of human error contributing factors and modify the examples to correspond with specific operations identified for the study (e.g. Tables 22-25).

3. Quantitative Study
  a. HEART
    i. Using data from the SME Surveys, input the corresponding data (Generic Task and EPC Values) into the HEART Human Error Probability (HEP) Equation (reference Table 27).
    ii. Use the HEART HEP results to identify areas of focus for priority or potential mitigation. **Note:** May consider focusing on higher HEP values first.

b. HFACS

    i. Sort the collected mishap data into the HFACS categories.
    ii. Build a table to identify "1" for a Mishap/Incident event and "0" for a non-event (e.g. Table 28).
    iii. Use the binary logistics regression statistical analysis to generate a regression equation. **Note:** Binary logistics model may need to be performed again with stepwise backward elimination for simplicity.
    iv. Verify the regression results to validate a good model by assessing the "p values," "Goodness-to-Fit" and "Odds ratio." If validation requirements are not met (see Results and Discussion chapter), then go back and review data to verify data inputs, accuracy and no duplications.
    v. Use the binary logistics regression equation to plug in "1" for an event, to predict the probability of a future occurrence, if a contributing factor occurs.
    vi. Review HFACS Fitted Probability values and Factorial Plots for validity. If factorial plots are not consistent with probability value, then go back and check the input data.

4. Data Validation
    a. Use Triangulation to cross check and validate information (reference Methodology chapter).
5. Research Objective Achieved
    a. If achieved, the research is complete. If not achieved, return to Data Collection step.

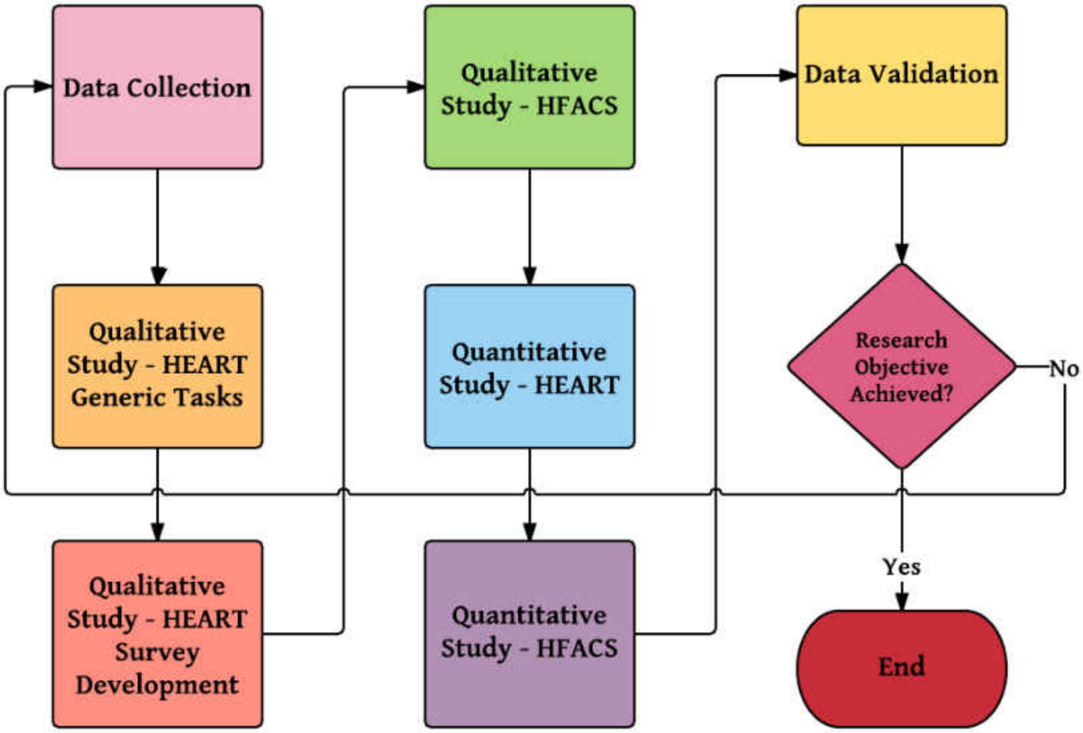


Figure 21: Research Methodology Contribution

Recommendations for Future Research

After completing this study, below are proposed recommendations for future research:

- The literature review of this research recognized a weakness within the area of a proven analysis framework for classifying, assessing, investigation and analyzing human causes of accident in complex space systems, such as NASA KSC Ground Processing Operations. Future research can broaden the current scope to explore and identify what other existing models of human error management can be integrated into complex space systems, beyond what was conducted with the NASA KSC Ground Processing Operations. This would provide further research and knowledge about other models and/or the combination of their use.
- This research identified contributing factors and the prediction of future potential human error related mishaps; however, it did not provide mitigation measures for controlling future occurrences. Broadening the focus of the current research to identify what current methodologies or tools would be most effective in minimizing human error related mishaps. With this focus, determine if a new methodology needs to be established and if so, why. This would be essential to developing a robust controlled method.
- Future research can also focus on determining if the categorized leading contributors in this analysis can be controlled by designing a methodology, model or tool to address the entire Ground Processing Operations process, in lieu of focusing on only 3 areas

(VAB, Pads A/B and OPFs), and if so, can this model be effective in creating an impact on minimizing human error?

- During the Literature Review, studies showed that the Human Error Assessment and Reduction Technique (HEART) has remedial measures which are design considerations for combating Error Producing Conditions (EPC) and tasks in a general sense (Williams, 1986). These remedial measures were not used or modified for this research. It is recommended for future research, that if the HEART technique is incorporated, that these remedial measures be reviewed and modified to effectively match NASA Aerospace tasks and be considered as measures for combating NASA Operations EPCs or any Aerospace Organization.
- It is recommended that the HEART Generic tasks be expanded to cover more aerospace human activities. The expansion will assist in creating more aerospace specificity to the generic task types, which may enable easier assignments of detailed tasks for Human Error Probability (HEP) calculations.
- Modify the Error Producing Conditions (EPCs) weighted values to be more in line with the NASA Aerospace tasks. This will assist in improved accuracy with HEP calculations.
- Compare the results of HEART Human Error Probabilities (HEP) to research study results from the Cognitive Reliability and Error Analysis Method (CREAM), Standardized Plant Analysis Risk HRA Method (SPAR-H) and Technique for Human Error Rate Prediction (THERP), which were recommended methods for flight crew operations per a 2006 study conducted by the NASA Office of Safety and Mission Assurance to assess

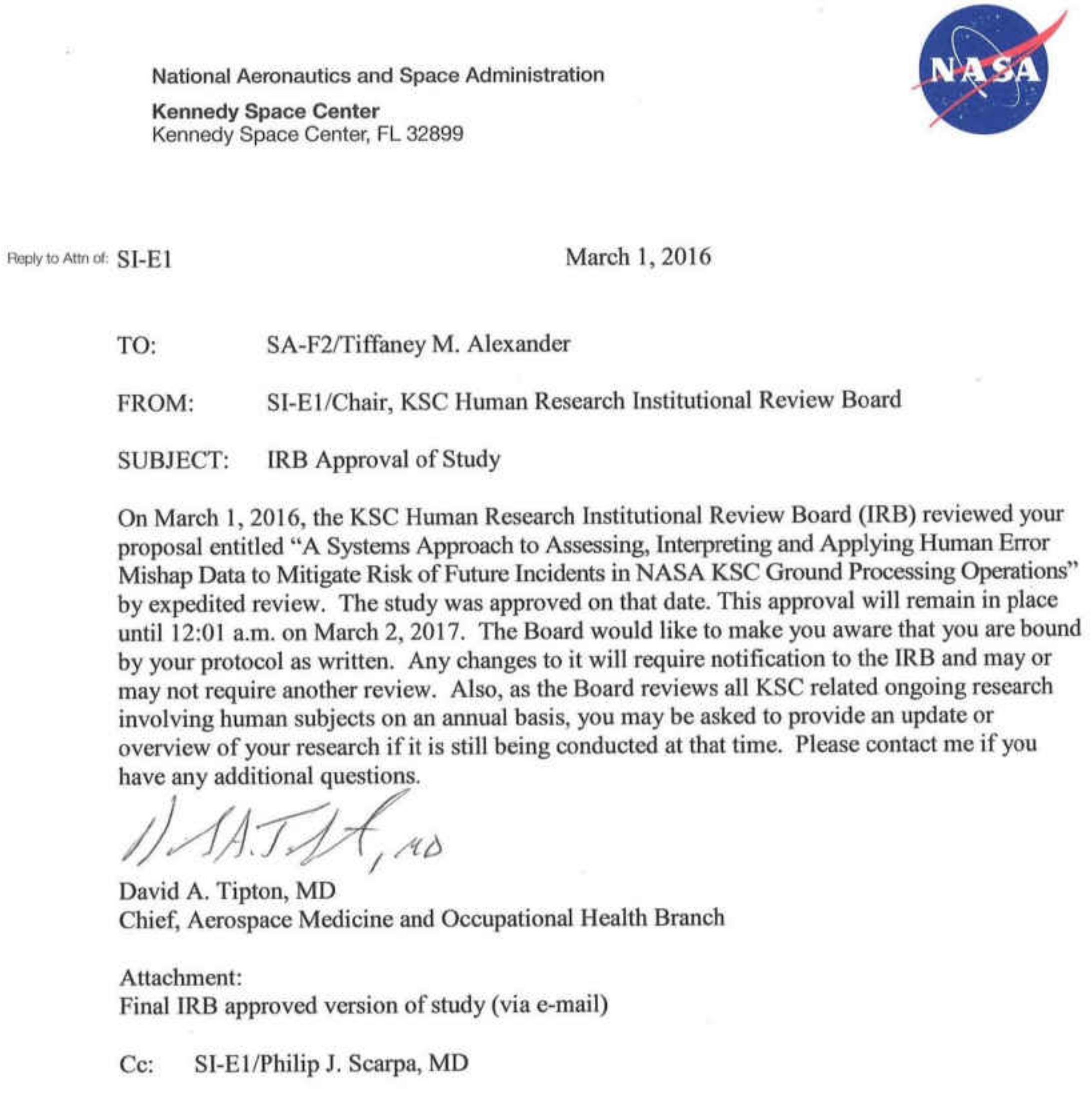
current Human Risk Assessments (HRA) methods and their applicability in the aerospace industry for potential use and adaptation for current and future NASA systems and missions (Chandler, 2006).

- For use in Aerospace Operations, incorporating the THERP, CREAM, NARA, or SPAR-H HRA techniques (or any combination) in place of the HEART Method, in this research's framework can be considered. Per the 2006 Chandler Study, these methods were acknowledged as most pertinent to NASA's HRA needs, for Space Missions (which excludes ground process and command and control) (Chandler, 2006). Using these HRAs within this research framework could identify beneficial analysis data for future use in minimizing human error in ground processing operations and beyond.

- For future research, it is recommended to focus more on identifying and analyzing latent failures (which ultimately lead to active failures), when using this research's framework. As previously stated in the Literature Review chapter, active failures (also known active errors) effects are felt almost immediately and latent errors, whose adverse consequences may lie dormant within the system for a long time, only become evident when they combine with other facts to breach the systems' defenses (Rasmussen & Pedersen, 1984; as cited in Reason, 1990). In the Results and Discussion chapter, research performed on Human Factors in Remotely Piloted Aircraft (RPA) Operations used root categories of latent errors and associated Nano codes with a binary logistic regression model for their analysis. Two binary regression logistics models from this study were proven to be good (Army and

Navy/Marines). Both had common latent error with a p value less than 0.05, relating to two common root causing factors: “Organizational Process” and “Psycho-Behavior” (Adverse Mental States). Future work focusing on these two latent factors, may be something to consider for future research in addressing and attacking latent human errors (Tvaryanas, 2006).

APPENDIX A: NASA IRB APPROVAL



National Aeronautics and Space Administration
Kennedy Space Center
Kennedy Space Center, FL 32899

Reply to Attn of: SI-E1 March 1, 2016

TO: SA-F2/Tiffaney M. Alexander

FROM: SI-E1/Chair, KSC Human Research Institutional Review Board

SUBJECT: IRB Approval of Study

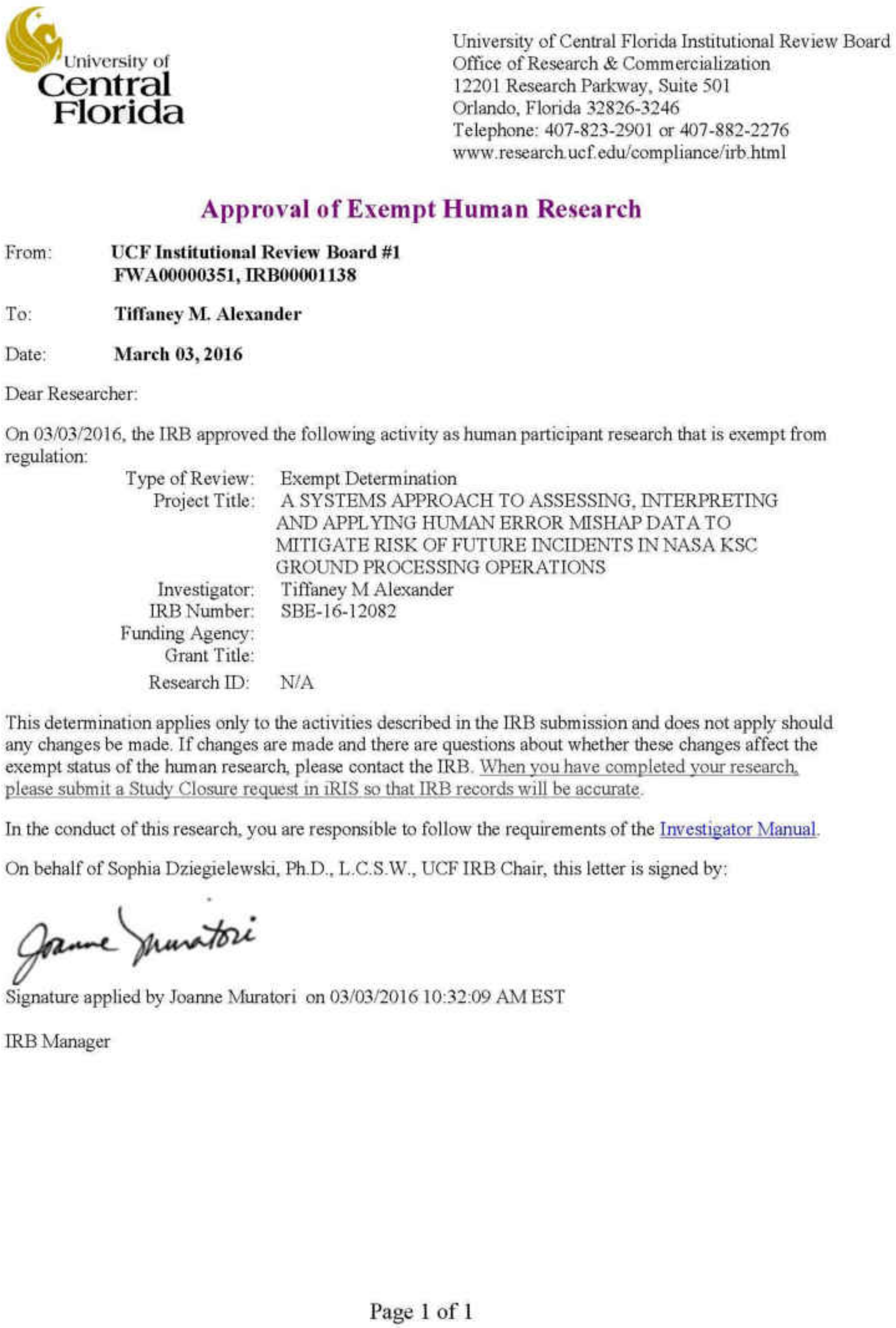
On March 1, 2016, the KSC Human Research Institutional Review Board (IRB) reviewed your proposal entitled "A Systems Approach to Assessing, Interpreting and Applying Human Error Mishap Data to Mitigate Risk of Future Incidents in NASA KSC Ground Processing Operations" by expedited review. The study was approved on that date. This approval will remain in place until 12:01 a.m. on March 2, 2017. The Board would like to make you aware that you are bound by your protocol as written. Any changes to it will require notification to the IRB and may or may not require another review. Also, as the Board reviews all KSC related ongoing research involving human subjects on an annual basis, you may be asked to provide an update or overview of your research if it is still being conducted at that time. Please contact me if you have any additional questions.

David A. Tipton, MD
Chief, Aerospace Medicine and Occupational Health Branch

Attachment:
Final IRB approved version of study (via e-mail)

Cc: SI-E1/Philip J. Scarpa, MD

APPENDIX B: UCF IRB APPROVAL



University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Exempt Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Tiffaney M. Alexander**

Date: **March 03, 2016**

Dear Researcher:

On 03/03/2016, the IRB approved the following activity as human participant research that is exempt from regulation:

Type of Review: Exempt Determination
Project Title: A SYSTEMS APPROACH TO ASSESSING, INTERPRETING AND APPLYING HUMAN ERROR MISHAP DATA TO MITIGATE RISK OF FUTURE INCIDENTS IN NASA KSC GROUND PROCESSING OPERATIONS
Investigator: Tiffaney M Alexander
IRB Number: SBE-16-12082
Funding Agency:
Grant Title:
Research ID: N/A

This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these changes affect the exempt status of the human research, please contact the IRB. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Joanne Muratori

Signature applied by Joanne Muratori on 03/03/2016 10:32:09 AM EST

IRB Manager

APPENDIX C: NASA SUBJECT CONSENT FORM

NASA Subject Consent Form

I, the undersigned, do voluntarily give my informed consent for my participation as a test Subject in the study: "A Systems approach to Assessing, Interpreting and Applying Human Error Mishap data to mitigate risk of future incidents in NASA KSC Ground Processing Operations".

I understand or acknowledge that: The research procedures were explained to me prior to the execution of this form. I was afforded an opportunity to ask questions, and all questions asked were answered to my satisfaction. A layman's description was provided to me along with this form. I can refuse to participate in the tests at any stage of their performance, and my refusal will be honored as promptly as possible. My withdrawal or refusal to participate in this investigation will not result in any penalty or loss of benefits to which I am otherwise entitled. The investigators may discontinue my participation in this study if necessary for safety or other reasons. In the event of an injury requiring immediate treatment during the course of this study, Kennedy Space Center and its contractors will provide or arrange for necessary initial treatment.

If I have further questions I will discuss them with the investigators or contact the Principal Investigator, Tiffaney Miller Alexander at 321-867-5384. In addition, if I have concerns about this study or my participation as a subject, I can also contact the KSC Institutional Review Board (IRB) directly through David A. Tipton, MD, at 321-867-6385.

I have read and fully understand the study description entitled: "A Systems approach to Assessing, Interpreting and Applying Human Error Mishap data to mitigate risk of future incidents in NASA KSC Ground Processing Operations – UCF Informed Consent" and will receive a copy of that document and this signed Document.

Signature: Signature:

Test Subject Date Person Obtaining Consent Date

I, the undersigned, the Principal Investigator of the investigation designated above, certify that:
I have thoroughly and accurately described the research investigation and procedures to the test subject and have provided him/her with a layman's description of the same and a copy of this consent form.
This study entails moderate risk to the test subject. All equipment to be used has been inspected and verified to be ready for safe and proper operation. The test subject is medically qualified to participate.
Except as provided for by Agency-approved routine uses under the Privacy Act, the confidentiality of any data obtained as a result of the test subject's participation in this study shall be maintained so that no data may be linked to him/her as an individual.

The test protocol has not been changed from that approved by the KSC Human Research IRB.

Signature:

Principal Investigator Date

APPENDIX D: UCF INFORMED CONSENT

Version 1.0 10-21-2009

University of
Central
Florida

EXPLANATION OF RESEARCH

Title of Project: A Systems Approach to Assessing, Interpreting and Applying Human Error Mishap Data to Mitigate Risk of Future Incidents in NASA KSC Ground Processing Operations.

Principal Investigator: Tiffaney Miller Alexander

Faculty Supervisor(s): Dr. Pamela McCauley, PhD
Dr. Luis C. Rabelo, PhD

You are being invited to take part in a research study. Whether you take part is up to you.

- The purpose of this study is to develop a model that can analyze and identify contributing factors to mishaps, close calls, or incidents during NASA KSC Ground Processing Operations and be used as a tool to accompany preexisting accident investigation and analysis systems in controlling and/or minimizing human error.

- The objective of this survey is to collect data from current and former KSC employees to provide a subjective assessment of Error Producing Conditions (EPCs) that affect or impact on specified Ground Processing Operations Generic Tasks.

Former KSC employees consist of: Strategically selected subjects from their years of experience in NASA KSC Ground Processing Operations, Human Factors, Mishap Control Board, Engineering, Safety and Mission Assurance and "On the floor" Technicians' background and experience.

As a subject participant in this research, you will be asked to use a given "Assessment Table" to provide your assessment of affect that "error producing" conditions have on the specified Ground Processing Scenarios. You will be given 6 KSC Ground Processing Operation Scenarios (two for the VAB, OPF, and Pad A/B), in which you will be asked to give your assessment of the "error producing" conditions that can impact the performance of the task. The range is listed from very low, low, moderate, high and very high affect.

- The expected time to complete the survey is no more than 30-40 minutes. After you have completed the survey, the survey will be taken by the Principal Investigator.

You must be 18 years of age or older to take part in this research study.

Study contact for questions about the study or to report a problem: If you have questions, concerns, or complaints please contact: Tiffaney M. Alexander, PhD Candidate Industrial Engineering and Management Systems, College of Engineering and Computer Science at (321) 867-5384, tiffaney.m.alexander@nasa.gov or Dr. Luis C. Rabelo, Faculty Supervisor, Department of Industrial Engineering and Management Systems at (407) 882-0091 or email at Luis.Rabelo@ucf.edu.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901.

APPENDIX E: SURVEY/VOTING INSTRUMENT

A SYSTEMS APPROACH TO ASSESSING, INTERPRETING AND APPLYING HUMAN ERROR MISHAP DATA TO MITIGATE RISK OF FUTURE INCIDENTS IN NASA KSC GROUND PROCESSING OPERATIONS

Principal Investigator: Tiffaney Miller Alexander, PhD Candidate
Faculty Advisors: Dr. Pamela McCauley, PhD
Dr. Luis C. Rabelo, PhD
Sponsor: NASA, KSC
Investigational Site(s): NASA, Kennedy Space Center, FL 32899

Survey Questions

1. **How long (years) have you worked at the Kennedy Space Center (KSC)?**

____

2. **How many years did you work/support NASA, KSC Ground Processing Operations for the Shuttle Program?**

____

3. **What was your job title(s) or function(s) during your time working for KSC Ground Processing Operations?**

____

Assessment Table

Percentage Range (Median)	Proportions of Affect	Description
(.10) 0.00 – 0.20	Very Low Affect	Human error is very unlikely to occur. Strong Controls may be in place.
(.305) 0.21 – 0.40	Low Affect	Human Error is not likely to occur. Controls have minor limitations and uncertainties.
(0.510) 0.41 - 0.60	Moderate Affect	Human Error may occur. Controls exist with some uncertainties.
(0.7) 0.61 - 0.80	High Affect	Human Error is highly likely to occur. Controls have significant uncertainties.
(0.9) 0.81 – 1.00	Very High Affect	Human Error is certain to occur. Controls have little to no affect.

Using the Assessment Table provided, please provide your "Assessment of Affect" the Error Producing Condition has on the Specified Ground Processing Scenario.

Table 1: VAB Scenario 1

Task: Performing Booster Hold-down Posts

Subtasks	**Error Producing Conditions**
Arming the Booster	Tiredness – Long hours – 3rd Shift.
Connecting the Booster Segments	Accessibility limitations.
Installing Safety Wires	Poor lighting.

Question 4: What proportion of affect would "Tiredness – Long hours – on 3rd Shift" affect performing Booster Hold-down Posts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Question 5: What proportion of affect would "Accessibility Limitations" affect performing Booster Hold-down Posts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Question 6: What proportion of affect would "Poor Lighting" affect performing Booster Hold-down Posts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Table 2: VAB Scenario 2

Task: Orbiter lift and mate to stack

Subtasks	Error Producing Conditions
Attaching sling and cranes	Heat (Orbiter lifting required doors to be closed and coveralls worn).
Lifting and lowering Orbiter into position for mate	Heights, climbing ladders to access platforms.
Install and attaching hardware	Tripping hazards.

Question 7: What proportion of affect would "Heat (Orbiter lifting required doors to be closed and coveralls worn)" affect performing Orbiter lift and mate to stack and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 8: What proportion of affect would "Heights, climbing ladders to access platforms" affect performing Orbiter lift and mate to Stack and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 9: What proportion of affect would "Tripping Hazards" affect performing Orbiter lift and mate to Stack and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Table 3: OPF Scenario 1

Task: Wire Inspections inside the Vehicle, Cargo Bay, under the Floor Board

Subtasks	**Error Producing Conditions**
Performing electrical tests	Accessibility limitations – Crawling around on wires bundle.
Repairing/replacing wiring	Physical Stress - twisting and turning.
Installing/removing protective tubing	Confined working space - breakable parts in or on way to/from work area (air ducts, phenolic brackets, tubing).

Question 10: What proportion of affect would "Accessibility limitations – Crawling around on wires bundle" affect performing Wire Inspections inside the Vehicle, Cargo Bay, under the Floor Board and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 11: What proportion of affect would "Physical Stress - twisting and turning "affect performing Wire Inspections inside the Vehicle, Cargo Bay, under the Floor Board and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 12: What proportion of affect would "Confined working space - breakable parts in or on way to/from work area (air ducts, phenolic brackets, tubing)" affect performing Wire Inspections inside the Vehicle, Cargo Bay, under the Floor Board and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Table 4: OPF Scenario 2

Task: Wing Closeouts

Subtasks	Error Producing Conditions
Elevon actuator servicing	Claustrophobia. Physical Stress - twisting and turning. Confined working space - Accessing and backing out of small tight areas with; wire harnesses, tubing, and struts.
Scheduled inspections	
Modifications and repairs	

Question 13: What proportion of affect would "Claustrophobia" affect performing Wing Closeouts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Question 14: What proportion of affect would "Physical Stress - twisting and turning" affect performing Wing Closeouts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Question 15: What proportion of affect would "Confined working space - Accessing and backing out of small tight areas with; wire harnesses, tubing, and struts" affect performing Wing Closeouts and any of its Subtasks?

○ **Very Low Affect** ○ **Low Affect** ○ **Moderate Affect** ○ **High Affect** ○ **Very High Affect** ○ **N/A**

Table 5: Pad A/B Scenario 1

Task: Pad Aft Closeouts

Subtasks	**Error Producing Conditions**
Removing access platforms and non-flight items	Confined working space - accessibility limitations; crawling and climbing around/near; wiring bundles/connectors, hydraulic/pneumatic lines, air ducts, etc. Physical stress - twisting and turning.
Inspections	Noise (air purge).
Repairs	Poor lighting.

Question 16: What proportion of affect would "Confined working space - accessibility limitations; crawling and climbing around/near; wiring bundles/connectors, hydraulic/pneumatic lines, air ducts, etc. Physical stress - twisting and turning" affect performing Pad Aft Closeouts and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 17: What proportion of affect would "Noise (air purge)" affect performing Pad Aft Closeouts and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 18: What proportion of affect would "Poor Lighting" affect performing Pad Aft Closeouts and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Table 6: Pad A/B Scenario 2

Task: Installing Engines at Pad

Subtasks	**Error Producing Conditions**
Installing and torqueing hardware	Accessibility limitations –when open below, required to wear safety harness and lanyard.
Connecting lines (inspect, clean, install seals, hardware install and torque)	Physical stress due to installing vertically.
Electrical connects	Tiredness – 3rd Shift Work.

Question 19: What proportion of affect would "Accessibility limitations –when open below, required to wear safety harness and lanyard" affect performing the Installation of Engines at the Pad and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 20: What proportion of affect would "Physical stress due to installing vertically" affect performing the Installation of Engines at the Pad and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

Question 21: What proportion of affect would "Tiredness – 3rd Shift Work" affect performing the Installation of Engines at the Pad and any of its Subtasks?

○	○	○	○	○	○
Very Low Affect	**Low Affect**	**Moderate Affect**	**High Affect**	**Very High Affect**	**N/A**

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