DISSERTATION

TECHNOLOGICAL ADVANCES, HUMAN PERFORMANCE, AND THE OPERATION OF NUCLEAR FACILITIES

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2017

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ABSTRACT

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Many unfortunate and unintended adverse industrial incidents occur across the United States each year, and the nuclear industry is no exception. Depending on their severity, these incidents can be problematic for people, the facilities, and surrounding environments. Human error is a contributing factor in many such incidents. This dissertation first explored the hypothesis that technological changes that affect how operators interact within the systems of the nuclear facilities exacerbate the cost of incidents caused by human error. I conducted a review of nuclear incidents in the United States from 1955 through 2010 that reached Level 3 (serious incident) or higher on the International Nuclear Events Scale (INES). The cost of each incident at facilities that had recently undergone technological changes affecting plant operators' jobs was compared to the cost of events at facilities that had not undergone changes. A *t*-test determined a statistically significant difference between the two groups, confirming the hypothesis. Next, I conducted a follow-on study to determine the impact of the incorporation of new technologies into nuclear facilities. The data indicated that spending more money on upgrades increased the facility's capacity as well as the number of incidents reported, but the incident severity was minor. Finally, I discuss the impact of human error on plant operations and the impact of evolving technology on the 21st-century operator, proposing a methodology to overcome these challenges by applying the systems engineering process.

PREFACE

In the course of this research, extensive benchmarking, evaluation, debate, and investigation revealed a key underlying hindrance to successful facility operation: a disproportionate dependence on “technology-only” enhancements. Technology is intended to make us more productive, but its use can carry a penalty. The computers, decision support systems, and complex control and logic programs used at plants can gradually diminish intuition and expertise and can ultimately become the replacement for a robust, knowledge-based training and Human Performance Improvement (HPI) program. Technology is a powerful tool, but in the operational setting, it must be properly balanced with thorough training and adherence to human error prevention techniques and conduct.

During my study of human error, I recognized that devising suitable steps to prevent human error is crucial in all aspects of a project and must permeate all phases of the systems engineering process. HPI is much more than employing a set of human performance tools. Human error psychology, effects, risks, error traps, and mental models must be examined, consciously applied, and woven into the operating structure of plant organizations, especially in light of the innate complexities associated with technological advancements. Therefore, this study seeks to present empirical evidence for the importance of human performance management in the context of nuclear facilities and to offer practical recommendations for the improvement of this function.

DEDICATION

Without the encouragement and motivation from my brother Nick, the completion of this program would have been an impossibility. In my youth, Nick was my protector; in my adult life, he was my number one fan; and throughout my whole life, he was my best friend. This is for you big brother.

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Systems engineering has been recognized for over 60 years as essential to the proper development of complicated systems (Mitchell & Jolley, 2013). It has been applied to a wide range of technological projects such as automobiles, urban infrastructure, environmental controls, aircraft, software, hardware, and ships. Systems engineers are often the technical leaders for vast and complex projects (Rutherford, 2011).

Systems engineers rely on the application of relationships and system science to analyze and determine system performance of a product under development. Twenty-first-century systems engineering guides the development of each part within the system through learned heuristics (Rutherford, 2011). Both engineering managers and systems engineers understand that the practice of systems engineering has significant value. For this reason, systems engineering concepts and practices are used in nearly all complex projects. Despite the acknowledged importance of systems engineering, some observers argue that it is less fully understood than other engineering disciplines (Steinberg, 2011).

Because of continually evolving technology and accompanying increases in the level of system complexity, 21st-century systems engineering is frequently confronted with greater depths of contextual embedding (Rutherford, 2011). Systemic behaviors today present an increasing number of specifications and environmental parameters for consideration (Mitchell & Jolley, 2013).

One clear example of a complex system that involves systems engineering, human performance, and technological advances is nuclear facilities—more specifically, nuclear power plants, nuclear material processing and fabrication facilities, and enrichment plants. Nuclear facilities are among the most complex systems ever designed (Loomis, 2011). They use state-of-the-art technology and must continually update their systems to remain safe, regulatory compliant, and economically sound. Unfortunately, like any complex system, nuclear facilities are not immune to failure, particularly with regard to human performance. As one can presume, many of the adverse incidents that have occurred at nuclear facilities were the result of some type of human error. Since these systems are astoundingly complex, any changes made in the technology have the potential to increase human error and result in a reduction in performance when they interact with machinery or software (Karakosta et al., 2013). Technological changes in the intricate systems involved in the operation and management of a nuclear facility may contribute to the increased impact of human errors, in terms of both cost and frequency (Loomis, 2011).

This dissertation investigates incidents at U.S. nuclear facilities that occurred due to human error by people who interacted with the complex systems involved with a nuclear plant, and especially with its changing technologies. Realizing that the top level goal is for the safe and efficient operation of nuclear facilities (and the potential application of other complex systems) and that an optimized human-machine system is the desired end state, this work focuses on the human performance component of this complex system.

1.2. PROBLEM STATEMENT

Numerous adverse incidents have occurred at nuclear facilities across the United States, sometimes with considerable negative consequences for the facilities involved, the environment, human beings, and the nuclear industry. Several have resulted in radiation being released to the environment and in fatalities. Many of these incidents have been attributed to human error. The challenge of grasping all the details of the complex, changing technologies at these facilities may be an important contributor to these errors. Much research has been conducted on the causes and consequences of adverse incidents at nuclear plants, but not specifically on how technological changes could be a key factor increasing the risk of human error. Accordingly, this dissertation focuses specifically on the role that human error related to technological advances has played in incidents at U.S. nuclear facilities.

1.3. PURPOSE

Extensive research exists on the safety procedures used by nuclear facilities, including publications by the International Atomic Energy Agency (IAEA), U.S. Nuclear Regulatory Commission (NRC), and U.S. Department of Energy (DOE) along with scholarly research published in books and reputable journals. Also, considerable research has investigated the effect of new technologies on human performance, especially when complex systems are involved. This literature includes the foundational works *Human Error* by James Reason; *Behind Human Error* by David Woods, Sidney Dekker, Richard Cook, Leila Johannesen, and Nadine Sarter; and *The Field Guide to Human Error* by Sidney Dekker. The systems involved with nuclear facilities are some of the most complex systems ever developed. This fact suggests that these systems could be especially exposed to the threat of human error following the implementation of technological changes. The purpose of this dissertation is to determine the relationship between human performance, technological advances, and the complex systems involved with nuclear facilities and to suggest a path forward.

1.4. THEORETICAL FRAMEWORK

This research applies theoretical frameworks from multiple disciplines. The following frameworks and techniques are reviewed in this section: human factors and ergonomics, sociotechnical systems, user-centered design, human reliability, probabilistic risk assessment, human reliability assessment, and latent human error.

Human factors and ergonomics, often abbreviated as HF&E, incorporates insights from numerous disciplines, including anthropometry, operations research, statistics, graphic design, industrial design, mechanobiology, biomechanics, engineering, and psychology (Karwowski, 2006). The field of HF&E emerged around World War II, at a time of considerable development in the complexity of weaponry and other machines, which placed great demands on operator cognition. During the information age, HF&E has been extended to human-computer interactions (Proctor and Zandt, 2008).

HF&E is now used in a wide variety of fields including virtual environments, training, transportation, product design, information technology, healthcare, geriatrics, aerospace, and nuclear facilities (Proctor and Zandt, 2008). At nuclear facilities, HF&E seeks to reduce the strain placed on operators in order to decrease the amount of cognitive and physical energy they must put forth in order to operate the facility (Karwowski, 2006).

The concept of sociotechnical systems refers to a type of organizational development that recognizes that the interactions occurring between technology and people at the workplace can be optimized through organizational work designs, which are often complex (Vermaas et al., 2011). The term can also be used to describe the intricate infrastructures present in society and how they interact with human behavior. Both definitions are applicable to nuclear facilities, as both elaborate infrastructures and complex interactions between people and advanced technological systems are involved in the proper operation of a nuclear facility (Neyer, Bullinger, and Moeslein, 2009).

Sociotechnical systems represent a type of theory regarding society, people, and the technical processes and organizational structures involved in complex systems (Gorman, Cooke, and Salas, 2010). The term *technical* does not always refer to material technologies; it can also describe knowledge and procedures. *Sociotechnical* emphasizes that an organization often involves goals and tasks that are both technical and social in nature. The sociotechnical analysis of a system strives to achieve a joint optimization of both the social aspects and technical performance of the system. This is especially helpful with nuclear facilities, which function in a social environment. For example, regulatory requirements that govern nuclear facilities and affect the systems with which the operators must interact are highly technical but also have a social aspect, since they must satisfy the demands of multiple stakeholders (Neyer, Bullinger, and Moeslein, 2009).

Probabilistic risk assessment, often abbreviated as PRA, is a relatively comprehensive, systematic methodology used to evaluate the risks associated with complex technological entities such as nuclear facilities (Mohaghegh, Kazemi, and Mosleh, 2009). In these cases, the risk is understood as a potential detrimental outcome of an action or activity. Two quantities are associated with risk: the likelihood of an occurrence and the magnitude of the adverse effects. These are often described as the probability of the problem and its severity. Consequences are generally expressed numerically by multiplying the probability times the total risk to calculate the expected loss (Stamatelatos and Dezfuli, 2011).

PRA is often used to assess nuclear facilities (U.S. Nuclear Regulatory Commission, 2011). Three steps are generally involved in a PRA. First, one must identify the problems that can occur at the facility and whether they could lead to an adverse consequence. Second, one must assess the severity of the potential problem, in terms of their possible consequences for the facility. The third item to be examined is the likelihood that these consequences will occur, typically described as a frequency or probability. Common methods of conducting a PRA are fault tree analysis and event tree analysis. PRA generally falls under the classification of safety engineering (Stamatelatos and Dezfuli, 2011).

User-centered design, a subdivision of user-interface design (Mohaghegh, Kazemi, and Mosleh, 2009), is a process in which attention is given to each stage in the design process to accommodate the limitations and needs of end users. This is a multistage process of problem solving that requires designers to foresee and analyze how human users of the technology are likely to interact within a system. The process involves testing in a real-world context the validity of assumptions with regard to users' behavior. This type of testing is necessary because it can be nearly impossible for product designers to understand the experience of a first-time user of the technology. One must also consider the learning curve of people interacting within the system. All these factors are crucial in the efficient, proper operation of a nuclear facility. User-centered design is critical for the proper organization of workstations and for other types of interaction between human users, and for the complex systems involved with a nuclear facility (U.S. Nuclear Regulatory Commission, 2011).

Human reliability assessment, or HRA (Tont et al., 2009), is concerned with evaluating the probability that human error will occur when a specific task is completed. This type of analysis informs actions aimed at reducing the likelihood of such errors and improving the overall safety system. This type of analysis is only one of many performed at nuclear facilities to ensure that incidents are minimal.

HRA has three main goals: error reduction, quantification, and identification (Tont et al., 2009). Several techniques are used for these purposes, among which the Technique for Human Error Rate Prediction (THERP) is one common approach. The techniques can be categorized as either first- or second-generation. First-generation techniques are based upon a dichotomy of either fitting or not fitting the error situation within a given context; second-generation techniques are based on theory and serve to quantify the errors. HRA techniques are used in a number of disciplines, including business, transportation, general engineering, healthcare, and nuclear facilities.

The Nuclear Regulatory Commission contracted with the author of THERP to design a more consistent tool for determining human error rates at nuclear facilities (Tont et al., 2009). This resulted in the development of the Accident Sequence Evaluation Program Human Reliability Analysis Procedure (ASEP), which tends to be more conservative than THERP. One significant advantage of the ASEP is that it does not require the user be an expert in human factors engineering. Additionally, the training needed to use the ASEP is relatively minimal. After it became computerized, ASEP began to be referred to as Simplified Human Error Analysis code or SHEAN (Tont et al., 2009).

Latent human error refers to human error due to systems or routines formed in such a way that humans are disposed to make these errors (Karwowski, 2006). This term is widely used throughout the aviation industry, but it is also prevalent in the safety literature for nuclear facilities. When this method is used at a nuclear facility, operator error data are gathered, grouped, collated, and analyzed to provide information for determining whether a disproportionate number of errors is present in a given system piece. If errors at a particular point in the system are too numerous, the system or routine can be analyzed, the potential for the problems identified, and changes made. This decreases the likelihood of future errors that could result in nuclear incidents (Salvendy, 2012).

1.5. RESEARCH QUESTION

The research topic of this dissertation is the relationship between technological advances and human performance in the complex systems at nuclear facilities. The research question is whether technological advances in the complex systems of nuclear facilities increase the cost associated with incidents caused by human error. This is an important question because most nuclear facilities continually update their technology. This continuous technological improvement can create a situation in which the operators must change their routine and method of interacting with the complex system and the new technology.

1.6. HYPOTHESES

The hypothesis is as follows:

H_1: Technological advances at a nuclear facility that affect how operators interact within the system **do** increase the cost of incidents caused by human error.

The null hypothesis is as follows:

H_0: Technological advances at a nuclear facility that affect how operators interact within the system **do not** increase the cost of incidents caused by human error.

1.7. SIGNIFICANCE OF THE STUDY

The operational life of nuclear reactors is measured in reactor-years (Loomis, 2011). One reactor year is equivalent to a reactor operating for one complete year. The United States has roughly 440 nuclear power plants that have been in operation for over 14,700 reactor-years. During this time, there have been 23 reactor core meltdowns, or one major nuclear accident for every 640 reactor years. According to the international design requirements for nuclear facilities, a reactor core meltdown should only occur about once every 20,000 reactor-years. This means that the incidence of U.S. reactor core meltdowns is been 32 times higher than what theory would predict (Karakosta et al., 2013). This significant departure from the theory indicates that additional unaccounted-for factors are violating the base assumptions of the model.

Of the 23 nuclear reactor meltdowns, 17 were caused by some type of human error (Marques, 2011). Instances of human error are difficult if not impossible to predict accurately, but these types of errors will almost certainly continue to occur. The significance of this dissertation lies in its attempt to determine whether the severity, in terms of cost, of human errors can be reduced through effectively and efficiently implementing necessary technological changes and human performance activities that directly impact how operations occur at complex nuclear facilities. In this dissertation, I define severity in terms of the cost of incidents caused by human error as a result of technological advances, rather than trying to examine other physical and environmental effects associated with the incidents, such as radiation releases, on which most research on nuclear accidents focuses. If the null hypothesis of this dissertation is determined to be statistically unlikely, then reducing the changes in procedures to be followed by nuclear facility staff and contractors, or improving the training and procedures associated with such changes, could decrease the probability and severity of future incidents. This could result in significant savings both economically and in avoiding adverse impacts on people and the environment (Högberg, 2013).

1.8. CHAPTER SUMMARY

This introductory chapter has provided background information on systems engineering and on the interactions between nuclear facility operators and complex machines and software. It has described nuclear facilities as elaborate systems that involve technological advances, human performance, and high levels of system engineering.

Since the inception of nuclear power, many significant incidents have occurred at nuclear power plants. Several of these incidents resulted in the meltdown of the nuclear reactor. The purpose of this dissertation is to determine the relationship between technological advances and human performance in the complex systems of nuclear facilities. Specifically, I will explore whether technological changes at nuclear facilities that affect how operators interact with the systems have increased the cost of resulting incidents. The study is important as there have been 23 reactor core meltdowns in U.S. history, far more than theoretical work would have anticipated. Human error is believed to be the primary contributor to the larger number of serious incidents. This dissertation will examine the role of technological changes in those errors.

CHAPTER 2: LITERATURE REVIEW

2.1. CHAPTER INTRODUCTION

Each time that significant technological developments offer the promise of greatly assisting people's lives, failed systems and prototypes also inevitably result to some degree (Proctor and Zandt, 2008). When researchers examine the effects of changes in technology, they often discover unintended and unanticipated consequences. Individuals using the new technologies frequently make performance errors because they must adapt to increasingly complex technology. Rather than assisting the user, these new technologies can add burdens, which are especially problematic during crucial phases of complex tasks (Karwowski, 2006).

The pattern of human performance degradation when novel technologies are introduced occurs in a wide range of endeavors (Duffy, 2012). For example, the implementation of new systems of airplane cockpit automation can also be an associated with a decline in pilots' performance; their reaction times and number of errors increase. The same is true in virtually all industries, including the nuclear industry, where human errors that affect system operation are unacceptable (Salvendy, 2012).

Although considerable research has been conducted on the human-machine interface, a wide range of problems still exists (Duffy, 2012). There remains a disparity between the optimism of technology developers and the real-life operational difficulties that accompany the introduction of these systems. The developers nearly always claim that the new technology will result in performance improvements. However, due to the operational complexities introduced, the technology may actually decrease the performance of those interacting with the system. Unfortunately, the complexities confronting operators are difficult for design teams to predict. To understand the complexity surrounding human interaction with advancing technologies, the human performance model must be examined and the concepts of escalation, active error, latent error, foreseeable error, and unexpected events should be examined.

2.2. MODELING HUMAN PERFORMANCE

Understanding human errors becomes possible through modeling human performance (Foyle and Hooey, 2008). This section will explain one such model. The reader should recognize that the explanations given for the behaviors represent an ideal situation. Error likely situations occur when the individual involved has deviated from the behaviors described by the model (Duffy, 2009).

Although many heavily automated technical systems exist today, all of them rely on routine human interaction as an integral characteristic of normal system functioning (O’Connor and Cohn, 2010). Operators must ensure that the proper conditions are present for the system to operate normally and must intervene when abnormal conditions exist so as to restore the system to a safe configuration. They must also account for any unforeseen problems with the system or compensate for anything that has been structured inappropriately due to design flaws. Many of these automated systems play a vital role in society, and tragedy can result when they are not supported properly. For this reason, increased attention has been devoted to human performance and human error when interacting with systems (Matthews et al., 2000).

We need to have reliable models in place that ensure the maintenance of a high level of human performance when people are interacting with complicated and automated systems (O’Connor and Cohn, 2010). This requires the understanding of different kinds of error. Quantitative models have been used to do performance analysis and system design in vehicle control for some time. Attempts have been made to extend the models used for vehicle control to other types of human decision making. One such attempt is optimal control theory. The first of the vehicle control systems to be analyzed was in the field of aviation (Reiman and Manske, 2009).

The optimal control model is not necessary if activities by people are no longer included in the control task (Duffy, 2009). In these cases, the concern is with an overall interface manipulation skill. Decision models can be constructed in these cases through independent development and a direct approach. Instead of a single quantitative model for predicting human performance, which would account for nearly any situation, it is likely that a set of models will be more applicable and reliable. Each of these models can be applied to particular work conditions and combined with a qualitative framework that will define and describe the relationships involved (Matthews et al., 2000).

When seeking to understand human performance while interacting with a complex system, we must remember that people are not merely deterministic devices engaged in input and output (Reiman and Manske, 2009). Instead, they are often goal-oriented and will pursue information that they consider relevant to achieve their objectives. People behave in a teleological fashion. In other words, their behavior is frequently modified as they seek to achieve their goal. Furthermore, this behavior is not always dependent on feedback received while the person is engaged in the activity. The factor of experience during previous attempts can also have an impact. People engage in reasoned reflection and will frequently control behavior systems through selection. In this case, the selection is represented by human design choice when interacting with a complex system (Foyle and Hooey, 2008).

Human movement and position within the physical environment are not always controlled by a simple feedback loop (O’Connor and Cohn, 2010). People adapt to unfamiliar situations based on their previous experiences of successful patterns of behavior. This process overcomes the limits of the human sensory system with regard to immediate feedback. In other words, the humans interacting with the system respond too quickly for them to learn while they are interacting. Instead, people rely on their memory of previous attempts to interact with a complicated system (O'Connor and Cohn, 2010).

When human beings rely on a higher level of conscious planning, they usually engage in a complex series of activities as well as feedback correction while working on a task (Foyle and Hooey, 2008). Changes to their behavior will happen due to mismatches between the outcomes and goals. This is generally an inefficient process when one is working with a complex system functioning at a rapid pace. Therefore, when people are engaged in familiar activities, they will resort to the use of a set of rules that has been successful in the past (Duffy, 2009).

2.2.1. SKILL-BASED BEHAVIORS

Skill-based behavior involves sensory motor performance in which one engages during activities that follow from a certain intention (Reiman and Manske, 2009). These behaviors occur without an individual's conscious control. They represent highly integrated, automated, and smooth patterns of behavior. Only on certain occasions is performance based on some type of feedback control that involves motor output in response to the observation of error signals. In many skilled sensory motor tasks, the human body becomes a type of control system with multiple variables that continuously synchronize movements according to the response of the environment. The performance in these cases includes feed-forward control, a command signal from an operator to a source elsewhere in its external environment, and is dependent upon an efficient and flexible internal model of the defined complex system. The feed-forward nature of the control must be assumed to explain how coordinated movements can occur rapidly, such as in sports or when one is operating a vehicle. Experiments have demonstrated how the feed-forward control takes place in complicated industrial control tasks (Matthews et al., 2000).

Controlling voluntary movements is an immensely complex process (Reiman and Manske, 2009). The success of these rapid movements will be independent of how the limbs were positioned initially. The person will function according to different schemata, which are used to generate the complex movements. The schemata access the individual’s dynamic internal map of the environment. Sensory input is not generally involved with these types of movements. In other words, the input from the environment does not realign or update the individual's internal information. Performing complicated tasks such as walking on a straight line or drinking from a glass must be understood as an integrated whole and cannot be broken down into elements (Foyle and Hooey, 2008).

Usually, the performance of skill-based behavior is continuous (O’Connor and Cohn, 2010). Higher levels of control are possible and will take the form of conscious intent to make changes in the skill, such as moving faster or more accurately. In some cases, the performance will include skilled routines that can be isolated. In these cases, the routines are sequences that guide the process of conscious execution. Many human activities involve sequences of skilled activities, as a response to the specific situation (Duffy, 2009).

2.2.2. RULE-BASED BEHAVIORS

Rule-based behaviors consist of sequences of subroutines for work situations, which are familiar to the individual and can be controlled through the use of previously established rules (O’Connor and Cohn, 2010). These rules are often derived on an empirical basis, based on the success of previous attempts to engage in the activity. Sometimes they are communicated from other people at the time of construction. They can also be gained from the process of consciously solving a problem or developing a plan (Matthews et al., 2000).

Performance is goal-oriented and structured (Foyle and Hooey, 2008). The feed-forward control is based on stored rules. Frequently, the goal will not be explicitly understood but, rather, is implicit in the situation and automatically results in the release of the appropriate stored rules. This is a teleological type of control, as the rule has been developed through previous successful experiences. This control will evolve according to the behaviors that work best. The rule reflects functional properties that serve to constrain the behaviors exhibited by the environment. It is usually based on properties discovered through prior empirical investigations (Reiman and Manske, 2009).

In most cases, a goal will be reached only through a considerable sequence of acts during which direct feedback correction related to the goal is not possible. The feedback correction that occurs during performance of a task requires a functional understanding as well as analysis of the responses provided by the environment. This can be considered a type of independent, concurrent activity that is occurring at a higher level and is knowledge-based (Reiman and Manske, 2009).

The distinction between rule-based and skill-based behaviors is not always clear (Duffy, 2009). It can depend on the individual’s attention level as well as on his or her level of training. Most often, skill-based performance occurs without conscious attention. For this reason, the actors will not be able to explain how they control performance or how they have used information to guide their performance. On the other hand, rule-based behavior occurs at a higher level and is usually based on some type of explicit knowledge. In this case, the person will usually be able to report on the rules involved (Matthews et al., 2000).

In an unfamiliar situation, the individual may be interacting with an environment for which previous experience has provided no rules by means of which to control the situation. In such a context, the performance must be controlled at a higher level of conceptual understanding, through the application of knowledge-based behaviors (O'Connor and Cohn, 2010).

2.2.3. KNOWLEDGE-BASED BEHAVIORS

When a knowledge-based behavior is occurring, the goal has been explicitly formulated (Foyle and Hooey, 2008). The individual develops a useful plan after careful consideration of multiple options. The plans are tested according to whether they can achieve the goal. These tests can take the form of physical processes, which consist essentially of trial and error. They can also be performed conceptually if the individual understands the functional properties within the environment and can predict accurately the effects that the plan will produce. This type of behavior involves functional reasoning in which the person has a mental model of the system involved (Reiman and Manske, 2009).

2.2.4. SYMBOLS, SIGNS, AND SIGNALS

The information gained from absorbing the environment is an important part of human performance. The type of information varies according to the category of behavior (Duffy, 2009). Information gained through observing the environment may be perceived in a variety of ways. This is also true for the interface between humans and complex machinery or systems. A major reason for problems with the human-machine interaction is that an unfamiliar situation may cause an individual to misinterpreting information while shifting from one motor behavior to another and misreading the relevant cues (Matthews et al., 2000).

During skill-based behavior, the perceptual motor system synchronizes the individual's physical activity by operating as a type of continuous control system (Reiman and Manske, 2009). The system manipulates external objects and enables the individual's body to navigate within the environment. To accomplish this control, information taken from the environment must be in the form of time and space signals (Foyle and Hooey, 2008). The signals are a type of quantitative indicator that is continuous and can be applied to the time-based behavior occurring in the environment. The signals do not have meaning or any significance unless they are applied as a type of direct physical data related to time and space. Individual performance occurs on a skill-based level and is released through the features that are assigned to patterns of information due to prior experience. This process replaces individual participation in the environment with feedback from time and space control outcomes. Instead, the information acts as a sign that can activate the organism (Foyle and Hooey, 2008).

When an individual is engaging in rule-based behaviors, the information will be primarily perceived as a sign (O'Connor and Cohn, 2010). In this case, the information will modify or activate some predetermined manipulation or action. The signs are a reference to proper behaviors or situations, which are based on prior experiences. They are not a reference to functional properties or concepts related to the environment. The signs are often labeled with names that refer to the situation or to states within the environment. They may also represent the individual's task or goals. The signs may be used only to modify or select, and thereby to control, the sequence of subroutines. They cannot be a part of functional reasoning or involved in the generation of new actions. They also cannot predict possible responses in the environment (O'Connor and Cohn, 2010).

For information regarding the behavior occurring in the environment to be useful in relation to causal results, the data must be comprehended as a type of symbol (O'Connor and Cohn, 2010). The signs are a reference to rules or precepts for action. The symbols include concepts, which are tied to the functional properties and may be used for computation and reasoning through a suitable representation. The signs can be understood as a type of external reference to the actions and states of the environment. The symbols are a reference to the internal representation needed for planning and reasoning. In sum, rule-based behaviors rely on signs whereas knowledge-based activities are dependent on symbols (Foyle and Hooey, 2008).

The distinction as to whether perceptual information is a symbol, sign, or signal does not depend on the form of the information (Duffy, 2009). Instead, it depends on the context in which the data have been observed. This will be determined by the expectations and intentions of the individual perceiving the phenomenon. The three levels of behavior are characterized by the use of information in different ways. From the view of information processing, the distinction is clear (Foyle and Hooey, 2008).

The signals are the sensory data that represent variables in time and space according to their configuration within the environment (Reiman and Manske, 2009). An organism can process this information as a type of continuous variable. The signs represent a state within the environment regarding certain conventions as they apply to acts. The signs have features present within the environment and are associated with connected conditions for the actions. Generally, the signs are not processed directly. They serve merely as a method of activating the stored behavior patterns. The symbols include properties, relations, variables, and other information, which can be processed formally. Symbols consist of abstract concepts, which are defined by and related to a formal structure. This structure is applied to the processes and relations by which conventions are associated with features in the external world (Matthews et al., 2000).

Within the context of men and machines, information functions as a type of time-space signal (Foyle and Hooey, 2008). The signals are processed in a direct manner and become part of the dynamic control structure for motor performance. They are separate from the information of signs, which can modify the actions to a higher order of abstraction (Duffy, 2009).

2.2.5. ERRORS AND LIMITATIONS

Within the domain of knowledge-based actions, the causal and functional properties of the environment may be represented in a variety of ways (Matthews et al., 2000). A variety of problems can occur at the level of the human data processor when it is interacting with a complex physical environment. The constraint of humans' attention span limits the elements of the problem that can be processed simultaneously to only a few. Therefore, when there exists a complex net of causal relations, the environment must be understood as a type of chain of mental operations. This situation gives rise to phenomena such as the point of no return and law of least resistance. These are strategies that depend on sequences of relatively simple operations and may be preferred intuitively. People often exhibit little tendency to pause within a certain line of reasoning in order to develop parallel paths or alternative explanations (Duffy, 2009).

An effective method of overcoming the limitations of our attention span may be to modify the data processing occurring in the mind (Matthews et al., 2000). The mental model can be altered so that the causal structure better fits the specific task and optimizes a transfer of previous successful results. This method will minimize the requirement for new information.

The human cognitive process operates efficiently only when there is an extensive use of the model transformations, combined with simultaneous updating of the mental models. This is true for all categories of inputted information. The type of updating that occurs is generally below the threshold of conscious control or attention (Reiman and Manske, 2009).

With regard to analyzing verbal protocols, several strategies can be used for model transformation, which facilitates cognitive data processing (Reiman and Manske, 2009). One of these is aggregation, which involves taking elements of the representation and placing or aggregating them into chunks or units. Another strategy is abstraction, which involves representing the properties for the environment or a system by transferring them to so that they become a category of a higher-level model. The use of ready-made solutions and technologies can also be an effective strategy. This approach involves transferring the representation to a category within a model that has an already evident solution or rules that may be available to generate the solution (Matthews et al., 2000).

An abstraction hierarchy has been formed to analyze the verbal protocols of process plant control and computer maintenance (Foyle and Hooey, 2008). In this hierarchy, systems' functional properties are represented through concepts that belong to different levels of abstraction. The lowest of these levels represents the physical form of the system, or its material configuration. The next higher level of abstraction is represented through the functions or physical processes of the components in the system. This level is presented in a language associated with particular mechanical, chemical, or electrical properties. Continuing to move upwards, the next level of abstraction includes the functional properties that are represented by general concepts. At this level, there is no reference to the physical equipment or processes involved with the functions being implemented (Duffy, 2009).

At the lower levels of abstraction, the component configuration for the physical implementation will match the elemental descriptions (Matthews et al., 2000). At the next level of abstraction, the changes in the properties of the system are represented through removing details regarding the material or physical properties. The information added at the higher abstraction levels governs the functioning of the elements at the lower levels (Foyle and Hooey, 2008). When a system is manmade, the principles of the higher levels can be derived according to the purpose of the system. For a change in the level of abstraction to occur, there must be a shift in the structure and concepts of the representation, along with a change regarding the information deemed suitable for characterizing the operation or function at the various levels. The observer will ask various questions regarding the environment according to the nature of his or her internal representation (Reiman and Manske, 2009).

Important functions within human-machine systems are related to the correction of circumstances that have resulted due to faults or errors (Duffy, 2009). The events are described as faults or errors only in reference to the normal function or intended state of the system. This means that the functional meaning of the system must be predetermined. The model’s functioning at the various levels of abstraction can play a role in coping with systems that are plagued by errors (O’Connor and Cohn, 2010). The reasons attached to the proper functions are taken from a top-down approach, beginning with the functional purpose. A relatively clear difference exists between the propagation of faults and causes and the reasons for functions within the hierarchy. The role that the abstraction hierarchy plays is evident in vertical protocols, which are involved in the diagnostic searches of information-processing systems. In these cases, the diagnosticians must consider the functions of the system at a variety of levels.

The person will identify the information flow as well as the functional state by approaching the subject from a top-down perspective (Foyle and Hooey, 2008).

2.2.6. TRANSLATION FOR THE OPERATOR IN THE INDUSTRIAL SETTING

An organization of the different types of information processing involved in industrial tasks was developed by Jens Rasmussen of Denmark. This pattern provides a useful framework for identifying the types of errors likely to occur in different operational situations, or within different facets of the same task that may place different information-processing demands on the individual. The classification system is known as the skill-based, rule-based, and knowledge-based approach. The three classifications refer to the degree of conscious control exercised by the individual over his or her activities (Reason, 1990).

In the knowledge-based mode, the task is carried out by the human in an almost totally conscious fashion. This would occur if a beginner (e.g., an operator in training) is performing a task, or if an experienced individual encounters a completely novel situation. In either of these circumstances, substantial mental exertion would have to be asserted to evaluate the condition, and his or her responses would likely be slow. In addition, after each action, the person would need to evaluate its effect prior to taking additional action, which would probably further slow his or her responses to the situation. Knowledge-based performance results in a nominal error rate of 1:2 (Reason, 1990).

In the skill-based mode, efficient performance of well-practiced, mainly physical actions of which practically no conscious reasoning occurs. Skill-based actions are normally commenced by an explicit occurrence, such as the requirement to operate a valve, that may arise from an alarm, a procedure, or an indication from another individual. The well-practiced task of opening the valve will then be executed largely without conscious thought. The skill-based performance mode results in a nominal error rate of 1:1,000 (Reason, 1990).

The last category involves the use of rules, which may have been learned as a result of interacting with the plant, through formal training, or by working with experienced process workers. The level of conscious control is midway between that of the knowledge- and skill-based modes. The rule-based performance mode results in a nominal error rate of 1:100 (Reason, 1990).

Next, it is important to describe and distinguish between slips and mistakes. Slips are defined as errors in which the intention is correct but a failure occurred in the actual carrying out of the activities required. For example, a worker may know that a receptacle needs to be filled but instead may fill a similar receptacle nearby. This slip may occur if the receptacles are poorly labeled, or if the worker is confused with regard to the location of the correct receptacle. Mistakes, by contrast, arise from an incorrect intention, which leads to an incorrect action sequence that may be quite consistent with the wrong intention. For example, a worker might wrongly assume that a reaction was endothermic and might apply heat, thereby causing overheating. Incorrect intentions may arise from lack of knowledge or an inappropriate diagnosis (Norman, 1981).

Slips can be described as due to misapplied competence because they are examples of errors in highly skilled, well-practiced activities that are characteristic of the skill-based mode. Mistakes, on the other hand, are largely confined to the rule- and knowledge-based performance modes.

In the skill-based mode, the individual can function very effectively by using pre-programmed sequences of behavior that do not require much conscious control. It is only occasionally needed to check on progress at specific points when operative in this mode. An undesirable consequence accompanying this efficiency is that strong habits can take over when attention to checks is diverted by distractions, or when unfamiliar activities are embedded in a familiar context (Reason, 1990).

With regard to mistakes, two separate mechanisms operate. In the rule-based mode, an error of intention can occur if an improper diagnostic rule is utilized. For example, a worker who has considerable experience in stagnant, shutdown-status power plant chemistry may have learned diagnostic rules that are inappropriate for operational, dynamic, and volatile power plant chemistry. If he or she attempts to apply these rules to evaluate the cause of a continuous process disturbance, a misdiagnosis could result, leading in turn to an inappropriate action. In other situations, diagnostic rules that have been successful in the past may be overused. Such sound rules are usually applied first even if they are not necessarily appropriate (Reason, 1990).

People often have a tendency to force a new situation into the mold of previous events. For example, in one incident, some modifications were made to a pump used to transfer a liquid. When movement of the liquid was complete, the worker pressed the stop button on the control panel and saw that the “pump running” light went out. He also closed a remotely operated valve in the pump delivery line. Several hours later, the high-temperature alarm on the pump sounded. Because the worker had stopped the pump and had seen the “pump running” light go out, he assumed that the alarm was faulty and ignored it. Shortly thereafter the pump exploded. The explanation for this unwanted sequence of events is that when the pump was modified, an error was introduced into the circuit. As a result, pressing the stop button did not stop the pump but merely switched off the running light. The pump continued running and overheated, and the material in it decomposed explosively. In this example, a major contributor to the accident was the worker’s assumption that when the “pump running” light went out, the pump must have stopped. That assumption prevailed even through the sounding of a high-temperature alarm, which would usually be associated with an operating pump. The rule “if Pump light is extinguished, then pump is stopped” was so strong that it overcame the evidence from the temperature alarm that the pump was still running (Reason, 1990).

In the case of knowledge-based mistakes, other factors are important. Most of these factors result from the considerable demands on information-processing capabilities that become necessary when a situation must be evaluated in unfamiliar conditions. Given these demands, it is not surprising that humans do not perform very well in high-stress, unfamiliar situations where they are required to “think on their feet” in the absence of rules, routines, and procedures to give them suitable direction. For example, operators may only utilize the finite information that is immediately available to evaluate the situation, rather than seeking more comprehensive data or assistance from others that are more knowledgeable. They may also become overconfident in the correctness of their knowledge. One typical behavior that occurs during knowledge-based problem solving is an insistence that one course of action is correct, leading an individual or the operating team to become tangled in one aspect of the problem and exclude all other aspects that should be considered. This behavior characterized the Three Mile Island nuclear accident in Pennsylvania. The opposite form of behavior can also be observed, in which the overloaded worker gives his or her attention superficially to one problem after another, without solving any of them (Janis, 1972).

In the skill-based mode, recovery is usually prompt and effective, because the individual will have familiarity with the expected outcome of his or her actions and will therefore get timely feedback with respect to any slips that may have prevented this outcome from being reached.

This highlights the role of feedback as a significant aspect of error recovery. In the case of mistakes, the mistaken intention tends to be very resistant to contrary evidence. People tend to ignore feedback information that does not support their expectations of the situation (Reason, 1990).

2.3. ESCALATION

To fully understand how technological advancements interact with human performance at nuclear plants, we should consider the principle of escalation (Karwowski, 2006), or the idea that problems tend to increase. What begins as a small problem or error leads to an increase in the coordinating and cognitive demands required to accomplish a task. This frequently results in larger errors and an increase in problems. In general, there is a positive relationship between the scope of a problem and the amount of information processing necessary to cope with it. When there are more problems in the underlying system, the additional information processing needed to resolve the situation increases. A more complex system requires greater effort to deal with unexpected problems or errors. As technology progresses, the complexity of the systems involved grows as well (Salvendy, 2012).

2.4. ACTIVE ERRORS

By definition, active errors have effects that are noticed immediately. They can occur across the spectrum of human behavior modes but are usually associated with individuals in frontline operations of a system. Examples include officers of ships, air traffic controllers, pilots, or control room operators in a nuclear facility. When examining active errors, it is important to take into account the complexity associated with human nature (Cacciabue and Cassani, 2011), which includes all the emotional, mental, social, biological, and physical characteristics that define people’s limitations, abilities, and tendencies (Stoop and Dekker, 2012). An important aspect of human nature relevant to this study is the innate tendency toward imprecision. Whereas machines tend to be precise, people are usually imprecise, especially when under stresses such as time pressure. Human fallibility can cause people to get into situations that are beyond their abilities. Logically, complex systems intensify a person’s susceptibility to make mistakes (Stern and Stern, 2012).

Because active errors are common and often very consequential, their most prevalent causes should be understood to aid in reducing them. For example, most individuals tend to overestimate their abilities in order to maintain control at their work station (Cacciabue and Cassani, 2011). In this instance, the maintenance of control means that the task occurs as it is supposed to with the person performing in the appropriate fashion. Such overestimation can occur for at least two reasons. First, consequential error is rare, and many times an error occurs with no adverse result. Thus, people conclude that errors will not be caught unless they are inconsequential. Second, people do not know or acknowledge their own capabilities. For example, most people can function on insufficient sleep or work during times of distraction. They can also perform work duties during poor environmental conditions such as extreme cold, heat, vibration, or noise. People can become accustomed to these conditions. However, if the limits of a person’s capabilities are exceeded, the chance making errors increases. The impact of physical or environmental limitations can be especially problematic when work is taking place within a complex system (Stoop and Dekker, 2012).

Stress is a prominent contributor to active errors (Chang et al., 2014). Stress is not always a problem; sometimes it is healthy and normal. Stress can focus attention and can aid an individual’s performance. However, elevated stress can overpower an individual and thus become detrimental to performance. Stress can be understood as the body's physical and mental response to perceived threats within the environment. The important word in this case is *perceived*, because the individual's perception is central to adaptation in order to cope with a threat. Stress tends to increase in conjunction with lack of familiarity with the situation. Extreme stress can lead to panic, which inhibit a person's ability to act or to sense, recall, or perceive essential elements of a situation. Fear and anxiety often follow when an individual believes that he or she cannot respond appropriately to a situation. This fear and anxiety and frequently accompanied by a lapse of memory and an inability to perform certain actions or to think critically (Ramanujam and Goodman, 2011).

Another important factor in mental errors is people's tendency to avoid mental strain (Cacciabue and Cassani, 2011). Most people engage only reluctantly in long periods of concentrated thinking. They also tend to avoid situations in which they must display heightened levels of attention for an extended period of time. Thought can be a slow and laborious process that requires significant effort. Therefore, people often seek familiar patterns and tend to apply solutions with which they are already familiar. This shortcutting is a type of mental bias designed to reduce the cognitive effort required in making decisions (Ramanujam and Goodman, 2011).

One of these mental biases is assumptions (Goodman et al., 2011). People frequently accept as true certain conditions that have not been verified. Another bias is habit, or an unconscious behavior pattern acquired through frequent repetition. Confirmation bias can also be problematic and is exemplified by a reluctance to abandon established solutions. Individuals tend not to change their way of thinking or behaving, even when there is conflicting information or when better solutions are available (Stern and Stern, 2012). Thus, people often defend their established position and ignore blatant evidence to the contrary. Next, frequency bias refers to a tendency to gamble that a familiar solution will work, or to viewing information as more important when it has occurred more frequently. Finally, people often suffer from availability bias, the tendency to use solutions that immediately come to mind or to place greater importance on facts that are readily available (Stoop and Dekker, 2012).

Limited working memory can be a factor in active errors (Rebhan, 2009). We rely on short-term memory to make decisions and solve problems. This short-term memory can be understood as a storeroom that demands attention and is temporary in nature. It is used to recall new information and is actively involved with recall, storage, and learning. When the limits of this memory are exceeded, errors can result (Chang et al., 2014).

2.5. LATENT ERRORS

Like active errors, latent errors may also have adverse consequences, but they may lay dormant within a complex system for a significant period of time before they manifest (Rebhan, 2009). They often become evident only when combined with other factors to result in a breach of a system's defenses. Latent errors are frequently committed by individuals whose activities are removed in space and time from the direct human system interface. For example, they may be committed by maintenance personnel, managers, construction workers, high-level decision makers, or system designers well before their manifestation (Rebhan, 2009).

An analysis of significant nuclear accidents such as Chernobyl or Three Mile Island found that latent errors frequently pose the most important threat when people interact with a complex system (Stern and Stern, 2012). Traditionally, accident investigations and reliability analyses have concentrated on direct equipment failures and operator errors (Ramanujam and

Goodman, 2011). Although operators do make mistakes, such as those presented above as examples in the section on active errors, many of these mistakes have an underlying cause connected to a latent error, such as when an operator of a complex system inherits the mistakes made by the designers or installers (Stern and Stern, 2012).

For these reasons, the study of latent failures may be more beneficial than a focus on operator mistakes (Stern and Stern, 2012). Unfortunately, most research on human factors has concentrated on improving the human-machine interface, an emphasis that entails a focus on active errors, even though latent errors inherent within the system can be associated with a broader range of possible problems. In other words, active errors may be only the outcome of latent problems that have long been embedded within the system (Chang et al., 2014).

Latent human error comes into play when individuals' propensity for error is enhanced by the environment in which they work and the systems with which they interact. According to James Reason (2000), two adverse effects can result from latent conditions: their ability to provoke errors, and their impact on the long-term health and welfare of the system that created them. These conditions do not necessarily contribute immediately to the possibility for error; rather, they can rest hidden within a system until the requisite elements align and cause the latent error to become activated (Reason, 2000).

Rapid technological advances across all industries have generated an additional focus on latent error (Rebhan, 2009). Many of today's complex systems have operators who are remote and removed from the processes that they control. As the systems have become more complex, they can intervene between people and the physical tasks involved. When nuclear technology was initially introduced, operators still engaged in direct manipulation and sensing of the systems that they were operating. In other words, they could still touch and see the system that they controlled. As technology has continued to advance, the remote manipulation of devices and sensing has further removed humans from the processes under their charge (Cacciabue and Cassani, 2011).

The most significant changes in how humans interact with complex systems have reslted from the decreased cost of powerful computing (Stoop and Dekker, 2012). Many system operators are now separated from their process by more than one component of a control system. At a lower level, the task interactive system controls the detailed parts of an operation. There is an intervention between the specialized system and the operators due to the need for a human system interface. The control system presents pieces of information to the operator, but the interface allows only a prescribed degree of interaction between the person and the remote process. This creates a situation of supervisory control. The person adjusts, monitors, and initiates processes and systems that are also automatically controlled (Chang et al., 2014). Nevertheless, the stimuli contained within the operational environment are impacting these remote operators at all times and can still contribute to errors. Moreover, their remoteness can increase the possible impact of latent errors introduced by people who designed or installed the system. In fact, those nuclear manufacturers, installation teams, and facility personnel who are considered the best in their field may be prone to making the worst mistakes (Reason, 2000). Although the focus in accident investigation may be placed upon the operators, another key source of errors arises when the systems themselves are not scrutinized for their own propensity to cause errors (Reason, 2000).

The increasing complexity and automation of systems at nuclear facilities are both making latent errors more difficult to detect and giving them greater capability to lead to a serious incident (Rebhan, 2009). If a latent error occurs in the development of a monitoring system, a remote operator may not become aware of any problems until it is too late to reverse the process. Or a latent error could be embedded in the design of a semi-automated control process. In this case, the operator might detect a problem with a plant parameter and might initiate the necessary actions to correct the problem. However, if a latent error is present, the control processes may not respond appropriately to the operator’s actions. As a result, alternative means costing more time and money may be required, or the severity of the problem could escalate (Goodman et al., 2011).

The problems described in the previous paragraph are related to the design of a monitoring and a control system, respectively (Rebhan, 2009). Unlike an active human error, such design problems could span numerous pieces of equipment and could potentially go undetected for years, even decades. Not until a problem in plant operation arises would such a latent error become detectable. For this reason, it is crucial for safety monitors and researchers to shift away from the traditional approach of concentrating on operator errors. Although active errors are important, latent errors can be even more catastrophic (Stoop and Dekker, 2012).

2.6. FORESEEABLE ERRORS

Human beings are notoriously error-prone (Chang et al., 2014). We now know a great deal about the specific types of errors that people are likely to make. These mistakes are frequently described as foreseeable errors. Since they are expected, they can be accounted for in a system. Complex modern systems can be designed to accommodate this category of human errors and ensure that they remain benign. This approach is called designing for error (Rebhan, 2009). As technology advances and complexity expands, the number of foreseeable errors tends to rise, requiring additional protective steps.

A number of factors must be considered when designing a complex system to accommodate foreseeable human error (Cacciabue and Cassani, 2011). One way to accomplish this is to do a human reliability assessment (HRA), which encompasses techniques for statistically determining the probability that a complex system will fail given certain circumstances. The techniques take into account the chance that various components of the system, including the operators as well as mechanical components, will fail in specific ways (Stoop and Dekker, 2012). In this way, the human operator is considered a part of the system that is fallible like any other (Ramanujam and Goodman, 2011).

Human performance varies across individuals and situations (Goodman et al., 2011). Tasks require different levels of manual skills, training, and attention. As noted above, the types of work in which people engage can be broken down into three general categories: knowledge-based, rule-based, or skill-based. Using these categories as constraints assists in the analysis of human behavior and error (Rasmussen, 1983).

The probability of human error is proportional to the necessary level of knowledge needed to perform the task (Goodman et al., 2011). Tasks that require a complicated series of actions must frequently be done in a specific order. For this to happen, an individual must have the knowledge ahead of time or must be provided with it at a key moment. Information that must be maintained in the operator’s memory is sometimes known as knowledge in the head (KIH). Processes that involve high levels of KIH also tend to result in a significant amount of errors (Stoop and Dekker, 2012).

Along with KIH, there is knowledge in the world, or KIW (Ramanujam and Goodman, 2011), which refers to knowledge held within the components of the task. In a KIW situation, the elements included in the task contain information necessary for the proper performance of the task. For example, in the case of an assembly that involves several washers and nuts, there may be only one sequence that results in the proper disassembly of these components. However, the disassembly sequence is contained within the elements of the task. These types of situations result in fewer errors than those requiring KIH, presumably because they do not depend on the reliability of human memory (Goodman et al., 2011).

Another approach to designing a system that can accommodate foreseeable human error is the Critical Incident Technique (Chang et al., 2014). This method assumes that problems do not occur spontaneously. Each failure is associated with critical incidents that allow the failure to occur. A critical incident is a situation in which the errors nearly cause a failure or a failure is already occurring, but where something prevents a disaster from ensuing. The Critical Incident Technique is an anonymous reporting tool (Mengolini and Debarberis, 2012). It usually relies on a survey to elicit information from operators. This approach works most efficiently when it is part of a continuing program and not just a single solicitation. The people supplying information for a critical incident program are generally encouraged to provide sufficient identification information so that they can be contacted by the investigators if necessary. However, this request for personal disclosure can discourage response. In all cases, for proper implementation of this specific technique, the individuals providing information must have their identity removed from any reports so that other individuals at their place of employment cannot identify them (Ramanujam and Goodman, 2011).

One effective way to design a system that accounts for foreseeable human errors is a fault tree analysis (Stern and Stern, 2012). This approach is diagrammatic and requires that the system be logically broken down into its functional components. The relationships among these components are then identified in a diagram that depicts the elements and their relationships to each other (Cacciabue and Cassani, 2011).

Most fault trees have two possible outcomes: a specific type of failure or a successful operation. These possibilities are represented at the top of the tree (Goodman et al., 2011). The elements that result in each outcome are listed below. The branches of the tree illustrate the logical relationships between the functional elements. Some fault tree analyses will include a probabilistic risk assessment (PRA) that calculates the statistical probabilities associated with each branch of the tree. This approach to accounting for foreseeable human errors has the advantage of being a top-down analysis that begins with the postulate of an outcome—for example, in the case of a nuclear power plant, a reactor core breach (Ramanujam and Goodman, 2011).

2.7. UNEXPECTED EVENTS

Unexpected events are a type of abnormal behavior of systems (Dauer et al., 2011). They are often caused by human errors and result in the loss of productivity. Many of the more popular practices and methodologies applied in systems engineering do not reduce the chance of unexpected events. However, engineers can reduce these operational risks if they take into account the limitations of human operators when interacting in a system (Lelieveld, Kunkel, and Lawrence, 2012). As with foreseeable errors, as technology advances and complexity grows, the possibility of unexpected events will rise and will require added analysis and remediation.

Many mishaps, though considered unavoidable, are attributable to some type of user error (Karakosta, Pappas, Marinakis, and Psarras, 2013). Human limitations provide numerous chances for unexpected events to occur. Usability engineering can frequently solve some of the problems, but this approach requires significant knowledge of system behavior in order to integrate safeguards (Mengolini and Debarberis, 2012). The methods used to mitigate risks of human error must be integrated within the system through engineering practices. This involves the addition of guidelines and methods to traditional system engineering to protect the system from unexpected events. These guidelines are based on a study of the known failures, interviews with system engineers, and background research (Saey et al., 2010).

To understand unexpected events, it is helpful to classify them (Mohan, 2011). One method of classification consists of three general categories: operator confusion, intra-system inconsistency, and inter-system mismatches. Operator confusion occurs when there is a mismatch between the operator's perception of the state of the system and its actual state; intra-system inconsistencies include problems that occur between units within a system; and inter-system mismatches are problems resulting from faulty communication between different systems (Wehrden et al., 2012).

During standard operations, the system units will comply with common scenarios (Mohan, 2011). This is often referred to as a normal system state. When operating, the system units are receiving event information. An event is considered normal if a unit is designed to respond properly to the specific event. If the unit is not designed to respond to the specific event, then the event is described as a slip. Many slips are caused by hardware faults or an unexpected action by the user (Mengolini and Debarberis, 2012). The occurrence of a slip changes the system to an exceptional state. A resilient system will contain protocols to return the system to its normal state. However, when protocols do not exist to combat the exceptional state, the next event may result in some type of mishap or unexpected outcome. This can then be described as an unexpected event (Law et al., 2013).

Most systems are designed for operation according to certain scenarios (Lelieveld, Kunkel, and Lawrence, 2012). The responses to an event by any of a system’s units are designed according to a specific operating scenario that includes various assumptions. During normal operations, a system assumes a certain scenario; this is referred to as the system context. When a system unit receives input indicating an exceptional event, the operating scenario may be different (Lelieveld, Kunkel, and Lawrence, 2012). For example, a unit failure may result in an operating scenario that changes to call for unit replacement. If the system’s units all operate according to the changed scenario, then the system is described as being context-compliant. If this does not occur and some of the system’s units are not complying with the new context, then the system enters a state of being context-inconsistent (Saey et al., 2010).

Events can be understood as expected if they are in compliance with the operating scenario, which defines the context of operation. For all the system units to work properly, they need to behave in compliance with the procedures that have been defined in the context. This includes the operator. Unexpected events result from the need for human control in exceptional situations such as an abnormal event, alert, or emergency. During design, the primary scenarios are anticipated, but it is impossible to predict all scenarios. To handle exceptional situations properly and safely, the system relies on a human operator. In such instances, the operator will have unusual control over the system. It is expected that human operators will use proper judgment when applying their exceptional control (Mohan, 2011).

Exceptional events have a wide range of sources (Wehrden et al., 2012), including designs that do not fit operational needs, interruptions in the normal operating procedure, unintentional actions that are not compliant with their context, failure to comply with a changing context, or false perceptions (Karakosta, Pappas, Marinakis, and Psarras, 2013).

2.8. TAXONOMIES

A taxonomy classification method can be used to classify and code errors. Such classification is essential to analyzing data and spotting error patterns within a system's design. However, when taxonomies are applied in a nuclear setting, no single taxonomy can cover all possible scenarios (Wallace and Ross, 2006). Taxonomies are industry-specific, and the classifications that work for one industry may not work for another. Even within the nuclear industry, taxonomies may change due to new data. Systems must be designed with this type of rapid evolution in mind.

A traditional system design is based on the assumption that certain required specifications will be met (Dauer et al., 2011). These specifications are based in turn on a requirement analysis performed in accordance with defined scenarios. In practice, however, specification documents are often not well associated with conceivable scenarios (Lelieveld, Kunkel, and Lawrence, 2012). Furthermore, most documents on procedure specifications do not describe the relationships that exist within the system’s states. They may also not describe the appropriate desired responses to all possible events. As a consequence, the system design derived from this input does not include the necessary means for matching the system’s activity with the operating scenarios (Law et al., 2013).

It is common for a system’s behavior to be properly understood only after an incident occurs (Christoudias and Lelieveld, 2013). This means that during the design, the event that resulted in a mishap was not anticipated. Frequently, this is due to not considering all possible states of the system during system design. It is crucial to solve this problem by thoroughly researching the maximum number of possible scenarios to ensure that a complex system will operate safely. Proper protection against unexpected events requires formalizing them within operational scenarios. There must also be a close relationship between the state of the system and the scenario (Lelieveld, Kunkel, and Lawrence, 2012).

2.9. THE INTERNATIONAL ATOMIC ENERGY AGENCY

The International Atomic Energy Agency (IAEA) is a crucial stakeholder in the global nuclear industry. It was established in 1957 and still operates as an autonomous organization promoting the use of nuclear power for peaceful purposes (Thomson, 2011). The IAEA also seeks to reduce the use of atomic energy for weapons or other military purposes. It functions independently from the United Nations but reports to the U.N. General Assembly (Mengolini and Debarberis, 2012).

The IAEA has three basic concerns: safeguards and verification, science and technology, and safety and security (Perko, Turcanu, and Carlé, 2012). These three concepts underlie all missions carried out by the IAEA. In its interaction with the U.N., the IAEA generally interfaces with the Security Council. The IAEA is composed of three general bodies: the Secretariat, the General Conference, and the Board of Governors (Budnitz, 2010).

The IAEA has three primary functions (Mengolini and Debarberis, 2012). It acts as a hub for the myriad fields of science, and it considers how nuclear technology can be peacefully applied. It also ensures the security and safety of atomic facilities through standards and by providing information on the nuclear industry. To fulfill its mission, the IAEA inspects the world’s nuclear facilities to ensure that they are being run properly and used in a peaceful manner. As an illustration of the diversity of nuclear science activities, in 2004 the IAEA introduced the Program of Action for Cancer Therapy (PACT), in a response to developing countries’ need for modern treatment programs using radiotherapy (Högberg, 2013).

2.9.1. THE INTERNATIONAL NUCLEAR EVENT SCALE

In 1990, the IAEA introduced the International Nuclear and Radiological Event Scale (INES) (Loomis, 2011) to provide simple and readily understandable information about nuclear incidents. The scale is logarithmic and similar in concept to the scale that measures the magnitude of earthquakes; each new level on the scale is 10 times as severe as the previous one. For earthquakes, intensity can be evaluated in a quantitative fashion. However, judgments of the severity of a nuclear incident are more subjective and require extensive investigation. For this reason, an INES level is generally not assigned to an incident until a significant period of time following the event. Unfortunately, this means that the scale is sometimes not useful for rapid deployment of disaster aid (Marques, 2011).

The INES has seven levels, from the least severe to the most problematic: anomaly, incident, serious incident, accident with local consequences, accident with wider consequences, serious accident, and major accident (Law et al., 2013). The first three levels are sometimes grouped together under the category of atomic incidents; the highest four categories are referred to as nuclear accidents. An eighth level, referred to as a deviation of level 0, indicates an event with no safety significance. For example, a reactor might need to be shut down because a cooling circuit leaked, but the event is not an atomic incident or accident if it does not result in the release of radioactive substances (Marques, 2011).

The first level of the International Nuclear and Radiological Event Scale, an anomaly, is achieved when a member of the public is exposed to radiation exceeding the yearly statutory limits (Loomis, 2011). This could be a minor problem involving safety components. However, there are significant defenses against harm. The second level is known as an incident and results

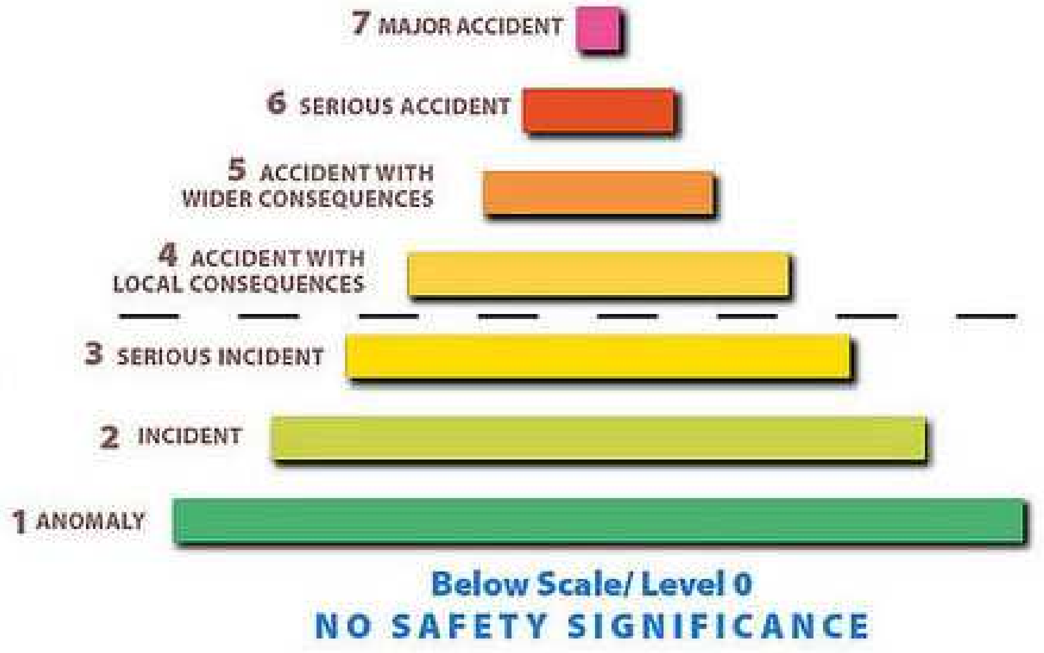

Figure 1. The International Nuclear and Radiological Event Scale (NRC website, n.d.).

in a worker being exposed to radiation beyond the yearly statutory limits (Christoudias and Lelieveld, 2013). It may also involve a member of the public being exposed to a radiation level in excess of 10 millisieverts (mSv). Typical problems at this level include improperly packaging radioactive sealed sources, the locating of an orphan source of radioactivity that is still sealed, or the discovery of a significant problem with safety provisions. The impact of level 2 problems on radiological barriers and controls can result in substantial contamination at the facility. Radiation levels in the operating area will exceed 50 mSv (Högberg, 2013).

Level 3 is considered a serious incident (Dauer et al., 2011). Although there may be severe contamination within the problem area, it is not likely that the public will be exposed to significant radiation. Workers in the area may be exposed to radiation levels exceeding 10 times the yearly limit. People may experience non-lethal health problems such as radiation burns. An example of a Level 3 incident is the delivery of a sealed, highly radioactive source without the observance of adequate procedures and standards (Thomson, 2011).

The fourth level of the INES is an accident with local consequences (Dauer et al., 2011). Substantial amounts of radioactive material may be released, and public exposure is highly probable. The fuel may be damaged, resulting in more than 0.1% of the core inventory being released. The results will likely include at least one death from radiation (Högberg, 2013).

The fifth level is an accident with wider consequences (Loomis, 2011). The probable result here is the release of significant quantities of radioactive material, with a substantial probability of public exposure. Severe damage to the reactor core may also occur, along with multiple deaths from radiation and a limited release of radioactive material into the environment that may require countermeasures (Law et al., 2013).

The sixth level of the INES is a serious nuclear accident (Dauer et al., 2011). This includes a release of radioactive material into the environment that requires the use of well-planned countermeasures (Budnitz, 2010).

The highest level of the INES, level seven, is a major nuclear accident (Mengolini and Debarberis, 2012) that has a significant impact on both the environment and people. Radioactive materials are released in large quantities, and both extended and well-planned countermeasures must be used. Only been two events in history have reached this level (Christoudias and Lelieveld, 2013).

Table 1 summarizes the INES levels.

Table 1. International Nuclear Events Scale (International Atomic Energy Agency, 2002)

	NATURE OF THE EVENTS	**CRITERIA OR SAFETY ATTRIBUTES**		
		OFF-SITE IMPACT	**ON-SITE IMPACT**	**DEFENSE-IN-DEPTH DEGRADATION**
7 MAJOR ACCIDENT	External release of a large fraction of the radioactive material in a large facility (e.g., the core of a power reactor). This would typically involve a mixture of short and long-lived radioactive fission products (in quantities radiologically equivalent to more than tens of thousands of terabecquerels of iodine-131). Such a release would result in the possibility of acute health effects; delayed health effects over a wide area, possibly involving more than one country; long-term environmental consequences.	MAJOR RELEASE: WIDESPREAD HEALTH AND ENVIRONMENTAL EFFECTS		
6 SERIOUS ACCIDENT	External release of radioactive material (in quantities radiologically equivalent to the order of thousands to tens of thousands of terabecquerels of iodine-131). Such a release would be likely to result in full implementation of countermeasures covered by local emergency plans to limit serious health effects.	SIGNIFICANT RELEASE: LIKELY TO REQUIRE FULL IMPLEMENTATION OF PLANNED COUNTERMEASURES		
5 ACCIDENT WITH WIDER CONSEQUENCES	External release of radioactive material (in quantities radiologically equivalent to the order of hundreds to thousands of terabecquerels of iodine-131). Such a release would be likely to result in partial implementation of countermeasures covered by emergency plans to lessen the likelihood of health effects.· Severe damage to the installation. This may involve severe damage to a large fraction of the core of a power reactor, a major criticality accident or a major fire or explosion releasing large quantities of radioactivity within the installation.	LIMITED RELEASE: LIKELY TO REQUIRE PARTIAL IMPLEMENTATION OF PLANNED COUNTERMEASURES	SEVERE DAMAGE TO REACTOR CORE / RADIOLOGICAL BARRIERS	
4 ACCIDENT WITH LOCAL CONSEQUENCES	External release of radioactivity resulting in a dose to the critical group of the order of a few millisieverts. With such a release the need for off-site protective actions would be generally unlikely except possibly for local food control.· Significant damage to the installation. Such an accident might include damage leading to major on-site recovery problems such as partial core melt in a power reactor and comparable events at non-reactor installations.· Irradiation of one or more workers resulting in an overexposure where a high probability of early death occurs.	MINOR RELEASE: PUBLIC EXPOSURE OF THE ORDER OF PRESCRIBED LIMITS	SIGNIFICANT DAMAGE TO REACTOR CORE/RADIOLOGICAL BARRIERS/FATAL EXPOSURE OF A WORKER	
3 SERIOUS INCIDENT	External release of radioactivity resulting in a dose to the critical group of the order of tenths of a millisievert. With such a release, off-site protective measures may not be needed. On-site events resulting in doses to workers sufficient to cause acute health effects and/or an event resulting in a severe spread of contamination; for example a few thousand terabecquerels of activity released in a secondary containment where the material can be returned to a satisfactory storage area.· Incidents in which a further failure of safety systems could lead to accident conditions, or a situation in which safety systems would be unable to prevent an accident if certain initiators were to occur.	VERY SMALL RELEASE: PUBLIC EXPOSURE AT A FRACTION OF PRESCRIBED LIMITS	SEVERE SPREAD OF CONTAMINATION/ ACUTE HEALTH EFFECTS TO A WORKER	NEAR ACCIDENT NO SAFETY LAYERS REMAINING
2 INCIDENT	Incidents with significant failure in safety provisions but with sufficient defense-in-depth remaining to cope with additional failures. These include events where the actual failures would be rated at level 1 but which reveal significant additional organizational inadequacies or safety culture deficiencies.· An event resulting in a dose to a worker exceeding a statutory annual dose limit and/or an event which leads to the presence of significant quantities of radioactivity in the installation in areas not expected by design and which require corrective action.		SIGNIFICANT SPREAD OF CONTAMINATION/ OVER EXPOSURE OF A WORKER	INCIDENTS WITH SIGNIFICANT FAILURES IN SAFETY PROVISIONS
1 ANOMALY	Anomaly beyond the authorized regime but with significant defense-in-depth remaining. This may be due to equipment failure, human error or procedural inadequacies and may occur in any area covered by the scale, e.g. plant operation, transport of radioactive material, fuel handling, waste storage. Examples include: breaches of technical specifications or transport regulations, incidents without direct safety consequences that reveal inadequacies in the organizational system or safety culture, minor defects in pipework beyond the expectations of the surveillance programme.			ANOMALY BEYOND THE AUTHORIZED OPERATING REGIME
0 DEVIATION	Deviations where operational limits and conditions are not exceeded and which are properly managed in accordance with adequate procedures. Examples include: a single random failure in a redundant system discovered during periodic inspections or tests, a planned reactor trip proceeding normally, spurious initiation of protection systems without significant consequences, leakages within the operational limits, minor spreads of contamination within controlled areas without wider implications for safety culture.	NO SAFETY SIGNIFICANCE		

2.9.2. SAFETY ANALYSIS OF NUCLEAR POWER PLANTS

The IAEA is responsible for regular safety analyses of nuclear facilities (Prasad et al, 2011). These analyses evaluate the physical environment at the nuclear plants. They are intended to demonstrate that the proper safety requirements have been met for all types of initiating events. These requirements include creating policies for ensuring the integrity of the barriers preventing the release of radioactive materials.

The IAEA conducts two basic types of analyses of nuclear plants: probabilistic and deterministic safety analysis (Sugiyama et al., 2012). Deterministic safety analysis involves predicting the responses to possible initiating events (Sugiyama et al., 2012). There is a precise set of rules and criteria for acceptance. Usually, the criteria and rules focus on structural, thermo-mechanical, radiological, thermo-hydraulic, and neutronic aspects of the plant. A variety of computational tools are used to do these analyses. The computations are done for predetermined modes of operation and specific states of the systems. The events include severe accidents with core degradation beyond the design basis, postulated accidents, and accidents that are anticipated and transient. The resulting computations yield physical variables and time related as well as spatial dependencies. These dependencies can include concentrations of radionuclides, chemical composition, tangible impacts and stresses to structural materials, and, in the case of nuclear power plants, problems with coolant flow rates, temperature, pressure, thermal power, and neutron flux (Hashemian, 2010). When an assessment of prospective radiological consequences is conducted, the dependency is the potential dose received by the public or plant workers.

When a deterministic safety analysis is prepared for the purposes of plant design, it is characterized by bounding analysis and conservative assumptions (Hashemian, 2010). This can be done using an iterative process within the design phase of the project. The limiting case for the minimum margin of the acceptance criteria is determined for each of the several postulated sequences or initiating events. To understand the specific limiting case for a given transient or set of transients, there must be consideration of the consequential failures that have resulted from the external or internal initiating event (Perkins, Bensi, Philip, and Sancakatar, 2011).

A sufficient set of best estimates for conservative assumptions for the boundary or initial conditions must be used (Hashemian, 2010). Furthermore, independent failures should be addressed which are both coincident and limited in number. Operator error must also be included. The frequency of accident occurrences will decrease as each of the coincident independent failures is considered (i.e. since some failures occur together, the overall chance of a failure is less than the sum of the independent failures). Only the combinations of the transients with a frequency within the design basis should be of concern (Perkins et al., 2011).

The time frame used for a scenario should encompass everything that occurs up to the moment when a plant achieves a stable and safe state of operation (Sugiyama et al., 2012). The states must be defined. In the case of nuclear reactors, it is assumed that a stable and safe state is present when the reactor core is properly covered and long-term heat removal has been achieved. Additionally, the core must be sub-critical (i.e. no fission occurring and reasonably shutdown) and include a given margin. The safety analysis should include provisions for removing the fuel in a secure manner and storing it in another location after it has cooled (Prasad et al., 2011).

To ensure a proper defense in depth, all the barriers and credible mechanisms of failure must be considered (Hashemian, 2010). Limiting faults such as rod ejections and secondary breaks in nuclear power plants should be included in the deterministic safety analysis. The leaks prior to the break criterion from best estimate analysis can be used in the definition of requirements for structures, components, and systems (Hashemian, 2010).

The second type of analysis, probabilistic safety analysis, is used to ascertain the probability of damage being caused by a failure of each barrier (Hashemian, 2010). This type of analysis is especially useful for evaluating the risk from low-frequency sequences that can lead to the damaging of a barrier. In contrast, deterministic analysis is better suited for events that occur frequently and are anticipated by the acceptance criteria. Probabilistic safety analysis is used for evaluating whether the in-depth defenses are adequate. This might include events such as a severe loss of coolant in nuclear power plants (Sugiyama et al., 2012).

Both deterministic and probabilistic safety analyses provide important data on accident scenarios (Perkins et al., 2011). Whereas deterministic safety analysis is used to identify challenges to the physical barriers or integrity of systems, probabilistic safety analysis uses data and codes for estimation. These data and codes must be consistent with the objectives of the analysis. The results of the probabilistic analysis can be understood as supporting the results of the more conservative deterministic analysis (Hashemian, 2010).

When a probabilistic safety analysis is performed, a fault tree is often used (Hashemian, 2010) to confirm whether the assumptions made in the deterministic calculation about the availability of the systems are correct. For example, this approach might be applied in determining the potential for common cause failures or the establishment of minimum system requirements. The probabilistic safety analysis fault tree can also be used to determine whether the technical specifications are adequate and to identify the most important individual potential failures (Prasad et al., 2011).

2.9.3. THE UNITED STATES

Although nearly all countries with a nuclear industry are regulated by the IAEA, the United States is an exception (Prasad et al., 2011), monitoring its nuclear facilities through an independent government agency, the Nuclear Regulatory Commission (NRC). This agency was formed following the Energy Reorganization Act of 1974, as the successor agency to the U.S. Atomic Energy Commission (AEC). The NRC licenses and regulates the nation's civilian use of radioactive materials to protect public health and safety, promote the common defense and security, and protect the environment. The NRC's regulatory mission covers three main areas:

- Reactors: commercial reactors for generating electric power, and research and test reactors used for research, testing, and training.
- Materials: uses of nuclear materials in medical, industrial, and academic settings and facilities that produce nuclear fuel.
- Waste: transportation, storage, and disposal of nuclear materials and waste, and decommissioning of nuclear facilities from service (NRC website, n.d.).

For the purposes of NRC administration, the United States is divided into four regions (Perkins et al., 2011). Region one includes the northeastern United States, region two consists of the southern states, region three is the Midwest, and region four covers the south central and western states as well as Alaska and Hawaii. Nationally, the NRC oversees more than 100 nuclear reactors that produce power along with several fuel cycle and waste facilities. There are also 33 nuclear reactors which are permanently shut down and several new reactors under construction (Sugiyama et al., 2012).

There are multiple levels of regulatory oversight of U.S. nuclear facilities. The first of these consists of resident inspectors who are charged with monitoring the plant's daily operations. Resident inspectors are generally found at nuclear power plants, whereas fuel cycle facilities are assigned project inspectors that are responsible for the plant, but not permanently stationed on site. NRC inspection teams inspect all aspects of plant operation and administration throughout an inspection cycle. Special inspection teams can also be chartered to investigate events, violations, and possible whistleblower reports (Sugiyama et al., 2012).

The United States currently has cooperation agreements with the IAEA (Perkins et al., 2011). Prior to the early 1970s, the United States had no agreement with the IAEA, causing concerns that the United States would have an industrial and commercial advantage over other countries when using nuclear energy for peaceful purposes. In response to this concern, the United States entered into an agreement with the IAEA for nuclear plant inspection. The agreement excludes any facilities that are producing or using nuclear power for national security. In 1993, the United States agreed to place any nuclear material in excess of its defense needs in storage according to IAEA standards (Prasad et al., 2011).

2.10. FLUCTUATIONS IN THE NUCLEAR INDUSTRY

The March 2011 disaster at the Fukushima power plant had a significant impact on public opinion concerning atomic policies (Law et al., 2013). For example, the Chinese government stopped all its nuclear projects. Public support for any type of atomic power in the Republic of Korea disappeared. Germany and Belgium enacted legislation to eliminate nuclear power by the second decade of the 21st century. Switzerland and the Netherlands also stopped any projects to build additional atomic power plants. Other world governments also revisited their plans for nuclear power (Sharma and Arora, 2011).

The global reaction to the Fukushima nuclear power plant accident was different from that in proceeding accidents (Christoudias and Lelieveld, 2013). In 2011, 19 atomic reactors were completely shut down, 18 of them as a consequence of the problems at Fukushima. Only seven of these reactors have resumed operation since. Germany, the first country to begin operating a new reactor following the Chernobyl incident, closed eight reactors after Fukushima. Fourteen months after that nuclear accident, Japan had only one reactor still in operation (Perko, Turcanu, and Carlé, 2012).

In 1992, the World Nuclear Industry Status Report was established (Saey et al., 2010). This report was first designed to assess the global impact of the Chernobyl incident on the nuclear industry. The report predicted that fewer atomic plants would be constructed. During the first decade of the 21st century, this prediction has been confirmed with the rapid growth of competitors to nuclear power such as solar and wind power (Lelieveld, Kunkel, and Lawrence, 2012). Public concerns regarding safety are not the only disadvantages facing atomic power plants, as their construction frequently involves cost overruns, construction delays, and long lead times. Nuclear power is increasingly viewed as a type of risky investment that many countries are choosing to avoid (Thomson, 2011).

In 2012, 31 countries had nuclear fission reactors for the purposes of producing energy (Perko, Turcanu, and Carlé, 2012). The only new reactor to come online between 2010 and 2012 was the Bushehr reactor in the Islamic Republic of Iran. In 2011, more than 2,500 kilowatt hours of electricity were produced at nuclear power plants, approximately equivalent to the amount produced in 2001 and 5% below 2006, which was the highest production year for nuclear power. In 1993, the proportion of all electricity produced by atomic power reached its highest level at 17%; by 2011, the percentage had fallen to 11% (Christoudias and Lelieveld, 2013).

In July 2012, there were 429 nuclear reactors operating in 31 countries (Sharma and Arora, 2011). This was a decline from the 444 plants operating in 2002. By July 2012, Japan had shut down 49 of its 50 nuclear power plants. Conversely, in 2012, 13 countries were building new nuclear power plants, down slightly from the 15 countries reported in 2011. In 2012, the total number of nuclear reactors under construction increased to 59. However, this was far below the peak of 234 nuclear construction projects in 1979 (Shultz et al, 2013).

Even though reactors continue to be built, their dwindling numbers illustrate the uncertainty of the use of nuclear power for energy (Perko, Turcanu, and Carlé, 2012). As of 2012, nine reactors had been under construction for over 20 years. The longest construction period belongs to Tennessee’s Watts Bar Nuclear Generating Station Unit 2, which began construction in 1973 but, due to several complications, was not completed until 2015 (Christoudias and Lelieveld, 2013). Currently, 18 nuclear power plants under construction have been associated with significant construction delays. More than 70% of the plants under construction are located in Russia, China, and India. These three countries have not provided reliable information about the status of their atomic power plant construction. Nevertheless, it is generally accepted that more than half of the Russian nuclear power plants under construction are experiencing delays of at least several years (Gang-yang, Song and Zhang, 2011).

Ordinarily, long lead times for atomic power plants result from long-term planning, extended construction times, and lengthy licensing procedures (Sharma and Arora, 2011). These projects also require extensive site preparation and complex financing. All these obstacles have reduced the number of new nuclear power plant construction projects or grid connections. The average operating age of the atomic power plants has been steadily increasing and is now at about 27 years. Some of the facilities have been operating between 40 and 60 years (Dauer et al., 2011).

Whereas the United States licenses nuclear power plants to operate for 40 years, many countries do not place a time limit on their licenses (Law et al., 2013). On the other hand, France, which first began operating an atomic reactor with pressurized water in 1977, has a policy of conducting an in-depth inspection of nuclear power plants once each decade and has permitted only two plants to operate beyond 30 years. Those two are scheduled for permanent closure in 2016, before they reach their 40-year anniversary of operation (Mengolini and Debarberis, 2012).

2.11. THE NUCLEAR DEBATE

Numerous costly incidents have occurred at nuclear facilities in the United States (Sehgal, 2012). Similar events have occurred worldwide and are not unique to any one particular country. In nearly every incident, the cause has been isolated and steps have been taken to alleviate problems and prevent future incidents. However, thousands of upgrades to various pieces of equipment take place over the lifetime of a nuclear facility. The vast majority of these changes do not result in difficulties. Although there is no way to know with certainty what problems have been averted through technological improvements, it seems reasonable to assume that these upgrades have reduced the number of incidents; in other words, fewer problems have been created by the new technology than would have resulted without the changes (Woods et al., 2010). However, it is also possible that the introduction of new technology increases the risk of human error. Since changing the technology associated with nuclear facilities is an ongoing and necessary process, the question of whether technology in the complex systems of nuclear facilities decreases human performance and increases the chance of incidents is an important question to investigate.

2.12. CHAPTER CONCLUSION

This literature review has covered a wide range of topics related to the intersection between human performance and the operation of the complex systems present at nuclear facilities. The review began by explaining skill-based, rule-based, and knowledge-based behaviors, the concept of escalation and then discussed active, latent, and foreseeable errors, followed by the concept of unexpected events. The chapter then considered issues related to nuclear power in general. Nuclear facilities were depicted as one of humanity's greatest technological achievements, yet extremely dangerous if the facility's operating limits are exceeded. Nuclear facilities in the United States and globally were described, along with the regulatory functions of the International Atomic Energy Agency and the U.S. Nuclear Regulatory Commission, the International Nuclear Event Scale used to assess the severity of nuclear incidents, methods of conducting safety analyses of nuclear facilities, and the ongoing debate over the benefits and risks of nuclear plants.

CHAPTER 3: RESEARCH METHODS

3.1. CHAPTER INTRODUCTION

This chapter describes how the present observational research study was conducted. It begins by discussing the research design, followed by the methods used. It then explains how the information for the study was obtained, covering the materials and instruments along with the data collection, processing, and analysis tools used. The chapter concludes with a discussion of the study's methodological assumptions, limitations, and ethical assurances.

3.2. RESEARCH DESIGN

The research design used in this investigation is that of an observational study (Creswell, 2013). An observational study draws inferences from the effect of certain variables on a situation. To draw those inferences, the situations must be divided into two categories, representing a treatment group and a control group. This is different from a traditional experiment, in which subjects are randomly assigned to a control group or to the treatment condition. The observational approach is used when the investigator does not have sufficient control over the situation to assign subjects to various groups. In the case of the present research, the nuclear facilities are grouped into those that have had accidents as a result of technological changes which affect the way the operator interacts with the system and those that have had accidents, but determined not to be caused by the introduction of technological changes which affect the way the operator interacts with the system (McCoy, Alamaniotis, and Jevremovic, 2013). The facilities that had accidents as a result of technological changes which affect the way the operator interacts with the system are considered the treatment group, whereas the nuclear facilities that have had accidents, but determined not to be caused by the introduction of technological changes which affect the way the operator interacts with the system are the control group. The variable affecting these plants (i.e., the treatment), is advances in technology that affects the way the operator interacts with the system (Mitchell and Jolley, 2013).

It is not feasible for any researcher to conduct an experiment that would involve requiring nuclear facilities to use certain technologies. Therefore, the effect of these changing technologies on the facility must be observed after the fact. The observational study is an excellent method of collecting real-world information. In this case, it is the most suitable way to assess evidence of the risks related to the introduction of new technologies at nuclear facilities. The observational study can be used to formulate hypotheses that can be tested in other experiments. It is also a good way to generate data that can be used to formulate effective policies and safeguards for the nuclear industry (Creswell, 2013).

When a randomized experiment cannot be conducted, any alternative method, including the observational approach, will suffer from the fact that the treatment has been applied in a nonrandom fashion (Mitchell and Jolley, 2013), resulting in potential experimental bias. In the case of this study, the application of the treatment of new technology was not random, meaning that bias may have been introduced into the results (Creswell, 2013). For example, it could be that the facilities that underwent technology changes were older on average, with the result that if these facilities had a higher prevalence of incidents, facility age could be an alternative explanation rather than the introduction of the new technology. In such situations, the best thing that a researcher can do is to examine the data carefully, anticipating potential problems and attempting to gauge their impact (Mitchell and Jolley, 2013).

3.3. METHODS

The INES was used to determine whether an event at a nuclear facility reached a sufficient level of severity to be considered in this study. As discussed in chapter 2, the IAEA adopted the INES as a method of quickly and efficiently communicating the safety significance of incidents occurring at nuclear facilities. Ratings on the INES are subjective. Because nuclear facilities are manmade, unique, and vastly different in design, incidents occurring at these plants are subject to certain interpretations when one attempts to estimate the magnitude of the problem (McCoy, Alamaniotis, and Jevremovic, 2013). In the present study, only incidents rated at Level 3 or higher were considered sufficiently severe to be included (Sugiyama et al., 2012). In the United States, the NRC, which carries responsibility for atomic safety in this country but cooperates with the IAEA, uses a nuclear event scale similar to the INES and transfers its ratings to the INES for reporting purposes (McCoy, Alamaniotis & Jevremovic, 2013). For the purposes of this study, ratings from the INES were used after the numbers were converted.

The information used for this study was available on regulatory agency databases and in books detailing the investigation results of the incidents. Available information on incidents at Level 3 or higher and plant data from the time period before the incident occurred were gathered to determine the level of technological advancement impacting human operators at the facility.

3.4. MATERIALS AND INSTRUMENTS

The IAEA and NRC both report on events that they have investigated (Prasad et al., 2011). However, possibly due to the diverse nature of their cultures, policies, and relevant laws, the IAEA data are not as complete or detailed as those provided by the NRC. As explained in chapter 2, NRC information is converted to INES levels. This study used the event notification reports of the NRC and its predecessor U.S. regulatory agencies (McCoy, Alamaniotis, and

Jevremovic, 2013). This approach provided an opportunity to use a standardized system that assesses the severity of each nuclear event while taking advantage of the more detailed reports released by the NRC.

Only events reaching a INES Level 3 or higher were used. Since this study began in 2013 and the cause of the only 2 incidents that occurred between 2011 and 2012 had not been determined at the time of the study, the time period examined was from 1955 through 2010. There were two reasons for using only those events reaching Level 3 and above. First and most importantly, any incident below Level 3 is relatively minor and unlikely to cause death, injury, or a problematic release of radioactive material. Second, I wanted to work with a reasonable number of incidents. As the incident level decreases, the occurrences increase exponentially, and using incidents below Level 3 would involve processing an overwhelming amount of data due to the excellent daily reporting criteria applied by the NRC. In fact, most days contain multiple reports of events below the Level 3 threshold.

3.5. DATA COLLECTION, PROCESSING, AND ANALYSIS

Data collection for this study began with an examination of the event notification reports provided by the NRC (Hashemian, 2010). I identified all events at a severity level of 3 or higher from 1999 to 2012. Information on serious events prior to 1999 was obtained from books addressing the topic, on the basis of which I determined whether the incident would have been classified as Level 3 or higher on the INES.

After identifying all U.S. incidents meeting this criterion for the 55-year time frame, I sought information online regarding technological changes at the plant shortly before the event. Examples of technological changes include system and/or component upgrades, user interface alterations, and control system changes. The events were then categorized as to whether they followed the implementation of technological changes that may have affected how personnel interacted with the facility’s systems. Changes that did not affect interaction between people working at the facility and its systems were discounted. For example, changes in the speed with which information is passed between computers would not normally be likely to affect the performance of human operators. However, if such a change modified the way in which the operators interacted within the system, then this would be considered a relevant technological change.

The statistical analysis of the data will make use of a *t*-test (Rutherford, 2011). This type of analysis is sensitive to the type of data being used. If the INES level were used as a measure of the problem created by an accident, the accuracy of statistical analysis would be impaired due to the logarithmic nature of the scale. Therefore, an alternative numeric measure is used to maintain the integrity of the *t*-test (Creswell, 2013).

Data can be roughly divided into nominal, ordinal, interval, and ratio types (Mitchell and Jolley, 2013). The nominal type of data is also known as qualitative. One example of this type would be ethnicity. An ordinal scale follows a rank order but does not account for the relative difference between the categories. An interval scale accounts for the degree of difference between items, but not the ratio (e.g., temperature). The ratio scale means that the data indicates the magnitude of a given continuous quantity present. An example of this would be an electric charge or mass (Steinberg, 2011).

The measure to be used for determining the deleterious effects of a nuclear incident is the cost of the incident in U.S. dollars. The reports on U.S. incidents contain cost estimates; accounting for inflation is necessary for comparison purposes, so all amounts are adjusted for inflation to 2005 dollars. A dollar amount has a zero value and is thus considered a ratio scale. This is an appropriate type of data for conducting a *t*-test (Rutherford, 2011).

3.6. METHODOLOGICAL ASSUMPTIONS

One significant methodological assumption of this study was that the reporting of events by the regulatory agencies is accurate. A report could be inaccurate if the staff of the regulatory agency under-report or do not correctly portray incidents that come to their attention.

An additional methodological assumption was that I would be able to determine reliably whether the incidents followed technological changes. I attempted to reduce bias in this regard by recruiting colleagues to assess available information on the incidents and assess whether, in their judgment, any relevant technological changes had occurred. I provided my colleagues with all the data that I had located and invited them to do further research if necessary to either corroborate or refute my assessment. There were no inconsistencies between my colleagues' determinations and my own, confirming that I was not inadvertently influencing the outcome of the study by placing incidents in the wrong group.

3.7. LIMITATIONS

This research had several limitations. One limitation was the possible inaccuracy of the information provided by the regulatory agencies on each incident. As noted in the previous section, it is conceivable that the agency reports contained some errors. There is no way to be absolutely certain that the data are correct.

Another problem was related to the assignment of each incident to the treatment or control group. Even with colleagues corroborating my work, it cannot be known with certainty that this classification method was reliable.

A more basic problem with the analytical methodology was that it is not a traditional experiment (Mitchell and Jolley, 2013). Of course, given the subject of the study, a traditional experiment is not feasible. Nevertheless, an observational study is inherently less powerful than a traditional experiment in which the researcher can manipulate the treatment through random assignment to multiple groups. It is possible that confounding factors were present that affected the analysis. For example, it is possible that the facilities with fewer technological changes were also those with older equipment. Since nuclear plants have limited operational lives, their owners and managing entities may spend less money on technological upgrades as a plant increases in age. Furthermore, the older plants would probably be more prone to experiencing events that must be reported to the regulatory agencies. If so, then the effect of technological changes would be artificially reduced due to the aging facilities having more problems but fewer technological changes. The potential presence of confounding variables is one primary reason why traditional experiments are more powerful than other approaches such as observational studies. This is not to say that an observational study cannot provide useful information, of course, but this methodological limitation is inherent in any observational study (Creswell, 2013).

3.8. ETHICAL ASSURANCES

A wide range of ethical issues must be considered in research involving human affairs (Mitchell & Jolley, 2013). These issues can be divided into six general categories: communicating the results, potential for harm, confidentiality and anonymity, informed consent, voluntary participation, and other specific issues (Steinberg, 2011).

This study involves data previously collected by nuclear regulatory agencies. Since the information is publicly available, there is no issue of voluntary participation. Since no individual subjects involved with the research, informed consent is not an issue. The anonymity and confidentiality of individuals who may be involved in the reports have already been protected because the reports do not mention any individuals specifically. This protection also minimizes the potential for harm to specific subjects. The remaining categories of ethical issues to address are the communication of the results and any other ethical issues specific to this project.

Appropriate communication of results is an important consideration in this study. Every attempt has been made to account for all information available relevant to the study (Mitchell and Jolley, 2013). This means that all information found was reported, even if it did not support the hypothesis. Furthermore, the data were reported accurately without exaggeration.

Plagiarism has been avoided by not copying any text directly. Instead, information pertinent to the research has been paraphrased and appropriately referenced to give the original authors or researchers credit for their work (Steinberg, 2011). This is true for both specific facts and general ideas or theories presented.

One specific ethical issue potentially relevant to this study is conflict of interest (Steinberg, 2011), which occurs when the researcher has an interest in the outcome of the experiment for some extraneous reason. For example, a physician reporting the outcome of a drug trial would have a conflict of interest if he or she owned significant shares in a company that had the rights to the drug patent. In this instance, however, I have no ties to regulatory agencies or to any of the nuclear facilities examined (Mitchell and Jolley, 2013).

3.9. CHAPTER CONCLUSION

This chapter covered the methods used to conduct the research. After a brief introduction, the research design was explained. This study falls into the category of observational research, since the treatment could not be manipulated by the researcher. This treatment, or independent variable, is the presence of technological change at a nuclear plant that affected how the operators of the plant interfaced with complex systems. This variable must be assessed by reviewing past performance history and is not within the researcher's control. Therefore, there is no randomized assignment in this study. Since the treatment was applied in a nonrandom fashion, bias could occur.

Information from the IAEA and NRC was used to identify nuclear incidents. Only incidents at severity Level 3 or higher on the INES were included in the study. This limitations kept the amount of data to be analyzed at a reasonable level. The facilities were grouped according to whether they had undergone technological upgrades that affected how the plant operators interacted with the system prior to the incident.

CHAPTER 4: FINDINGS

4.1. CHAPTER INTRODUCTION

This chapter describes the study's findings. Table 2 describes the incidents rated at Level 3 or higher on the INES that occurred at U.S. nuclear facilities from 1955 to 2010, including the date of the incident, the cost, and whether the incident was due to human error after new technologies were installed. See Appendix A for a description of each incident and how it was classified as either due or not due to human operator error when working with new technologies. The final section in the chapter presents the findings of the statistical analysis.

Table 2. Incidents at United States Nuclear Reactors from 1955 until 2010

Date	Location	Incident Description	Cost (in millions of dollars)	Due to Human Error after New Technologies Were Installed
February 1, 2010	Vernon, Vermont	Underground pipes at the Vermont Yankee Nuclear Power Plant deteriorated and leaked radioactive tritium into the groundwater supply.	695	No
September 10, 2009	Crystal River, Florida	During an attempt to replace the steam generator, the structure was cracked, ultimately resulting in a permanent closure of the facility.	1,000	Yes
March 6, 2006	Erwin, Tennessee	The nuclear fuel services plant spilled 35 liters of highly enriched uranium. This caused a shutdown of the facility for more than seven months.	95	Specifics not available
August 4, 2005	Buchanan, New York	The Entergy Indian Point Nuclear Plant leaked strontium and tritium into an underground lake from 1974 until 2005. The incident was the discovery of the long-running problem.	28	No
June 16, 2005	Braidwood, Illinois	The Braidwood nuclear station leaked nuclear contaminants and tritium into the local water supply.	40	No
January 15, 2003	Bridgman, Michigan	A fault in the primary transformer for the Donald C. Cook Nuclear Generating Station resulted in a fire that damaged the backup turbines and main generator.	9.5	No
February 16, 2002	Oak Harbor, Ohio	Severe boric acid corrosion of a reactor head forced the Davis-Besse reactor to be closed for two years.	600	Yes
February 15, 2000	Buchanan, New York	An NRC alert was issued after a steam tube ruptured at Indian Point Unit two.	2	Yes
September 29, 1999	Lower Alloways Creek Township, New Jersey	A major freon leak at the Hope Creek Nuclear Generating Station caused a ventilation chiller to trip. This resulted in a release of toxic gas that damaged the cooling system.	18	Yes
May 25, 1999	Waterford, Connecticut	A steam leak in the feed-water heater caused a manual shutdown and damage to the control board annunciator located at the Millstone Nuclear Power Plant.	6	No

Table 2. Continued

Date	Location	Incident Description	Cost (in millions of dollars)	Due to Human Error after New Technologies Were Installed
September 9, 1997	Bridgman, Michigan	Cook units one and two were shut down due to a failure in their ice condenser containment systems.	10	No
September 20, 1996	Seneca, Illinois	The surface water systems failed and resulted in a closure of units one and two of the LaSalle County Nuclear Generating Station for more than 24 months.	69	No
September 5, 1996	Clinton, Illinois	A reactor recirculation pump failed, leading to the shutdown of the Clinton boiling water reactor.	36	Yes
September 2, 1996	Crystal River, Florida	Malfunctioning equipment led to extensive repairs and a shutdown of Crystal River unit three.	378	No
May 15, 1996	Morris, Illinois	Rapidly reduced water levels at the nuclear fuel reactor core led to a shutdown of the Dresden Generating Station.	Information not available	Information not available
February 20, 1996	Waterford, Connecticut	A leaking valve forced the shutdown of the Millstone Nuclear Power Plant's units one and two, and there were associated multiple equipment failures.	249	No
May 16, 1995	Lower Alloways Creek, New Jersey	There was a ventilation systems failure at Salem units one and two.	32	No
January 14, 1995	Wiscasset, Maine	A crack in the steam generator tubes at the Main Yankee nuclear reactor resulted in a shutdown of the facility for 12 months.	60	No
December 25, 1993	Newport, Michigan	Improper maintenance led to a main turbine failure.	65	Yes
March 2, 1993	Soddy-Daisy, Tennessee	Broken pipes led to shutdown of the reactor unit.	3	No
February 27, 1993	Buchanan, New York	A system failure resulted in the shutdown of the energy center.	2	No
February 3, 1993	Bay City, Texas	Two reactors shut down rapidly due to failure in the feed-water pumps.	3	No
April 21, 1992	Southport, North Carolina	A diesel generator failure resulted in shutdown of the reactor units.	2	No
November 17, 1991	Scriba, New York	Safety issues resulted in the reactor being shut down for 13 months.	6	No
March 17, 1989	Lusby, Maryland	Cracks in the pressurized heat sleeves resulted in the shutdown of two reactor units.	125	Yes
March 5, 1989	Tonopah, Arizona	Failure of the atmospheric dump valves led to a primary transformer fire and the shutdown of the reactor.	15	No
September 10, 1988	Surry, Virginia	Failure of the seal on the refueling cavity caused a failure in the internal pipe system, resulting in a 12-month shutdown.	10	No
March 29, 1988	Burlington, Kansas	A worker was electrocuted after falling into a manhole.	1	No
December 19, 1987	Scriba, New York	System malfunctions caused the reactor to be shut down.	160	Yes
July 15, 1987	Burlington, Kansas	A safety inspector died from electrocution due to a wire being improperly labeled.	1	No
March 31, 1987	Delta, Pennsylvania	A cooling malfunction resulted in two reactors being shut down.	410	Yes
April 11, 1986	Plymouth, Massachusetts	Equipment malfunctions resulted in a reactor shutdown.	1,025	Yes
June 9, 1985	Oak Harbor, Ohio	Operator error resulted in the reactor pumps being shut down and the auxiliary pumps being turned on.	1	No
March 9, 1985	Athens, Alabama	A malfunction in the instrumentation resulted in nuclear operations being shut down.	1,850	Yes
September 15, 1984	Athens, Alabama	The reactor was shut down for six years due to design problems and safety violations.	115	Yes

Table 2. Continued

Date	Location	Incident Description	Cost (in millions of dollars)	Due to Human Error after New Technologies Were Installed
February 26, 1983	Fort Pierce, Florida	A core barrel support and a thermal shield were damaged, resulting in facility shutdown.	57	Yes
February 12, 1983	Forked River, New Jersey	The facility failed a safety inspection and was shut down until repairs could be made.	34	Yes
June 18, 1982	Seneca, South Carolina	The thermal cooling system of the reactor was damaged when a feedwater heat extraction line was breached.	11	Yes
March 25, 1982	Buchanan, New York	The reactor was shut down due to the steam generator tubes being damaged.	58	Yes
March 20, 1982	Scriba, New York	The reactor was shut down for two years due to the failure of the recirculation system.	46	Yes
February 26, 1982	San Clemente, California	Seismic readings resulted in a temporary reactor shutdown due to the risk of an earthquake.	1	No
January 25, 1982	Ontario, New York	Radioactivity was released into the environment due to the rupturing of a steam tube.	1	No
November 22, 1980	San Clemente, California	A worker was electrocuted after making contact with an energized line of the pressurized water reactor.	1	No
March 28, 1979	Middletown, Pennsylvania	A partial core meltdown occurred due to a loss of coolant.	2,483	Yes
February 4, 1979	Surry, Virginia	A reactor was shut down due to the steam generators having two faulty bundles.	12	No
June 10, 1977	Waterford, Connecticut	The boiling water reactor was shut down after three buildings were damaged in a hydrogen gas explosion.	16	No
November 5, 1975	Brownville, Nebraska	The boiling water reactor was damaged after an explosion of hydrogen gas.	13	No
March 22, 1975	Athens, Alabama	The core cooling systems were disabled after more than 1,500 control cables were damaged by fire.	244	Yes
August 11, 1973	Covert Township, Michigan	The pressurized water reactor was shut down due to leaks in the steam generator.	11	No
July 16, 1971	Cordova, Illinois	The reactor on the Mississippi River was shut down after an electrician was electrocuted.	1	No
October 5, 1966	Monroe, Michigan	A partial core meltdown occurred due to a malfunction in the sodium cooling system.	20	Yes
July 24, 1964	Charlestown, Rhode Island,	An accidental criticality occurred due to worker error.	1	No
January 3, 1961	Idaho Falls, Idaho	An explosion occurred at the reactor testing station.	23	Yes
July 26, 1959	Simi Valley, California	A partial core meltdown occurred at the reactor during an experiment.	33	Yes
November 29, 1955	Idaho Falls, Idaho	There was a partial core meltdown and power excursion at the breeder reactor.	5	No

Note: All monetary values were adjusted to 2005 dollar values.
Sources: Sovacool, Benjamin K. 2009. "The Accidental Century - Prominent Energy Accidents in the Last 100 Years." *Exploration & Production Oil & Gas Review*. 7 (2): 132 and Sovacool, Benjamin K. 2010. “A Critical Evaluation of Nuclear Power and Renewable Electricity in Asia.” *Journal of Contemporary Asia*. 40 (3): 393–400.

Because the INES is a logarithmic scale, each level is roughly 10 times as severe as the previous one. This means that an accident with local consequences (INES Level 4) will be about a thousand times as problematic as an anomaly (Level 1).

4.2. DATA ANALYSIS

4.2.1. INCIDENT COST

The *t*-test was used to determine whether a significant difference between the two groups (incidents determined to be caused by human error as a result of technological advances and those determined not to be caused by human error as a result of technological advances) existed. An independent samples *t*-test determines whether two independent groups are different from each other, and the two groups are not related, so an independent samples *t*-test can be used in this case. Before conducting the *t*-test, since it is a parametric test and requires normally distributed data, the outcome variable (costs of incidents) was checked for normality and homoscedasticity of variance by examining the distribution of the data using histograms and Q-Q plots.

For the 53 incidents reported in Table 2, the average cost of the incidents was $190,518,900 (SD = $461,511,400). Among the 53 incidents, 22 were determined to be due to human error as a result of technological advances and 31 were not. Of this latter group of 31 that did not include human error, the cost of the incidents ranged from $1,000,000 to $695,000,000, with an average of $54,274,200 (SD = $142,559,800). For the 22 incidents due to human error as a result of technological advances, the cost ranged from $2,000,000 to $2,483,000,000 with an average of $382,500,000 (SD = $657,543,610). See Table 3.

For the first assumption of the t-test, normality of data, the Kolmogorov-Smirnov test was used to compare the scores in the sample to a normally distributed set of scores. If this test result is significant, then the distribution of scores of this sample is significantly different from a normal distribution of scores. The Kolmogorov-Smirnov test was significant ($p < .001$). Thus, the first assumption of the *t*-test was violated.

A Q-Q plot of the scores also indicated that the data were not normally distributed (see Figure 2). A histogram (see Figure 3) reveals that the data were positively skewed. Therefore, the data were log-transformed. Log-transforming data can make skewed data more normally distributed (see Figures 4 and 5).

A Q-Q plot is a form of scatterplot created by plotting two sets of quantiles against one another to assess normality of the data. Quantiles are not the same as the actual observations and different ranges of values can be presented relative to histograms. When the data contain extreme values, as in this study, these may not be rendered in the graph as seen in the histogram (as displayed in Figures 4 and 5). Thus, it is not expected that the exact ranges of values should be consistent between histograms and Q-Q plots since they plot different factors: quantiles for Q-Q plots and actual values for histograms.

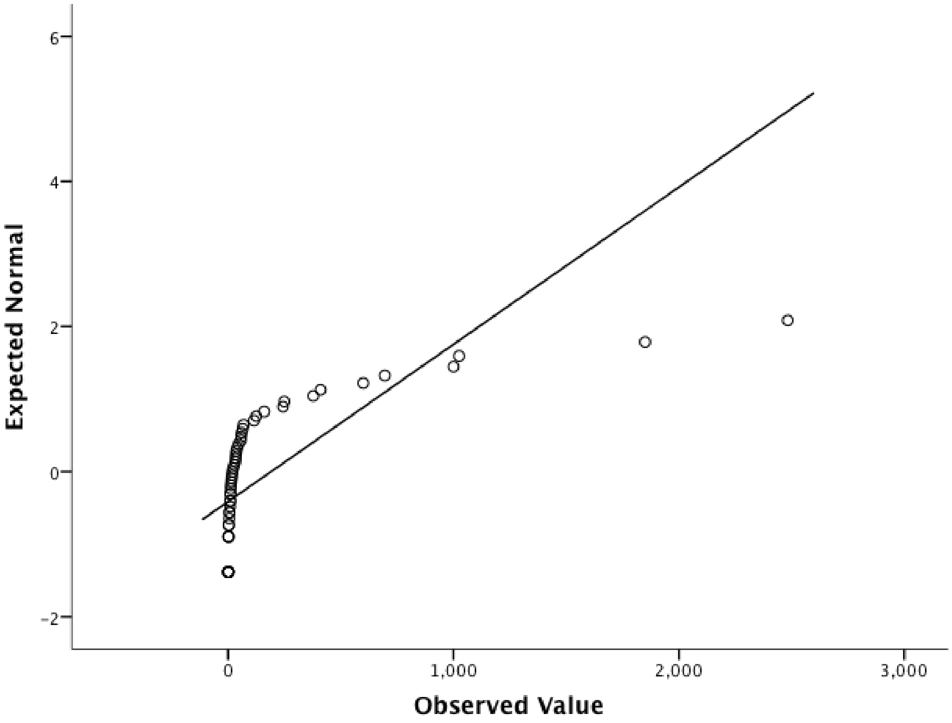

Figure 2. Q-Q Plot of Cost

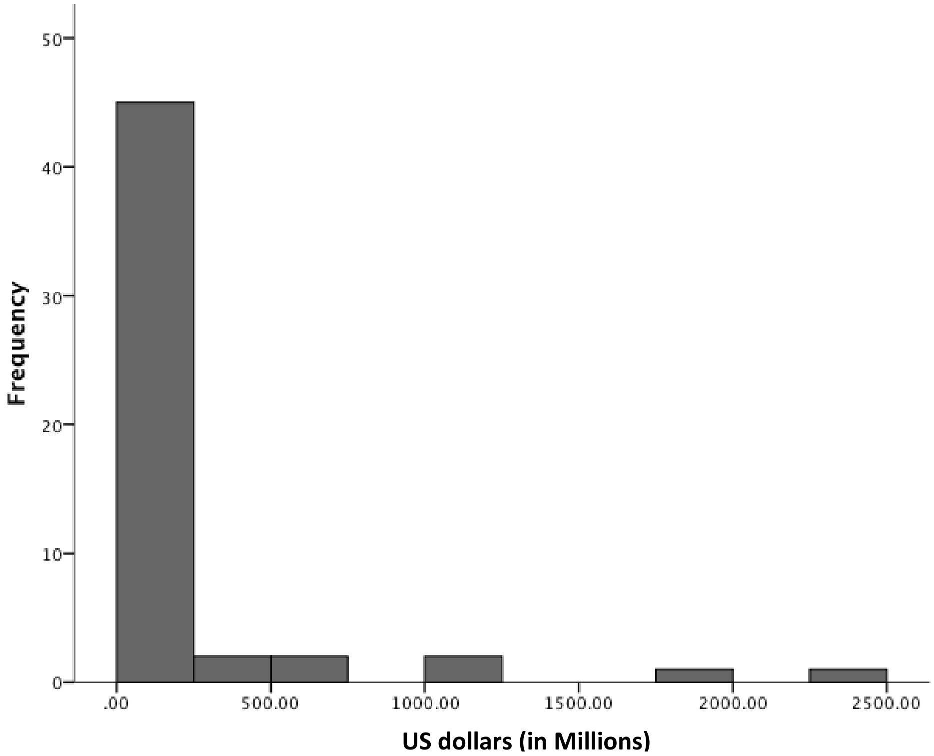

Figure 3. Histogram of Cost

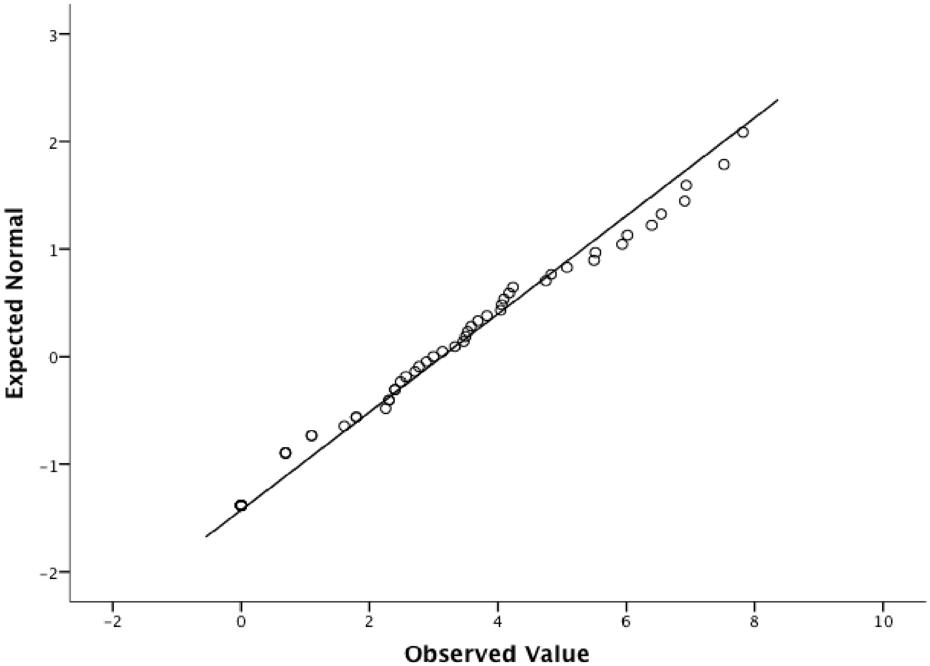

Figure 4. Q-Q Plot of Log-Transformed Cost

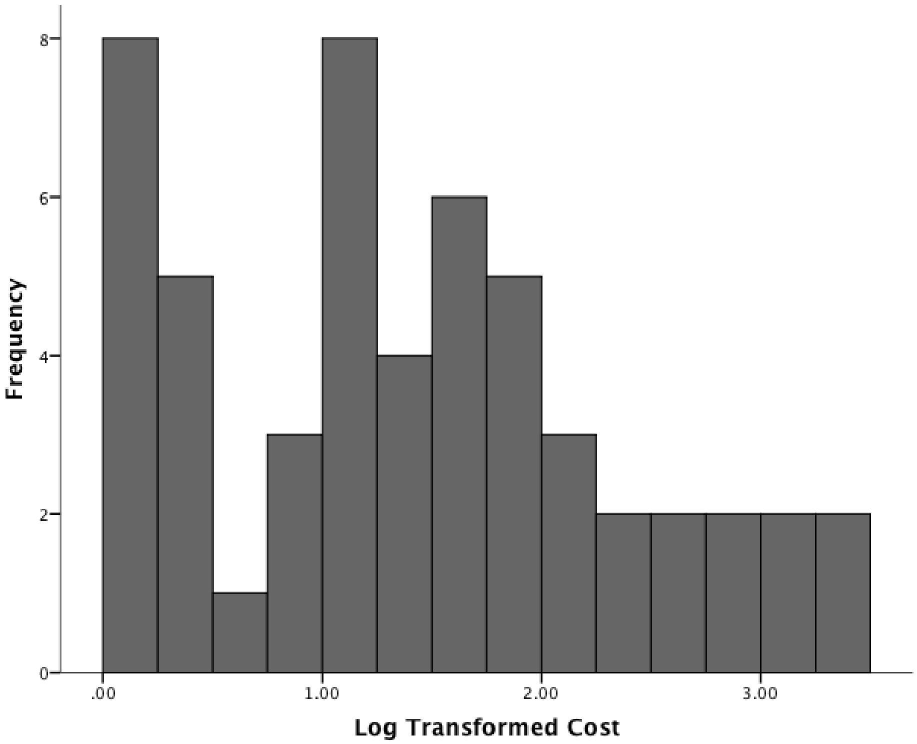

Figure 5. Histogram of Cost (Log-Transformed)

Using the log-transformed data, an independent samples *t*-test was conducted. Once again, normality of the data was checked using the Kolmogorov-Smirnov test. This time, the result was non-significant (*p* = .200), indicating that the distribution of the log-transformed cost scores was not significantly different from a normal distribution. To test the second assumption of a *t*-test (homoscedasticity of variance), Levene's test was used to see if the variances of the groups were equal or unequal. The result was non-significant (*p* = .953), so it can be assumed that the variances are equal and the assumption was not violated. On average, the log-transformed costs of incidents determined not to be a result of human error related to technological advances were lower (M = .92, SD = .81) than the log-transformed costs of incidents determined to be caused by human error related to technological advances (M = 1.99, SD = .78), and this difference was significant, *t*(51) = –4.81, *p* <.001, one-tailed. The difference between the log-transformed means of cost between the two groups represented a large-sized effect, $d = 1.34$. Therefore, incidents caused by human error related to technological advances were more costly than incidents not meeting this criterion, thus rejecting the null hypothesis.

In addition, non-parametric tests were conducted. The Wilcoxon-Mann-Whitney test is the non-parametric equivalent to the parametric independent samples *t*-test. The Wilcoxon-Mann-Whitney test does entail the assumptions that the data are normally distributed, the dependent variable is ordinal or continuous, and the independent variable consists of two categorical, independent groups. The present data meet these assumptions.

The results from the Wilcoxon-Mann-Whitney test suggested a statistically significant difference between the underlying distributions of the cost of incidents caused by human error related to technological advances and the cost of incidents determined to not be the result of human error related to technological advances, $z = 4.187$, $p < .001$. The average cost of incidents determined to be caused by human error related to technological advances was greater than the average cost of incidents determined not to be the result of human error related to technological advances.

Another possible way to deal with non-normally distributed data is to remove outliers. As seen in Figures 2 and 3, several outliers were present. Removing the four outliers with low costs ($2,483,000, $1,850,000, $1,025,000, $1,000,000) produced a somewhat more normal distribution (see Figure 6). However, the Kolmogorov-Smirnov test was significant ($p < .001$). Thus, the first assumption of the *t*-test was violated and the data with the outliers removed were not normally distributed. An independent samples t-test is not suggested when the data is not normally distributed. Excluded outliers are values that are approximately three standard deviations from the mean.

Since simply removing the outliers did not make the data normally distributed, the next alternative was to conduct a log-transformation of the data after removing the outliers. Log-transforming the data reduced the positive skewness of the data, as seen in Figure 7. After the log-transformation, the data appeared more normally distributed (see Figure 8). Normality of the transformed data with no outliers was checked using the Kolmogorov-Smirnov test. The test was non-significant (*p* = .200), indicating that the distribution of the log-transformed cost scores was not significantly different from a normal distribution. Levene's test was used to check for homogeneity of variance; the result was non-significant (*p* = .137), so it can be assumed that the variances are equal and that the assumption was not violated. On average, the log-transformed costs of incidents determined to not be due to human error related to technological advances were lower (*M* = .91, SD = .81) than the log-transformed costs of incidents caused by human error related to technological advances (M= 1.72, SD = .59), and this difference was significant, *t*(47) = –3.69, *p* = .001. The results of the non-parametric tests again indicate that incidents determined to be caused by human error related to technological advances were more costly than incidents determined to not meet this criterion, thus further reinforcing the rejection of the null hypothesis.

Table 3. Average Costs for Each Incident Category

Category of Incident	Mean	SD	Median
No human error as a result of technological advances (n = 31)	$54,274,200	$142,559,800	$9,500,000
Human error as a result of technological advances (n = 22)	$382,500,000	$657,543,610	$61,500,000

Note: All monetary values were adjusted to 2005 dollar values.

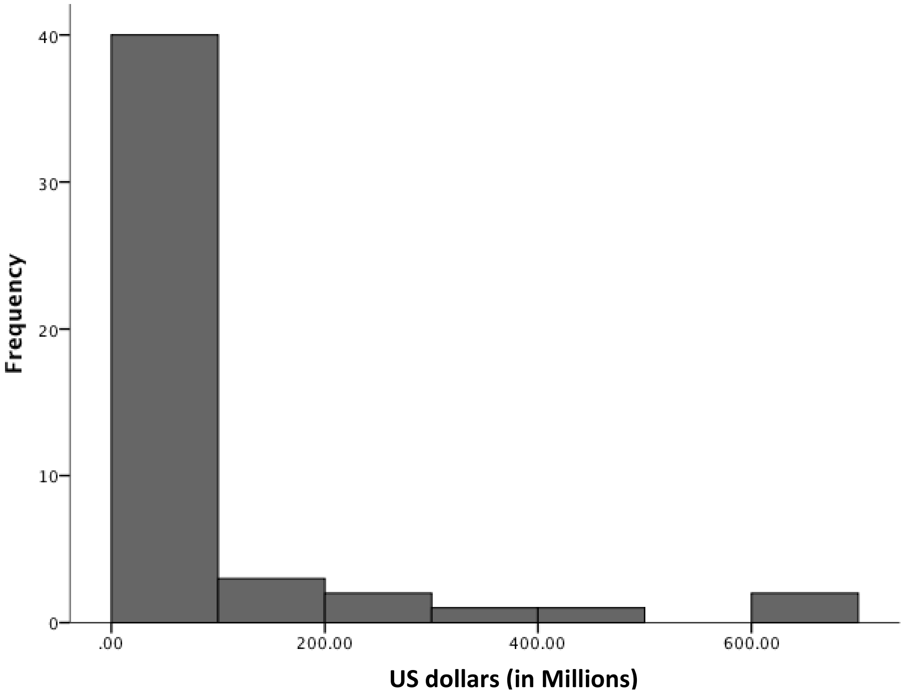

Figure 6. Histogram of Cost (Outliers Removed)

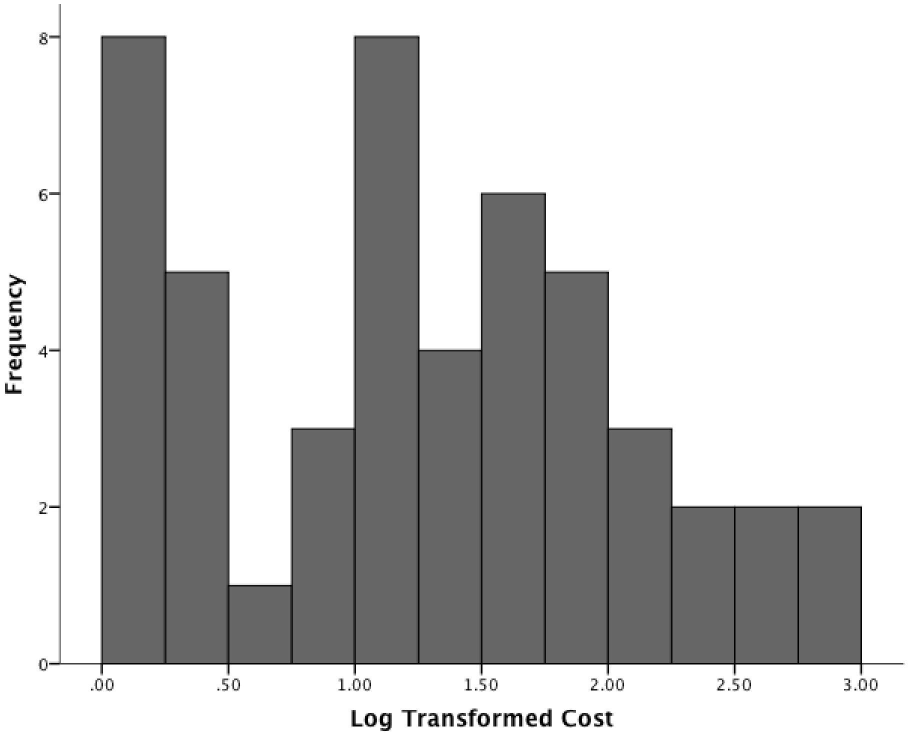

Figure 7. Histogram of Cost (Outliers Removed, Log-Transformed)

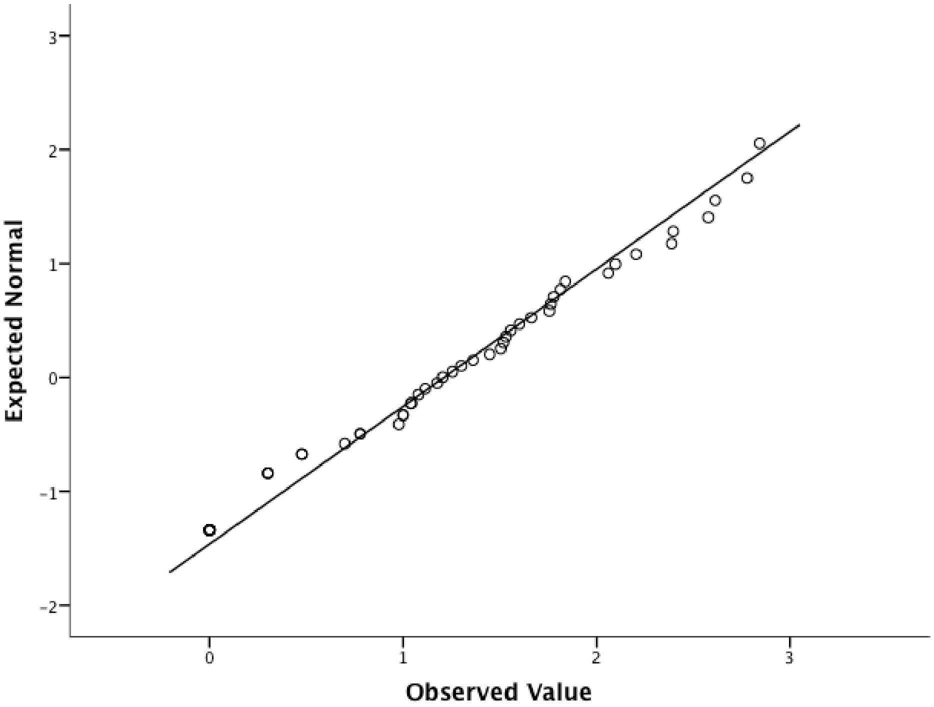

Figure 8. Q-Q Plot of Cost (Outliers Removed, Log-Transformed)

4.2.2. INCIDENT FREQUENCY

As a means of further analysis regarding the frequency of incidents, the two groups of incidents were examined individually. A post-hoc *t*-test analysis was conducted for the 22 incidents in which human error due to technology advances was determined to be the cause.

The median-log transformed cost (median = 4.12) was used to create two subgroups, low-cost and high-cost, within this group of incidents. An independent-samples *t*-test was conducted between the low-cost and high-cost subgroups. The analysis revealed a significant difference, $t(20) = -.293$, $p < .008$. More interesting was the shape of the frequency distributions for high- and low-cost incidents. For lower-cost incidents, the frequency of occurrence appeared to approximate a normal distribution (Figure 9). The mean cost of a lower-cost technology-induced incident was $30.7 million (SD = $18.06 million). However, the high-cost group did not approximate a normal distribution (mean = $734 million; SD = $797 million). The frequency of incidents with costs over $500 million was much smaller. The relationship appears to be non-linear (see Figure 10).

To analyze the cost of incidents determined to be not the result of human error related to technology advances, a similar median split was performed on the log-transformed cost. An independent-samples *t*-test was conducted comparing the high- and low-cost errors in this group (n = 31). The analysis revealed a significant difference, $t(29) = -2.21$, $p < .035$. For lower-cost incidents determined not to be due to human error related to technological advances (n = 16), the frequency of occurrences did not approximate a normal distribution (Figure 11). The average cost for the lower-cost incidents determined not to be due to human error related to technological advances was $2.70 million. However, the cost per incident dramatically decreased after about $4 million. It's not that there are necessarily less incidents with a cost of $4 million or less. Rather, the cost per incident vary more and there is a greater gap in cost (i.e. some were way less than $4 million) in low cost incidents. Among the higher-cost incidents determined not to be due to human error related to technological advances (n = 15), again, the distribution did not approximate a normal distribution. The higher-cost incidents averaged $109 million, but there were only three incidents at $200 million or more (see Figure 12).

Finally, an independent samples *t*-test was conducted on lower-cost incidents, comparing incidents determined to be due to human error related to technological advances with incidents determined not to be due to human error related to technological advances. The analysis revealed a significant difference, $t(25) = 6.14$, $p < .0001$. Human error determined to be caused by technology advances had significantly greater cost impact (mean = $30.73 million) than incidents determined not to be due to human error related to technological advances (mean =

$2.81 million) among "low-cost" incidents. Additionally, an independent samples *t*-test revealed a significant difference between incidents resulting from human error related to technology advances (mean = $734 million) and incidents determined not to be due to human error related to technological advances (mean = $109 million), $t(24) = 2.94$, $p < .007$.

This additional analysis justifies the conclusion that incidents determined to be caused by human error as a result of technological advances are more costly than other incidents at nuclear facilities. A median split of the incidents determined to be due to human error related to technological advances found that lower-cost incidents (with a mean cost of about $30 million) were more evenly distributed around the mean than higher-cost incidents determined to be due to human error related to technological advances (mean cost of about $734 million). This finding confirms the Section 4.2.1 analysis, which indicated that incidents determined to be caused by human error related to technological advances are fewer in frequency, but more costly. Again, this results in a rejection of the null hypothesis.

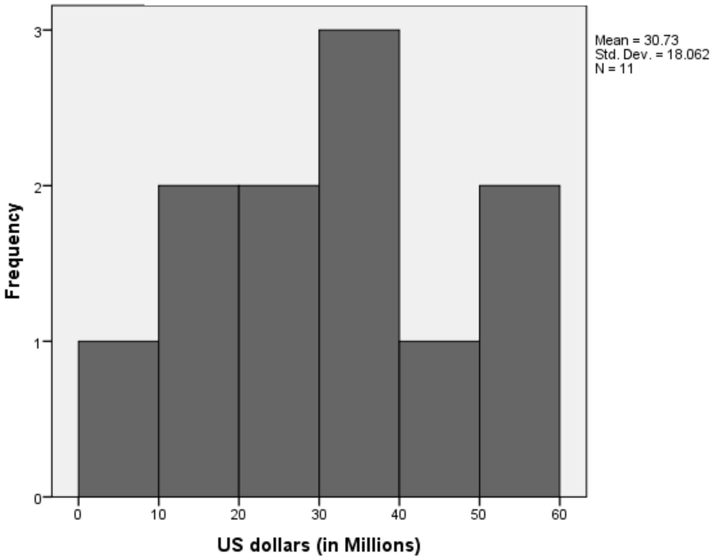

Figure 9. Histogram of Frequency Distribution of Cost per Incident for Lower-Cost Technology-Induced Human Errors

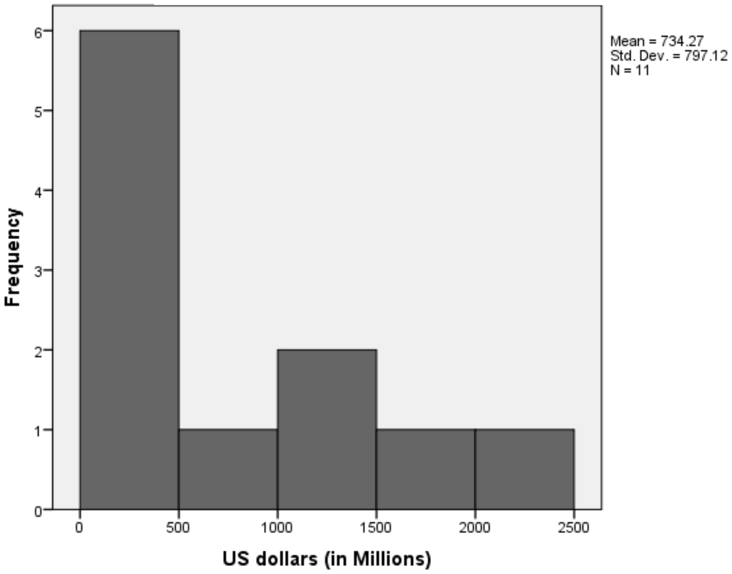

Figure 10. Histogram of Frequency Distribution of Cost per Incident for Higher-Cost Technology-Induced Human Errors

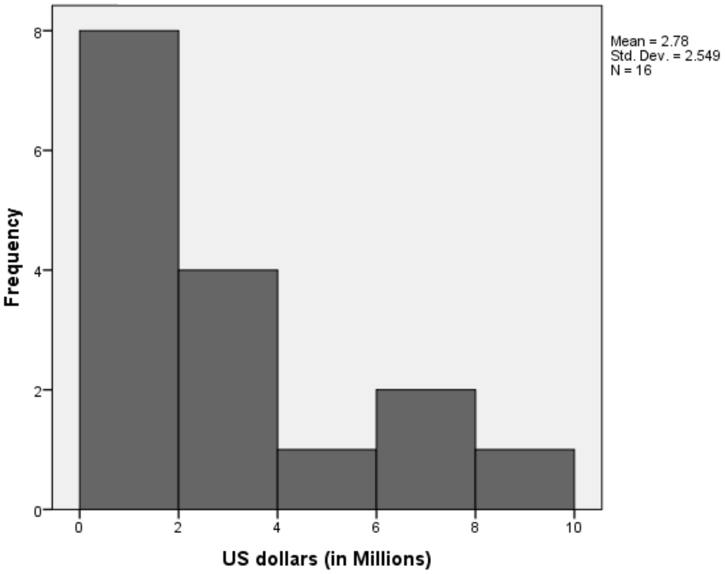

Figure 11. Histogram of Frequency Distribution of Cost per Incident for Lower-Cost Non-Technology-Related Human Errors

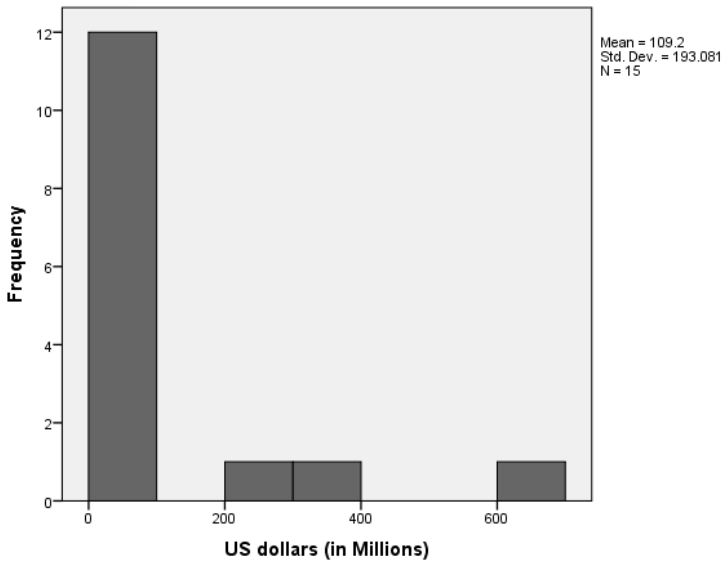

Figure 12. Histogram of Frequency Distribution of Cost per Incident for Higher-Cost Non-Technology Related Human Errors

4.3. CHAPTER CONCLUSION

This chapter presented the findings of the study. It began by summarizing U.S. nuclear incidents from 1955 to 2010, their probable causes, the cost associated with the incidents, and whether the incident was caused by human error due to advances in technology at the plant. Statistical analysis of the data rejected the null hypothesis of the study and indicated that incidents caused by human error related to technological advances were more costly than incidents not meeting this criterion. An explanation of these findings, along with an analysis of whether organizations benefit overall by incorporating advanced technology at their facilities, is undertaken in the following chapter.

CHAPTER 5: THE RELATIONSHIP BETWEEN TECHNOLOGICAL IMPROVEMENTS AND ECONOMIC AND SAFETY FACTORS

5.1. CHAPTER INTRODUCTION

As discussed in chapter 4, the data analysis performed in this study resulted in a rejection of the null hypothesis. Therefore, there is evidence that technological advances at a nuclear facility that affect how operators interact within the system can increase the cost of incidents caused by human error. Given this finding, are organizations better off thanks to incorporating advanced technology at their facilities?

5.2. THE ECONOMICS AND SAFETY OF TECHNOLOGICAL IMPROVEMENTS

To determine the economic and safety factors involved with technological improvements, information on 12 nuclear facilities for the years 2008 through 2013 was collected to represent a reasonable number of recent events. With regard to safety, the number of reported incidents was used as an independent variable (Morgan, Gliner, and Harmon, 2006); the capacity factor (explained in the next paragraph) was used as the independent variable for economic analysis. The cost of the upgrades was used as the dependent variable. An analysis of variance (ANOVA) and a regression analysis were performed on the data. The ANOVA was used to indicate the significance of the results; the regression equation indicated the extent to which the upgrades affected the plant's capacity factor and the number of reported incidents (Hair, 2010). The data used for the 12 facilities can be found in Table 4; the results of the analyses appear in Tables 5 to 7.

Table 4. Economic and Safety Factors Related to Technological Improvements at 12 Nuclear Facilities, 2008–2013

Facility	CF 2013	$ upgrades	# Incidents	CF 2012	$ upgrades	# Incidents	CF 2011	$ upgrades	# Incidents	CF 2010	$ upgrades	# Incidents	CF 2009	$ upgrades	# Incidents	CF 2008	$ upgrades	# Incidents
Cooper Nuclear Station	97	35	96	87	20	22	86	21	39	100	30	45	72	15	26	90	20	22
Duane Arnold Energy Center	89	22	42	83	17	23	99	31	95	89	16	25	92	20	33	103	36	52
Grand Gulf Nuclear Station, Unit 1	86	22	56	70	14	20	94	32	93	88	19	20	100	32	34	86	15	23
Hope Creek Generating Station, Unit 1	80	17	26	93	29	42	103	34	95	93	25	38	95	25	38	108	38	95
Palisades Nuclear Plant	85	20	43	74	16	22	96	30	92	92	25	49	90	24	34	99	30	62
Pilgrim Nuclear Power Station	74	12	22	98	29	41	85	20	38	99	28	42	90	26	38	97	30	58
River Bend Station, Unit 1	84	21	20	91	22	30	90	20	35	98	30	92	113	39	102	82	15	20
Seabrook Station, Unit 1	100	37	48	75	17	21	77	10	23	100	31	50	81	17	22	89	21	30
South Texas Project, Unit 1	91	25	50	93	30	92	94	29	55	101	32	34	90	22	31	95	29	39
Three Mile Island Nuclear Station, Unit 1	78	10	24	100	33	92	92	25	52	94	28	44	86	19	27	107	31	98
Vermont Yankee Nuclear Power Plant, Unit 1	98	30	90	92	30	91	90	22	42	88	26	40	99	31	44	80	17	26
Watts Bar Nuclear Plant, Unit 1	90	18	22	87	17	25	84	22	43	99	33	48	94	30	46	82	14	22

Notes: Upgrade costs are in millions of dollars from previous year; CF = capacity factor.
Sources: U.S. Nuclear Regulatory Commission Information Digests (NUREG 1350) 2015-16, 2014-15, and 2012-13, NRC.gov, and NRC Agencywide Documents Access and Management System.

Table 5. Regression Statistics

Regression Statistics	
Multiple R	0.926410175
R Square	0.858235811
Adjusted R Square	0.854126705
Standard Error	2.717930638
Observations	72

Table 6. Analysis of Variance Data

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3085.7869	1542.89343	208.861884	5.35853E-30
Residual	69	509.71314	7.38714695		
Total	71	3595.5			

Table 7. Regression Statistical Data

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-32.835	4.137640	-7.9357	2.6E-11	-41.089	-24.581	-41.089	-24.581
Capacity Factor	0.59165	0.051067	11.586	7.6E-18	0.489769	0.69352	0.48977	0.693522
Incidents	0.07526	0.017708	4.250	6.6E-05	0.03994	0.11059	0.03994	0.110593

The capacity factor for a power plant is calculated as the ratio between the observed output over a given period of time and the potential output if the facility were consistently running at its stated capacity. The calculation of the capacity factor involves dividing the amount of energy produced by a plant during a certain time by the amount of energy that would have been produced if the facility were always running at full capacity. The facility's capacity factor depends on the type of fuel used, the facility's design, and its age, among other factors.

There were 12 facilities in the sample and the information was collected over six years, yielding 72 data points for the ANOVA, which implies 71 degrees of freedom (Morgan, Gliner, and Harmon, 2006). The *F*-test yielded an *F* statistic of 208.86, which was significant at the $p < 0.01$ level. The regression analysis indicated that the regression coefficient for capacity factor was 0.592. The coefficient for incidents was 0.075. Both of these coefficients indicate that an increased amount of upgrades would result in a higher capacity factor for the facility (Mitchell and Jolley, 2013). However, the number of incidents also increases with greater investment in upgrades. The relationship of these factors is shown in Figures 13 and 14.

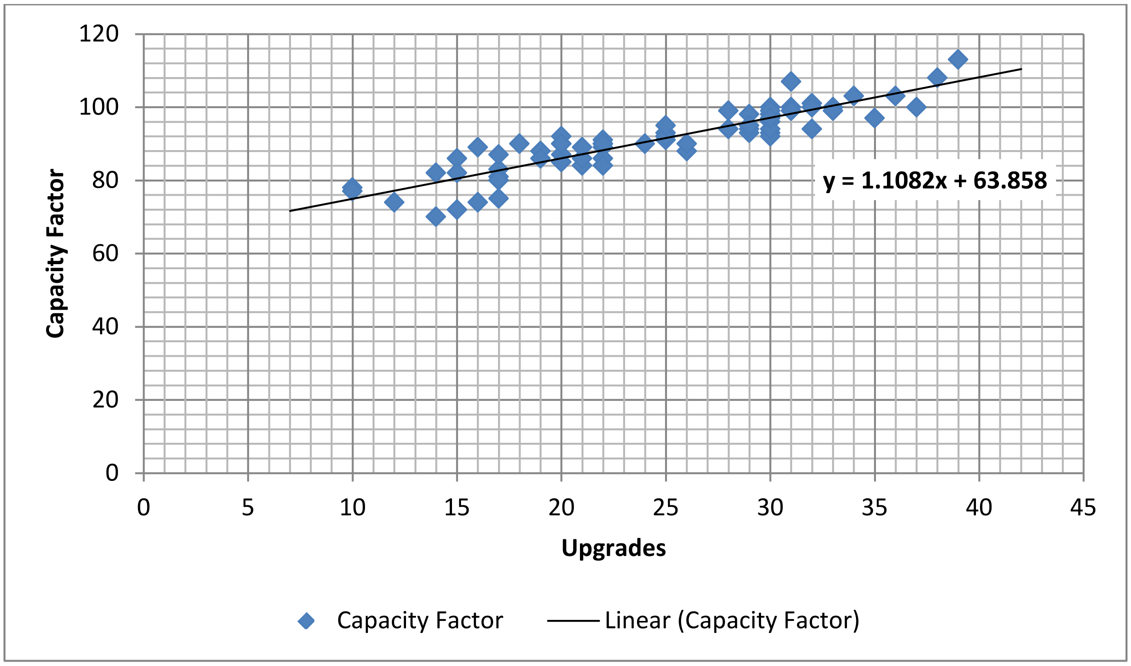

Figure 13. Scatterplot Showing the Relationship between Upgrades and Capacity Factor

Figure 14. Scatterplot Showing the Relationship between Upgrades and Incidents

The ANOVA procedure (Hair, 2010) was chosen rather than using multiple *t*-tests to avoid increasing the probability of a type I error. The ANOVA does not suffer from this limitation. In an ANOVA, the observed variance of a variable is partitioned (Hair, 2010). The partitioning creates components that are attributable to the sources of the variation. In so doing, the means of multiple groups can be tested for equality. In essence, this creates the same result as that of the *t*-test without increasing the type I error rate beyond the 0.05 level. In the case of this study, the *F* statistic was found to be significant at $p < 0.001$. This means that there is less than one chance in a thousand that the results observed in this study would be found by chance.

The study discussed here is of the random effects type (Hair, 2010), as I did not have control over the amount of upgrades conducted at any of the facilities but the facilities were chosen randomly from the population of operating nuclear facilities in the United States to represent a reasonable number of recent events. The use of the ANOVA model requires several assumptions regarding the data (Mitchell and Jolley, 2013): homogeneity of variance, normality, and independence. Since this study used a random effects model, the homogeneity of variance was assumed only for the residuals that are a consequence of the unit treatment activity. This means that the assumption of homogeneity relies upon the randomization involved in choosing the 12 facilities (Hair, 2010). The residuals and standard residuals for the predicted upgrades are displayed in Table 8.

5.3. INTERPRETATION OF THE OUTCOMES

An examination of Figures 13 and 14 and consideration of the regression coefficients reveal that increasing the amount of upgrades is associated with a higher capacity factor (a positive outcome) and more incidents being reported (a negative outcome).

The U.S. Energy Information Administration calculated the capacity factors for various types of power plants in the United States in 2009. Oil plants had the lowest capacity factor at 7.8%. Other types of power-generating facilities had higher capacity factors, with hydroelectric at 39.8%, other renewables at 33.9%, natural gas at 42.5%, and coal at 63.8%. In contrast, the capacity factor for U.S. nuclear facilities during 2009 was 90.3%. As shown in Table 4, the capacity factors for the 12 facilities examined in this study from 2008 until 2013 ranged from 70% to 113%. Capacity factors in access of 100% can be achieved by system upgrades that result in capacity’s exceeding the initial plant design capacity. Compared to other forms of fuel, nuclear power has a distinct advantage with regard to its capacity factor (U.S. Energy Information Administration, 2011).

The number of incidents was recorded as a way of measuring the level of safety associated with the upgrades (Morgan, Gliner, and Harmon, 2006). As the amount of money

Table 8. Residual Output

Observation	*Predicted Upgrades*	*Residuals*	*Standard Residuals*
1	31.78	3.22	1.20
2	22.98	-0.98	-0.37
3	22.26	-0.26	-0.10
4	16.45	0.55	0.20
5	20.69	-0.69	-0.26
6	12.60	-0.60	-0.22
7	18.37	2.63	0.98
8	29.94	7.06	2.63
9	24.77	0.23	0.09
10	15.12	-5.12	-1.91
11	31.92	-1.92	-0.72
12	22.07	-4.07	-1.52
13	20.29	-0.29	-0.11
14	18.00	-1.00	-0.37
15	10.09	3.91	1.46
16	25.35	3.65	1.36
17	12.60	3.40	1.27
18	28.23	0.77	0.29
19	23.26	-1.26	-0.47
20	13.12	3.88	1.45
21	29.11	0.89	0.33
22	33.25	-0.25	-0.09
23	28.45	1.55	0.58
24	20.52	-3.52	-1.31
25	20.98	0.02	0.01
26	32.89	-1.89	-0.70
27	29.78	2.22	0.83
28	35.25	-1.25	-0.47
29	30.89	-0.89	-0.33
30	20.32	-0.32	-0.12
31	23.05	-3.05	-1.14
32	14.45	-4.45	-1.66
33	26.92	2.08	0.78
34	25.51	-0.51	-0.19
35	23.57	-1.57	-0.59
36	20.10	1.90	0.71
37	29.72	0.28	0.11
38	21.70	-5.70	-2.13
39	20.74	-1.74	-0.65
40	25.05	-0.05	-0.02
41	25.28	-0.28	-0.11
42	28.90	-0.90	-0.34
43	32.07	-2.07	-0.77
44	30.09	0.91	0.34
45	29.48	2.52	0.94
46	26.09	1.91	0.71
47	22.24	3.76	1.40
48	29.35	3.65	1.36
49	11.72	3.28	1.22
50	24.08	-4.08	-1.52
51	28.89	3.11	1.16
52	26.23	-1.23	-0.46
53	22.97	1.03	0.38
54	23.27	2.73	1.02
55	41.70	-2.70	-1.01
56	16.74	0.26	0.10
57	22.75	-0.75	-0.28
58	20.08	-1.08	-0.40
59	29.05	1.95	0.73
60	26.24	3.76	1.40
61	22.07	-2.07	-0.77
62	32.02	3.98	1.49
63	19.78	-4.78	-1.78
64	38.21	-0.21	-0.08
65	30.40	-0.40	-0.15
66	28.92	1.08	0.40
67	17.19	-2.19	-0.82
68	22.08	-1.08	-0.40
69	26.31	2.69	1.01
70	37.85	-6.85	-2.56
71	16.45	0.55	0.20
72	17.34	-3.34	-1.25

spent on upgrades increased, the complexity of the system rose as well as the number of incidents. However, these were only incidents which were at a severity level of 1 or 2. None of the 12 facilities randomly chosen this specific analysis had a major incident during the six years of the data being collected.

The data indicates that spending more money on upgrades can increase the capacity of the facility as well as the potential number of incidents (Mitchell and Jolley, 2013). However, the incidents that occurred at these 12 facilities over the six years studied were relatively minor. Given that nuclear facilities produce vast amounts of power and that the upgrades significantly increased the capacity factor, there appears to be a financial advantage in conducting upgrades; however, this should be weighed against the increased rate of level 1 and 2 incidents observed. Also, as we have observed previously, many incidents at Level 3 or higher (see Table 1) appear to have been associated with human error while working with new technological advances. Since it does not seem likely that nuclear power facilities can become fully automated at any point in the near future, engineers must continue to increase facility capacity factors with upgrades while minimizing human errors.

5.4. CHAPTER CONCLUSION

This chapter has presented the results of an additional analysis beyond the primary statistical analysis in this observational study. The additional analysis sought to determine whether organizations gain overall benefit from incorporating advanced technologies into their facilities. An examination of these results was presented. In the next chapter, the impact of human factors on plant operation and on the systems engineering process will be discussed.

CHAPTER 6: DISCUSSION OF RESULTS

6.1. CHAPTER INTRODUCTION

Based on the information and analysis presented in chapter 4, there is evidence that technological advances at a nuclear facility that affect how operators interact within the system can increase the cost of incidents caused by human error. Additionally, as shown in chapter 5, the economic impact of incorporating advanced technologies into facilities is sufficiently great to outweigh the minor safety risks involved. This chapter will discuss the impacts of human factors, including human error tendencies, on plant operation and on the systems engineering process.

6.2. THE IMPACT OF HUMAN FACTORS ON PLANT OPERATION

To recognize design considerations necessary to combat human error during system design and integration, it is important first to understand the impact of human factors on plant operation. The reasons why incidents related to human error occur at nuclear facilities are complex, and the degree of complexity increases as technology advances (Karwowski, 2006). Both the human mind and the systems with which it interacts at these facilities represent high levels of sophistication that can be difficult to fully understand; moreover, the complexities can tend to become masked as advanced technology becomes increasingly incorporated into system design. However, progress has been made toward determining the root causes of these problems. Detailed investigation of human errors indicates that there are both micro-ergonomic and macro-ergonomic reasons for them (Smith, 2012). The incidents are nearly always the result, in some form, of the ways in which the systems operate and humans interact with them.

Of course, the systems themselves are designed by humans, and errors can also occur in the design phase. Designers attempt to create systems in such a way that operators can work effectively with them and avoid errors. However, an error at the design level can ultimately result in an operator error. Moreover, many errors are attributable to other aspects of the complicated operational processes involved, such as unresponsive management systems, ineffective training, organizational designs that are not adaptable, poorly designed response systems, and environmental disturbances of a chronic nature (Proctor and Zandt, 2008).

6.2.1. HUMAN BEHAVIOR MODELS

To understand human error, we must first understand human behavior. Hollnagel (1998) used Cognitive Reliability and Error Analysis (CREAM) taxonomies to map out the possibilities for human error. CREAM was among the first Human Reliability Analysis (HRA) programs to be used. Hollnagel believed that human behavior could be described as a process that progresses from thinking to doing (Hollnagel, 1998). CREAM is one of the more recognizable human behavior models within the safety community. Hollnagel believed that the modern industrial complex allows more thinking in its workforce with little doing. This presents a unique challenge when one is attempting to develop safety regulations.

6.2.2. ERGONOMICS

Human factors engineering, sometimes termed ergonomics (Smith, 2012), is concerned with improving the safety, health, productivity, and comfort of workers. It is also concerned with enabling smooth interaction between the people using the technology and the environment within which they are working (often called the human-machine environment). When this context is considered at the micro-ergonomic level, the focus is on the level of the human and machine (Proctor and Zandt, 2008)—for example, the design of the individual control panels, workstations, the visual displays, and the ergonomically fitted seats on which employees such as nuclear facility operators spend most of their work hours sitting. Problems that arise at this level may be due to improperly designed displays and workstations. For example, many problems identified in the analysis of nuclear incidents resulted from the installation of new technology that had not been designed well in ergonomic terms. In one incident, the operator reported that the display was too bright and that after three hours on the job, the operator could no longer view the display clearly. This difficulty caused the operator not to notice that the power plant was operating outside its normal parameters (Woods et al., 2010).

Also within the realm of human factors and ergonomics are considerations related to the operators' body size, or anthropometrics (Perrow, 1999). Other concerns include human decision making, cognitive capacity, information processing, and overall human skills. One real-life impact of anthropometrics involved an incident that occurred when an operator was away from his station. Normally, operators remained at their station with only a few short breaks during an eight-hour shift. However, new seating had recently been installed. It was supposed to improve comfort, as the company that provided the seating had a long history with the nuclear industry and good reviews by nuclear plant operators (Krivit, 2011). Indeed, most operators rated the seating as excellent with regard to comfort. However, one particular operator, unusually tall at 6'7", experienced difficulty with the new seats, which were designed for shorter people. As a result, the operator began taking more frequent and longer breaks to stretch and avoid muscle cramps. While the operator was away from his station, a release valve malfunctioned and the system continued to operate longer than should have been permitted given the state of the valve (Proctor and Zandt, 2008).

The building blocks for technological systems such as nuclear facilities include the people as well as the engineered components (Smith, 2012). However, the organization and its structure can also be important. These aspects of the workplace are referred to as macro-ergonomics. In both of the cases just described, the operators had reported the problem to their supervisor. The operator with the bright display panel had reported the problem once (Woods et al., 2010); the one with the uncomfortable seat had complained twice verbally and once in writing prior to the incident. If either of these supervisors had followed up on these complaints, an adverse incident may have been avoided. Therefore, it is crucial to have systems in place that encourage operators working with new equipment to alert their supervisor if difficulties arise. With regard to human factors, usually only the operators of the facility can gauge the success of the new system. Often, problems related to human factors engineering are not evident until a complaint or concern is raised or an incident occurs (Smith, 2012).

Performance levels and the inherent potential for mishaps in complicated technological systems are usually a function of the human and engineered subsystems (Perrow, 1999). The engineering may include such items as workstation design and the appearance of control boards; human engineering encompasses organizational and personnel systems as well as operational matters. Many system failures (typically about 70% at nuclear facilities) are attributed to operator error, but this is often an oversimplification (Smith, 2012), as it does not fully take into account various factors beyond the control of the operator, such as ineffective response systems, organizational designs that are not adaptable, unresponsive management systems, ineffective training, and overly complicated operational processes. These threats can be especially problematic when new equipment has been installed (Smith, 2012).

6.3. THE IMPACT OF HUMAN ERROR ON PLANT OPERATION

Reducing the negative impact of technological advances on human error entails improving human performance (Perrow, 1999). This type of performance improvement is a systematic process that seeks to analyze and discover performance gaps, monitor performance, determine the desired level of performance, and develop effective interventions. Once the interventions have been developed, they must be implemented and continually evaluated with regard to their results. The ultimate goal for human performance is to make the nuclear facility as close to event-free as possible. This can be achieved through the proactive management of human performance. It is also necessary to strengthen the facility defenses along with operator performance. Optimization of both the organization and operating processes can reduce errors to a minimum level (Proctor and Zandt, 2008).

Even the best-trained and most motivated operators of nuclear facilities will still make mistakes (Krivit, 2011). No amount of training or coaching can prevent all errors, as the interaction between the organization, the workplace, work tasks, operating systems, and operators creates the potential for a wide range of errors. The first step in preventing further problems is to understand why and how problems occur (Sehgal, 2012).

Errors at a nuclear facility can be reduced through using self-checks and specific tools (Proctor and Zandt, 2008). Random errors can never be fully eliminated, but they can be reduced. For example, a maintenance professional at the facility may be required to tighten a valve. No matter how well trained the individual is, there is always a chance of a mistake when this task is performed. The valve may be too tight or not tight enough (Perrow, 1999). The question to ask is why the individual has made the mistake and what can be done to prevent future occurrences. In the case of such a mistake, multiple barriers should be present to prevent system failure, so as to minimize the possibility of severe consequences. There must also be an organizational infrastructure in place that both identifies errors and protects the operators from injury or death. This creates a situation in which more significant problems can be avoided (Woods et al., 2010).

Although errors are inevitable, steps can be taken to manage, predict, and prevent them (Krivit, 2011). One beneficial approach is to recognize error traps and communicate them to others so as to proactively manage problem situations and minimize errors (Karwowski, 2006). The work situation can be changed to reduce, prevent, or remove conditions that lead to errors. Individual factors and tasks can be altered within the work environment to minimize future errors. For example, in the case of the seats that made an extremely tall operator uncomfortable, the difficulty could have been prevented if the manufacturer had requested a physical description of the operators (Sehgal, 2012).

Organizational values and processes significantly influence the behavior of an individual working at a nuclear facility (Woods et al., 2010). The values and processes of an organization can be developed in a manner that encourages individuals to take actions that increase the chances of achieving the organization’s goals. In the case of a nuclear plant, the organization’s values may focus on precision, accountability, and excellence for all individuals working at the facility (Krivit, 2011). This would encourage safe behaviors that decrease the number and severity of errors. Facility managers can guide workers’ behavior toward producing results that are more desirable and contain fewer errors. Improving staff performance requires excellence with regard to management systems, culture, and organizational processes. Exploiting the social interactions involved in work at a nuclear facility in positive ways can significantly decrease the likelihood of errors (Sehgal, 2012).

Improvements in human performance can be achieved through taking corrective actions after analyzing problem reports and events (Perrow, 1999). These corrective actions are part of the learning that should ensue after a problem occurs. Though reactive rather than proactive, they are important for improving the systems and technology involved. Combining reactive and proactive methods of learning facilitates anticipation of problematic events and the prevention of errors. This is often more cost-effective than using only the reactive approach (Proctor and Zandt, 2008).

The collective behaviors of people at all levels in a facility determine the performance outcome achieved (Perrow, 1999). The individual’s work is a product of his or her mental processes, which have been influenced by a variety of factors and demands which are present in the work environment. The work is also a function of the capabilities of each of the people involved. When the facility achieves high performance, the individuals will nearly always be taking responsibility for their own behaviors (Krivit, 2011). They will also be committed to personal improvement as well as to improving the work environment and their completion of tasks. Individuals working in a high-performance facility will be active in confirming the integrity of the facility defenses, anticipating situations that are likely to precipitate errors, and communicating with others to create a shared understanding of the facility and the work to be done (Woods et al., 2010).

6.4. THE IMPACT OF HUMAN ERROR ON THE SYSTEMS ENGINEERING PROCESS

To understand the ways in which human error can be manifested in system design, it is important to grasp the key aspects of the systems engineering process and the complexity and potential for human error that are inherently imbedded.

Systems are becoming increasing complex and challenging. Preexisting, simpler systems, especially those related to information, are old, incapable of meeting current demand, and rapidly becoming obsolete (Carayannis and Coleman, 2005). To facilitate system upkeep, safety, and reliability and to ensure that innovation is consistent and ongoing to meet clients' needs, the systems engineering process must be relatively complex.

The systems engineering process is composed of several progressive stages and encompasses a breadth of evaluations and considerations that are performed as a function of the process. To comprehend how human performance impacts this process and vice versa, a brief discussion of the process is necessary.

Although there is common agreement regarding the doctrines and intentions of systems engineering, execution differs from one system or design team to the next. The steps involved and the general methodology will depend on the background and prior experiences of the individuals on the design team. The most common and widely accepted systems engineering process and lifecycle progression are displayed in Figure 15 (Blanchard and Fabrycky, 2011).

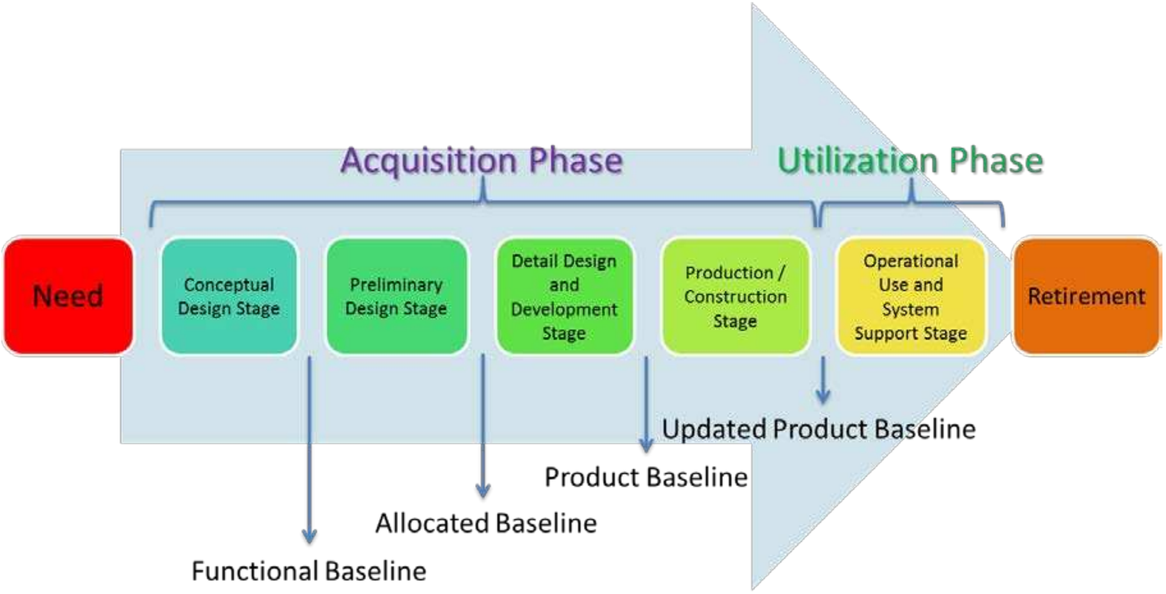

Figure 15. The Systems Engineering Process

The process begins with the identification of a need—for instance, the need to replace an obsolete system with a serviceable one, to improve a system in order to increase plant efficiency or capacity, or to upgrade a system due to new regulatory requirements. Once the need has been identified, then the conceptual design stage commences with the creation of a project management plan. During this stage, the problem is formally defined, specific system needs are identified, requirements are analyzed, maintenance and support are conceptualized, technology is evaluated, and the technical approach is selected. Conceptual design focuses on the system as a whole. At the conclusion of conceptual design, the system engineering management plan (SEMP) and the test and evaluation master plan (TEMP) are written, the conceptual design review (system requirements review) is conducted, and the functional baseline system specification is defined (Blanchard and Fabrycky, 2011).

Next comes the preliminary design stage. During this stage a functional analysis is conducted, requirements allocation is performed, trade-off studies are executed, early prototyping may be achieved, and acquisition, contracting, and supplier activities are accomplished. This stage focuses on the subsystem level. At the conclusion of this stage, the system design review is conducted and the allocated baseline, development, process, product and material specifications are defined (Blanchard and Fabrycky, 2011).

After preliminary design comes detail design and development. This stage consists of subsystem/component design, additional trade-off studies and evaluation of alternatives, development of engineering and prototype models, and development test and evaluation. This stage focuses on the component level. At the conclusion of this stage, the critical design review takes place and the product baseline, process/product and material specifications are defined (Blanchard and Fabrycky, 2011).

Next comes the production/construction stage. This stage consists of the production and/or construction of system components, acceptance testing, system distribution and operation, development and operation test and evaluation, and system assessment. This stage focuses on modifications for improvement of the designed system. At the conclusion of this stage, an updated product baseline is produced (Blanchard and Fabrycky, 2011).

The last stage in the systems engineering process is the operational use and system support stage. This stage consists of system operation in the user environment, sustaining maintenance and logistic support, operational testing, system modifications for improvement, contractor support, and additional system assessment (field data collection and analysis). This stage again focuses on modifications for improvement. At its conclusion, there exists an operating system that adequately fulfills its original intended purpose, meets acceptance criteria for all tests and milestones, and operates until its eventual retirement and disposal (Blanchard and Fabrycky, 2011).

Feedback is integral to the systems engineering process. It is important that the right information be reported and fed back to the responsible engineering and management personnel promptly and efficiently manner. Those responsible need to know in timely fashion exactly how the system is performing against specifications in the field, so that design modifications can be initiated. The primary objective is to provide a good assessment of just how well the system is performing in the user’s operational environment; a secondary objective is to identify any problems and initiate the required steps leading to corrective actions and the incorporation of necessary design changes and system modifications (Blanchard and Fabrycky, 2011).

6.5. CHAPTER CONCLUSION

This chapter has discussed the complexities associated with why incidents associated with human error occur at nuclear facilities and the need to reduce the negative impact of technological advances on human error by improving human performance. It has also covered the stages of the systems engineering process and the complexity involved from system design through deployment. Based on this information discussed in this chapter, a way forward leveraging the systems engineering process will be presented and discussed in the next chapter.

CHAPTER 7: HUMAN ERROR REDUCTION UTILIZING THE SYSTEMS ENGINEERING PROCESS

7.1. CHAPTER INTRODUCTION

The previous chapter discussed the impact of human factors, including human error, on plant operation and on the stages of the systems engineering process. As technology continues to advance, these impacts will only become more complex and the risk of human error will grow. This chapter will discuss the impact of evolving technology on the contemporary operator and ways to overcome these challenges utilizing the systems engineering process.

7.2. ISSUES RELATED TO ADVANCED TECHNOLOGY AND THE 21ST-CENTURY OPERATOR

Today’s sensory and processing technologies are perceptive and precise. They can discern the environment, solve complicated problems, make assessments, and learn from experience. Although they do not think as humans do, they can replicate many human intellectual aptitudes. Throughout the last century, for varying reasons, companies have implemented advanced technology and removed the human from many aspects of operation.

Human reliance on technology may be demanding a high price. Is our own understanding declining as we become more dependent on advancing technology and its scale of influence broadens? Computers have ventured into many different kinds of knowledge work: pilots rely on computers to fly planes, doctors consult them in diagnosing illnesses, and architects use them to design buildings. Automation is impacting virtually every industry.

Computers are not taking away all the jobs performed by talented people, but they are changing how the work gets accomplished.

As technology continues to develop, the people using it become less likely to refine their own capabilities. Technology that offers many prompts and tips could be responsible for this trend; simpler, less helpful programs push operators to think harder, perform, and learn. Humans' skills become sharper only through practice when we use those skills regularly to overcome different and difficult challenges.

There should also be a balance between advancing technologies integrated into plants and the interaction between humans and these new technologies. New technologies should be designed and incorporated into existing systems to keep the human operator in the decision cycle, which consists of an ongoing process of action, feedback, and judgment. This will ensure that operators remain attentive and engaged and promotes the kind of challenging activity that strengthens skills. Technology should play an essential but secondary role. It should broadcast warnings when parameters are exceeded, provide vital information that enhances the operator's outlook, and protect against the biases that often alter human thinking. The technology will then become the operator's partner, not the operator's replacement. This approach to technology application will not stifle technological progress. It requires only a slight shift in design priorities and a rekindled emphasis on human strengths and weaknesses.

Incorporating advances in technology is, in many regards, a necessary enterprise, but should be properly balanced within the confines of the system. It is easy to forget that humans are a vital part of this system. Technology is strongly suited to perform many functions, but it lacks the ability to rationalize. Decisions concerning the incorporation of new technology into a plant must consider the human factor. Even the smartest software lacks the common sense, ingenuity, and vitality of the skilled operator. In the control room, human experts remain indispensable. Human insight, imagination, and perception, enhanced through hard work and experience, cannot be replicated by the most cutting-edge technologies today and into the near future. If we let our own skills fade by relying too much on the technology crutch, we will render ourselves less capable, less resilient and more submissive to our machines.

Cognizance of these realities is imperative during system design. The human, including the human's propensity for error, should be considered a vital element of the system that is considered in design and accounted for through a rigorous systems engineering process. Engaged human participation is compulsory for successful system operation, but like all systems, it has its failure modes. The human's natural susceptibility for error in system operation should be addressed from multiple fronts.

7.3. THE IMPROVEMENT OR UPGRADE OF EXISTING SYSTEMS

Many organizations find a need for the improvement of existing systems or system upgrade necessary for three purposes: replacing obsolete technology or equipment, regulatory reasons, and economic motives. Therefore, the outcomes of the improvement or upgrade of existing systems can be observed as two-pronged, encompassing safety-related and economic factors. So how can organizations improve or upgrade systems and account for human error in system design?

7.3.1. A WAY FORWARD LEVERAGING THE SYSTEMS ENGINEERING PROCESS

Human error reduction and system design and deployment are often treated as two separate subjects with their own distinct processes that commonly intersect upon the conclusion of design, immediately prior to operation. This traditional approach to system design may have been acceptable for the antiquated, obsolete technologies of the past, but it is problematic for designing today’s more complicated systems. As the complexity of advancing technologies crescendos, human-system interaction warrants a more prominent role in system design and therefore compels early consideration, deliberation, and integration in the beginning stages of the systems engineering process. Incorporation of methods of human error prevention into the systems engineering process yields the fruit of the sound development of systems with an improved probability of successful operation and reduced error frequency.

At this juncture, it is important to discuss the difference between human performance and human factors as they relate to system design. Both concepts have been discussed throughout this dissertation, but there are subtle differences between them. Human factors in the context of the study of design, refers to the practice of designing products, systems, or processes to take proper account of the interaction between them and the people who use them. In substance, it is the study of designing equipment and devices that fit the human body and its cognitive abilities (Hollnagel and Woods, 2005). Alternatively, human factors in the context of the study of humans, can be described as the study of how human beings function within various work environments as they interact with equipment in the performance of various roles and tasks (at the human-machine interface) (U.S. Department of Energy, 2009). Common human factors considerations include anthropometric, sensory, physiological, and psychological factors. Human factors, like reliability and maintainability, are an inherent consideration within and throughout the systems engineering process (Blanchard and Fabrycky, 2011).

On the other hand, human performance is a field of study related to process improvement methodologies that can reduce human errors. It focuses on improving performance at the societal, organizational, process, and individual levels (Rothwell, Hohne, and King, 2013). In other words, it is a series of behaviors executed to accomplish specific results (U.S. Department of Energy, 2009). Human performance improvement methodologies are traditionally initiated after systems or plants are designed and installed and plant operations are underway; they are not conventionally employed, at least explicitly, during system design.

In essence, human factors influence human performance, but human performance does not necessarily influence human factors in the design of a system. Human performance, not human factors, is the primary concept in view in this chapter. Figure 16 depicts the traditional association between human performance and the systems engineering process.

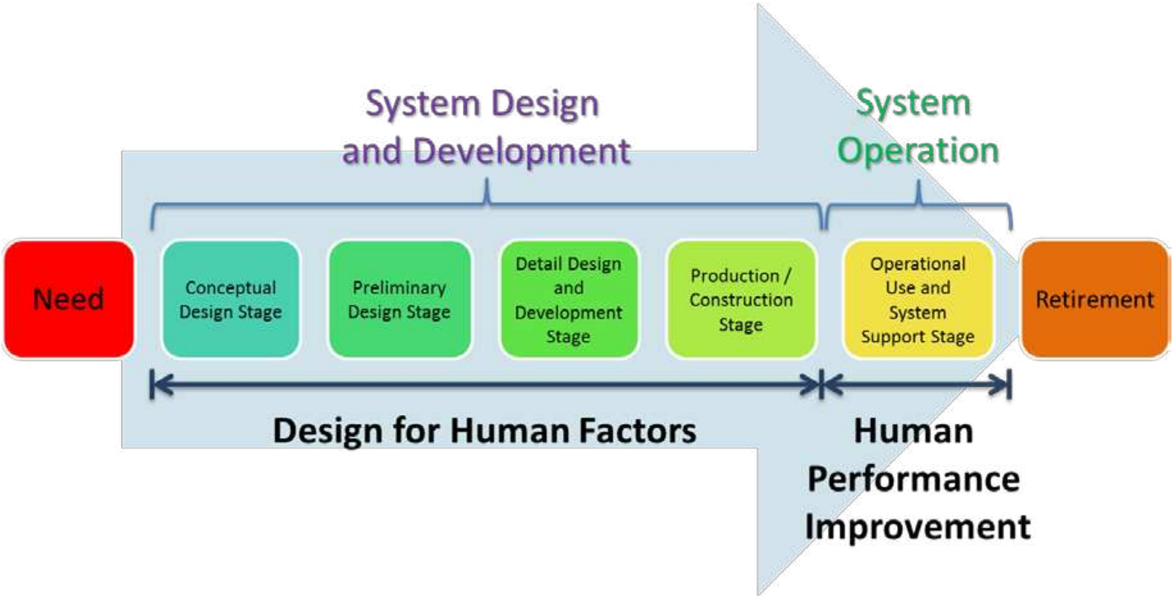

Figure 16. The Traditional Relationship of Human Performance and Human Factors within the Systems Engineering Process

As shown in chapter 4, human errors resulting in incidents at nuclear facilities can be very expensive and potentially harmful to the employees, the public, and the environment. In chapter 5, it was found that incorporating advanced technologies into nuclear facilities does increase capacity, but also results in an increased frequency of incidents. These incidents affect the public's perception of the company involved and the nuclear industry generally, along with stock values, insurance rates, regulatory oversight, and potential civil penalties. Following incidents at nuclear plants, operating experience and human performance lessons have been documented, disseminated to the industry, and incorporated into plant operations to ensure that similar situations would not occur in the future. The incorporation of industry operating experience and human performance methodologies into plant operation is a routine and expected aspect of nuclear plant operational life that promotes continuous improvement and a constant striving for safe operations. If human performance considerations have a positive impact after deployment, then it would be logical to consider that they could have a positive impact if taken into account before deployment. The focus of this chapter is the systematic incorporation of human performance into all stages of the systems engineering process. Figure 17 depicts a proposed integration of human performance improvement throughout the systems engineering process.

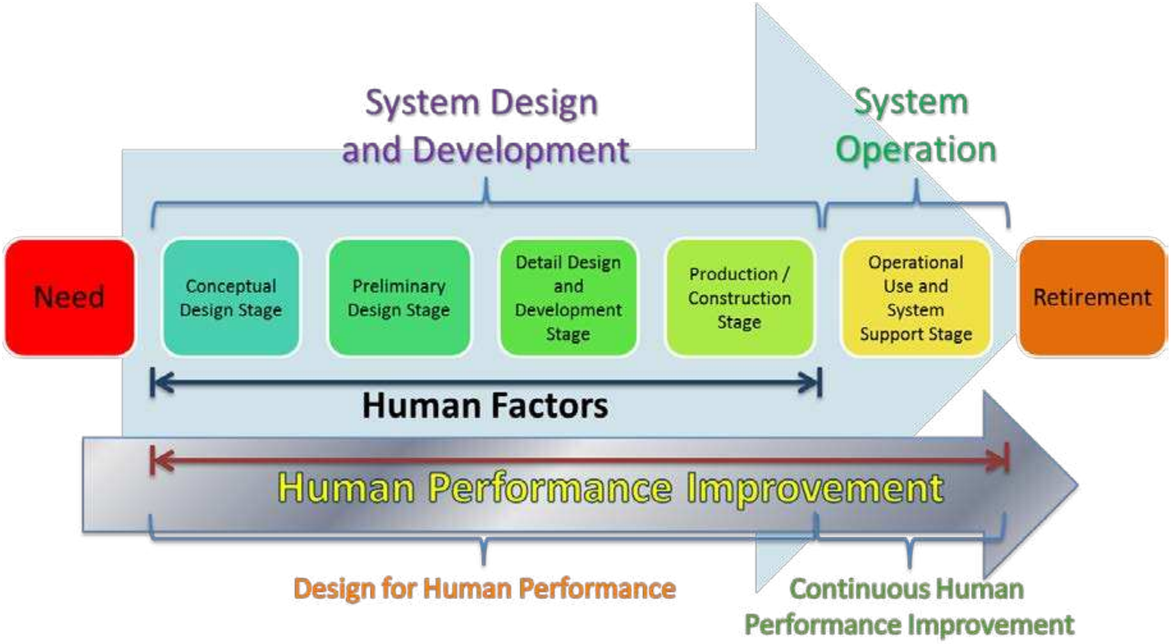

Figure 17. Human Performance Improvement Throughout the Systems Engineering Process

The cultivation of human performance–enhanced system design and operation can stem from (1) operator involvement in the systems engineering process; (2) human performance association with system operational requirements and system testing, evaluation, and validation; (3) iterative procedures and operator training development throughout all stages of the systems engineering process; and (4) selection and cultivation of aptly inclined operators chosen and groomed specifically for the systems being designed. Figure 18 illustrates the proposed human performance interface with the systems engineering process. As shown, feedback exists throughout the process, not only between the steps of the traditional systems engineering process, but between the systems engineering process and the human performance elements. The human performance feedback is represented as a solid line to articulate a more focused role in this context, whereas feedback in the traditional process is represented as a dashed line as it is more general in nature. Feedback goes both directions in all cases, as the process iteratively progresses.

7.3.2. OPERATOR INVOLVEMENT IN THE SYSTEMS ENGINEERING PROCESS

Whether a system is being newly created or an existing system is undergoing a minor modification, plant operations personnel should be involved in the systems engineering process from the onset. Operators are a significant system stakeholder. Not only do they bring a unique yet vital perspective to the design team, but they will eventually inherit the system being designed. Operators bring an essential perspective from the field, understanding the environment in which the system will operate, how the operator will interface with the system, and the robustness and redundancy that the system will need to possess to operate as required.

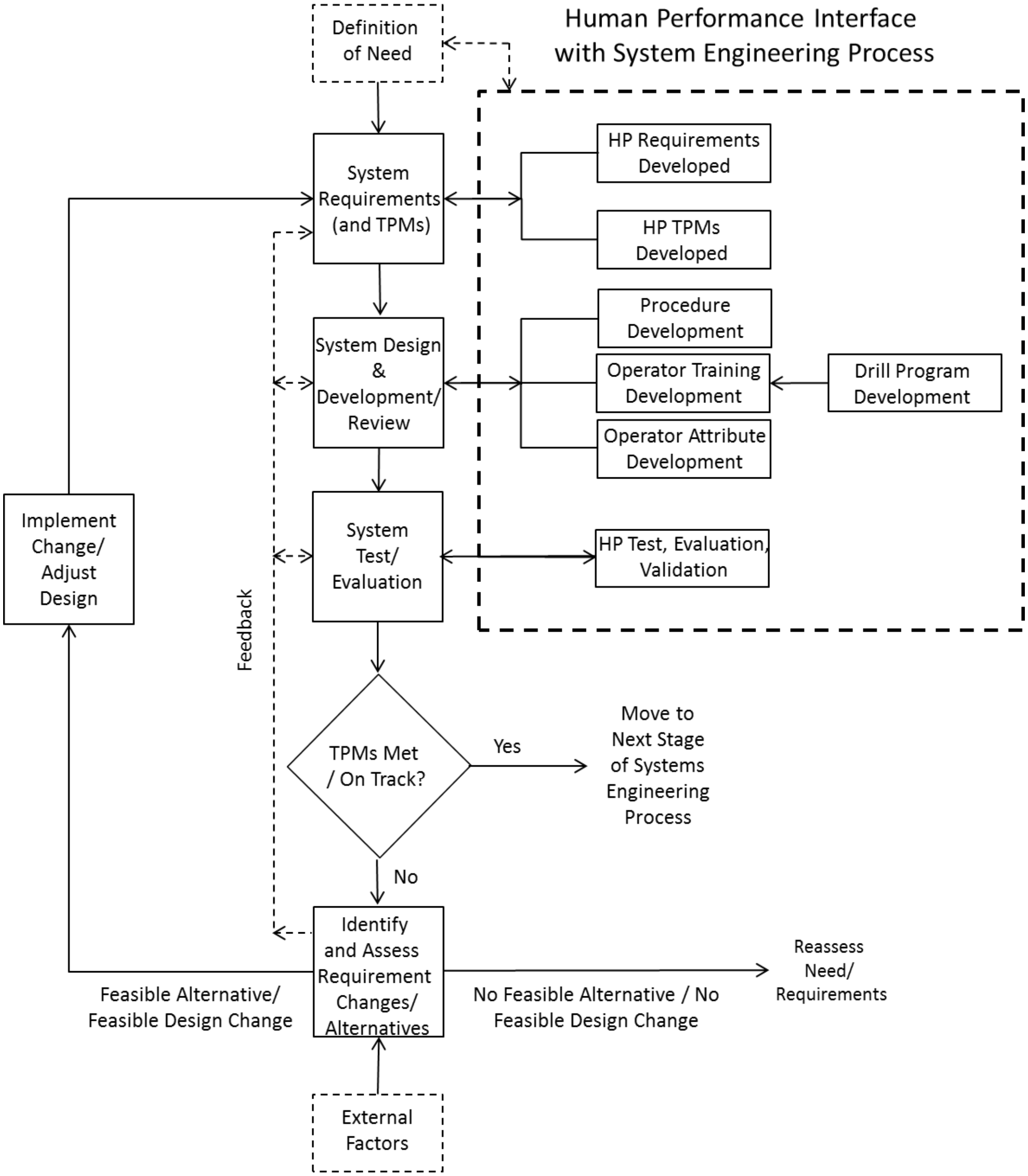

Figure 18. Human Performance Interface with the Systems Engineering Process

Achieving balance of innovation and practicality is often difficult, as designs are conceptualized, iterated, and deployed. The process may necessitate reverting to the design stages for necessary alterations. In most cases, some duplication of effort can be avoided by appointing members of the operations staff to the system design team and leveraging their experience from initial identification of needs through system design and development.

7.3.2.1. LIFE-CYCLE ENGINEERING

Designing for the system lifecycle is a foundational concept of systems engineering. The system lifecycle begins with the needs identification process and continues through design and acquisition to utilization. Lifecycle engineering transcends the siloed, isolated view of systems by embracing all aspects of the system including maintenance, support, operation, and eventually phase-out and disposal. Because system utilization encompasses a large portion of the system’s life, the participation of operations personnel in system design is vital not only for system operational success and support, but also for human error reduction in the operation of new technologies.

7.3.2.2. FAILURE MODES AND EFFECTS ANALYSIS

Failure mode and effects analysis (FMEA) is a design method that can be used to identify and examine potential system weaknesses. It includes the necessary steps for examining all the means by which a system failure can occur, the potential consequences of failure for system performance and safety, and the significance of these effects (Carlson, 2012). FMEA can be used during all stages of the systems engineering process. Operations personnel can play a role in FMEA during all stages of system design. Having operated similar systems, having been exposed to a breadth of systems failures, and having witnessed and responded to the resulting impact of these failures on the plant, operators have valuable insights that should be incorporated throughout design and development.

7.3.2.3. SYSTEM DESIGN EVALUATION

The fulcrum of the systems engineering process lies in system design evaluation. Evaluation is an obligation intrinsic to the systems engineering process and must be conducted frequently as the design activities progress. Likewise, the establishment of a clear set of system design criteria must precede evaluation. Design criteria can and should come from a number of diverse sources, but those that originate from the plant operations staff should be given elevated attention because the operators will in effect be the primary system owners throughout the system's useful life.

Evaluation in the context of systems design requires finesse and fidelity. System design should harmonize union, examination, and evaluation, and these technical activities should be integrated and employed iteratively and persistently over the system lifecycle. The active engagement of operations personnel is central to all these steps.

System evaluation in the context of human error reduction will be further developed in the next section.

7.3.3. THE ASSOCIATION OF HUMAN PERFORMANCE WITH SYSTEM OPERATIONAL REQUIREMENTS AND SYSTEM TESTING, EVALUATION, AND VALIDATION

The conceptual design stage is the first and most important stage of system design and development, because it lays the groundwork for what follows. As discussed in chapter 6, the identification and definition of a need provide an effective and proper starting point for this stage. Inherent to this foundational stage are the generation of operational requirements and the establishment and commencement of system testing, evaluation, and validation.

7.3.3.1. HUMAN PERFORMANCE AND SYSTEM OPERATIONAL REQUIREMENTS

Upon designation of the need and technical approach for the system, the operational requirements are then defined. Because system operational requirements should be identified and specified early, wisely, and as completely as possible, the identification of human performance requirements should occur at this point in the process.

System operational requirements address the following elements: mission definition, performance and physical parameters, operational deployment, operational lifecycle, utilization requirements, effectiveness factors, environmental factors, and economic factors (Blanchard and Fabrycky, 2011). Embedded in these elements should be specific, exclusive human performance system requirements that can be easily assessed and discernible in system design. Once human performance system requirements have been established, specific human performance technical performance measures (TPMs) can be detailed.

7.3.3.2. HUMAN PERFORMANCE AND SYSTEM TESTING, EVALUATION, AND VALIDATION

System testing, evaluation, and validation are usually planned during the conceptual design stage and take place parallel to the definition of the overall system design requirements. The testing and evaluation endeavor consists of the testing of discrete components, of various system elements, and then of the complete system as an integrated unit. The idea is to embrace a gradual and ongoing approach that will enable continuous application and enhancement as system design and development progress. Testing and evaluation activities are associated primarily with the design activities and extend through production and construction and then to the system utilization and support stages. Validation, on the other hand, refers to the process needed to ensure that the system configuration as designed meets all specifications. A complete, integrated method should be established for the validation of the system and its elements as an integrated unit. System validation is complete when the system functions effectively and efficiently within its accompanying higher-level system-of-systems composition, hence meeting operational requirements (Blanchard and Fabrycky, 2011).

Central to evaluation is the establishment of comprehensive technical performance measures (TPMs), which are predicted and/or estimated values of attributes or characteristics inherent in the design. TPMs are assessed routinely through the stages of the systems engineering process (Blanchard and Fabrycky, 2011). TPMs may comprise such quantitative factors as mean time between failures, utilization rate, availability, human factors, size, and weight. TPMs arise primarily from the establishment of system operational requirements and the maintenance and support model. They may come from various sources, as with design criteria, and they cover a breadth of issues, but sufficient attention should be devoted to creating human performance TPMs that evaluate the integration of human error reduction tools with the technology necessary to achieve the functionality related to the system’s purpose. These human performance TPMs should be created by and will most likely be assessed by plant operations personnel.

Human performance TPMs are derived from error precursors, also referred to as performance-shaping factors. Error precursors are unfavorable conditions that generate divergences between a task and the individual. Error precursors hinder successful performance and increase the likelihood for error. By definition, they exist before an error occurs (U.S. Department of Energy, 2009). Error precursors are unique to the situation, the plant, and the personnel involved, and therefore they require systematic evaluation, logical selection or generation, and potential modification before their adaptation into human performance TPMs. A comprehensive listing of error precursors can be found in Appendix B.

By way of illustration, Table 9 presents hypothetical results from a human performance TPM identification and prioritization effort involving a team of individuals representing the designers, operations personnel, and key management personnel. The quantitative requirement of human error significance levels refers to a defined severity level grouping for potential issues and is discussed in greater detail in Section 7.3.8.

In this example, the performance factors of Familiarity with Task/First Time, Operator Knowledge of System, and Operator Proficiency and Experience are the most critical, so emphasis in the design process must be directed to these items with respect to human performance. The method and instrument to determine the quantitative metric are discussed below in section 7.3.8.

7.3.4. PROCEDURE AND TRAINING DEVELOPMENT IN THE SYSTEMS ENGINEERING PROCESS

The stereotypical perception of human error is that it indicates a flaw present in the human and initiating an undesirable consequence. This misconception places the obligation to prevent such consequences solely on the human. Industry leaders guided by this erroneous understanding continually try to remediate humans incorrect actions within the system. This leaves organizations and their employees struggling to achieve perfect task performance and always needing to be “more careful.” Furthermore, formal corrective actions in response to the error take the form of increased training, reinforcing management’s expectations, and occasionally punishment. If these methods are applied to a qualified and experienced employee,

Table 9. Sample Prioritization of Technical Performance Measures

Technical Performance Measures	Quantitative Requirement (Metric)	Relative Importance (user desires) (%)
Absence of Confusing Displays and Controls	0 Significance Level 1 human errors	7
	Less than 1% Significance Level 2 human error rate per year	
	Less than 5% Significance Level 3 human error rate per year	
Absence of Hidden System Response	0 Significance Level 1 human errors	8
	Less than 1% Significance Level 2 human error rate per year	
	Less than 5% Significance Level 3 human error rate per year	
Alternative Indications	0 Significance Level 1 human errors	11
	Less than 2% Significance Level 2 human error rate per year	
	Less than 8% Significance Level 3 human error rate per year	
Operator Proficiency and Experience	0 Significance Level 1 human errors	14
	Less than 1% Significance Level 2 human error rate per year	
	Less than 5% Significance Level 3 human error rate per year	
Operator Knowledge of System	0 Significance Level 1 human errors	17
	Less than 1% Significance Level 2 human error rate per year	
	Less than 5% Significance Level 3 human error rate per year	
Absence of Work-arounds / Decreased Propensity for Out-of-Specification Instruments	0 Significance Level 1 human errors	5
	Less than 3% Significance Level 2 human error rate per year	
	Less than 10% Significance Level 3 human error rate per year	
Familiarity with Task / First Time	0 Significance Level 1 human errors	19
	Less than 1% Significance Level 2 human error rate per year	
	Less than 5% Significance Level 3 human error rate per year	
Absence of Repetitive Actions / Monotonous Operation	0 Significance Level 1 human errors	9
	Less than 2% Significance Level 2 human error rate per year	
	Less than 7% Significance Level 3 human error rate per year	
Scarcity of Irrecoverable Acts	0 Significance Level 1 human errors	10
	Less than 1% Significance Level 2 human error rate per year	
	Less than 3% Significance Level 3 human error rate per year	
		100

they produce peripheral performance enhancements at best, narrowly focused and rarely long-lasting.

As discussed in detail in Chapter 2, human error and error rates are a reflection of mental response to a task. In chapter 2, Rasmussen's (1983) three modes of task accomplishment based on the mental processing behaviors exercised at each level were noted: skill-based, rule-based, and knowledge-based. Skill-based tasks are made up of very familiar actions performed in a well-known environment. The human being is virtually on autopilot. Error rates are approximately 1:1,000. Rule-based tasks are known to the operator. Upon accurate recognition of a situation or condition, the performer can apply a known rule to navigate toward a known end objective. Tasks in this performance mode are inclined to follow "if-then" logic, and error rates are approximately 1:100. Finally, knowledge-based tasks are new, unfamiliar, or unique to the performer. Successful performance of a knowledge-based task depends heavily upon the performer's fundamental knowledge, diagnosis, and analysis skills. Unlike the case of rule-based tasks, the operator is not able to navigate toward a previously known end objective. These tasks are best defined as trial and error. Error rates are generally 1:2 (Reason, 1990).

The performer's comprehension of the task, not just the task itself, determines how and at what rate errors are made. An activity could be rule-based for one operator but knowledge-based for another. Therefore, considering the human-machine interface solves only half of the equation; the human-task interface must also be taken into consideration. Substantial gains in human performance improvement (and ultimately the bottom line) will be achieved only when we match machine to operator in an atmosphere in which the operator can thrive. To fully understand this, it is important to distinguish between errors and events.

Does an organization that seeks improvements in safety initiate a program of error reduction or event prevention? Preventing human error necessitates strict control over external and internal human factors. This control is outside the reach of organizations and can be attempted only through research and precisely controlled examination. The organization that adheres to a safety-conscious work environment concept should make every effort to understand the factors affecting human error rates and associated liabilities, and it should strive to minimize, to the greatest extent possible, human error.

Events, on the other hand are immediately apparent from an organizational perspective. Consequences of these events will steer organizational priorities and provide necessary resources. From this outlook, error can be perceived as a symptom of an event made possible by procedures, processes, and training that are not suitable to protect against human imperfection. Processes, procedures, and training can be easily analyzed and dissected, whereas the human mind tends to be perplexing from an error prevention standpoint. Moreover, events tend to be repeated given similar circumstances and known causes, whereas identical errors rarely yield similar results.

So the question now becomes, how do you minimize errors? Rasmussen (1982) examined human error and recognized that two aspects must be taken into consideration in this regard: human-machine and human-task. The classical view of human error would contend that any faults in the machine or task are also present due to human error. This is unquestionably true. In business, however, that perspective is only valid to the extent that the business has influence over the task and machine. The business organization can use the same method in event prevention with respect to these components irrespective of its influence, bolstering the benefit of undertaking event prevention tactics.

After a new system has been designed and installed, whether due to economic considerations or necessity, the plant at that point has essentially inherited the flaws intrinsic to that system. Although conceivable latent human error embedded in the design or construction of the component can and should be addressed where appropriate, there are limited cost-effective avenues to proactively predict, evaluate, and address such deficiencies once they have been installed and prior to emergence. Transitioning from system design and development to system operation launches the use of operations procedures and reliance on operator training, thereby shifting the focus from the physical system to the operation of that system. This stage of the systems engineering process is the longest-lived and is the primary recognized motivation for the process (after all, the system is designed to be operated). For this reason, operations procedures and training should not be an afterthought to system design, but an integral component of it. Examination of the human-task relationship in system design should begin at the conceptual design stage in the systems engineering process and evolve as the process progresses.

7.3.4.1. CAREFUL PROCEDURE WRITING

Beginning with the task, the plant needs to devote considerable attention and due diligence to the generation of processes, programs, and procedures associated with system operation. Specifically, the preparation of operation procedures, a written sequence of steps that establish, maintain, or restore the plant within acceptable operating limits, should begin at the conceptual design stage in the systems engineering process, and the procedures should be further developed and refined as the process advances. This will ensure that procedures are properly developed and that when system production is complete, management is in a position to promptly commence operations. Proper application of human error prevention tools and techniques needs to be soundly intertwined into the framework of these documents and programs. Once generated, these programs, procedures, and processes must be systematically verified and validated to ensure not only adequate system operation, but also that operation remains free of human error trips and traps through appropriate consideration of the task portion of the human-task relationship.

7.3.4.2. KNOWLEDGE-BASED OPERATOR TRAINING AND DRILL PROGRAM

There is a limit to the amount of detail and information that can be built into procedures. If procedures were written for a person to operate a complex piece of equipment for which he or she had no prior training or background, they would be much too long, detailed, and convoluted for a reader to follow them sufficiently.

For procedures, processes, and programs to be effective, the operator must possess a minimum level of prior knowledge. This necessity leads to an examination of the “human” portion of the human-task relationship. Applying a systems engineering approach to the development of a suitable mechanism enabling humans to adequately and safely operate new technologies is a very complicated and confounding task. When the focus is on the operator, the foundation of safe operation now becomes effective and thorough operator training.

Operator training can be divided into two general categories: skill-based and knowledge-based. Skill-based learning concentrates on developing and applying specific skills and behaviors. Learners spend most of their training time learning, developing, and practicing skills through a variety of hands-on, real-life scenarios. Skill-based training will fall short if insufficient time is dedicated to application of the skills and behaviors during the training. The ultimate objective of skills training is to enable the learner not just to acquire proficiency in the skill, but to have the confidence to apply it competently on the job. On the other hand, knowledge-based learning is designed to enable the learner to move facts, information, process understanding, and other knowledge from short-term to long-term memory. Much knowledge-based training falls short of this goal due to poor engagement. If the learner is focused more on just finishing the training than on actively trying to assimilate it for further use, the learning impact will be minimal.

When learning to manipulate technologically advanced, complex systems, operators should be trained utilizing the knowledge-based approach to ensure adherence to design boundaries, efficiency in operation, and an adequate safety margin. This training should not only communicate the particulars of a system, its components, operation, procedures, and processes, but it should also teach deeper, underlying fundamentals and theory. This ensures a thorough, deeply rooted understanding of not only the specific task and components manipulated, but the impact of that task and manipulation on the system as a whole. Armed with this deeper understanding, the operator can anticipate expected plant response and quickly detect and react to abnormal situations that could turn into plant events. Again, the objective of the operator training program should be to drive performance into the skill-based mode. As with the generation of operations procedures, generation of operator training programs should begin at conceptual design and be further developed as the systems engineering process advances.

A vigorous plant casualty control drill program should also be included. A well-developed and consistently administered drill program can effectively provide training and evaluation of facility operating personnel in controlling abnormal and emergency operating situations involving the newly designed system. To ensure that the drills are fulfilling their intended purpose, there should be evaluation criteria for assessing operators’ knowledge and skills. Training and evaluation of staff skills and knowledge such as component and system interrelationships, reasoning and judgment, team interactions, and communications can be accomplished through drills.

Proper response to abnormal conditions is vital to ensure personnel safety and protect facility equipment and the environment. Personnel must be able to take the immediate actions necessary to safely mitigate the consequences of an unexpected or abnormal and potentially dangerous condition involving the newly designed system. Drills focus on the actions necessary to respond to these abnormal conditions.

The primary objective of a drill program is to train and qualify personnel. To successfully achieve this goal, drill participation should be integrated into initial and continuing training. An effective drill program is one of the best means available to ensure that the operating staff can safely deal with unplanned and potentially hazardous situations. As with the development of procedures and training, the drill program involving the system in design should be developed during the conceptual design stage and revised iteratively as the systems engineering process progresses. In addition to training operations staff in casualty control with respect to the new system, drill scenario development provides another avenue for system design review and evaluation by having additional set of eyes view the process from an alternative perspective. This early deliberation of system casualties and necessary operator response not only guides the development of the drill program, but also provides necessary feedback to system designers on desirable improvements and cultivates the continued development of operator training and procedures. Again, the earlier this activity is initiated in the systems engineering process, the better the results will be for system design and operator training.

The rigor and detail of a drill program will differ with facility intricacy and hazard potential. For example, a drill conducted at a reactor facility may involve several people and require a high level of detail, whereas a drill at a site support facility may comprise only a few people and necessitate less detail. Drills on safety-related systems or components at high-hazard facilities may require a large drill team using a detailed drill scenario; drills conducted on safety systems at a low-hazard facility may require a drill team of only a few persons.

To ensure proper implementation of a drill program, the duties, roles, and responsibilities of personnel involved and the mechanics for conducting the drill should be delineated. This ensures consistency of development, conduct, evaluations, critiques, and feedback into the training and drill programs. Alternative methods of conducting drills should be included as an integral part of the drill program to ensure that it is fulfilling its intended mission of training facility operating personnel. Facility management should determine the appropriate level of effort and resources to implement each element of the drill program, consistent with the risk and complexity of the facility.

Regardless of the size, complexity, and risks of a facility, an effective drill program should include the following essential elements: developed drill scenarios, trained drill team personnel, protocol for drill conduct, criteria for drill evaluation, drill critiques, incorporated feedback from drills, and alternative methods of conducting drills.

7.3.5. OPERATOR ATTRIBUTE DETERMINATION

The determination and development of necessary operator skills and training requirements should begin at the conceptual design stage in the systems engineering process and be refined as the process advances. These operator attributes can even manifest as system requirements determined during requirements analysis. At the conclusion of each stage, in addition to adjusting operations procedures and training, employee critical skills, knowledge, and education requirements should be examined and, if necessary, improved. Workforce planning should be built into all stages of the systems engineering process to ensure that personnel with the necessary attributes are available when needed. Human development should be considered as important as system design. Workforce design is too often considered late in the systems engineering process and the initial plant startup and early operations suffer due to inadequate workforce planning or excessive costs associated with accelerated operator training and qualification.

Embedded in the determination and development of the required workforce are population studies to canvass the local population for demographics such as industry expertise, education levels, and education ability. With this baseline assessment of the population, training programs can be efficiently developed in view of the general strengths and weaknesses of the available workforce, and specific needed skill sets can be assessed, targeted, and fostered if necessary. Nonetheless, as discussed above, this needs to happen early and iteratively so that issues can be addressed and corrected during design.

Another important subtlety in workforce development is the development of leaders. As the systems engineering process proceeds and, more generally, as the speed of business increases and the complexity of technical advances rises, it is easy to focus only on immediate needs and pay less attention to the systemic issues that ultimately drive long-term success. As the process progresses, management needs to be constantly assessing the connection between leadership practices, employee work passion, customer devotion, and the bottom line. There is a clear connection between the quality of an organization’s leadership practices, as perceived by employees, and employees' intentions to stay with an organization, perform at a high level, and apply discretionary effort.

7.3.6. SYSTEMS ENGINEERING INFRASTRUCTURE

The design and development of an innovative system necessitate an adaptive and equally unique and innovative systems engineering infrastructure. One should not fall into the trap of developing a 21st-century product in the framework of 20th-century systems and processes. It is important to remain apprised of and consistent with industry standards and best practices with respect to organizational design, management processes, software development and functionality, and administrative methods—not necessarily with the techniques that everyone has used in the past and is comfortable with. Business is always evolving and striving to reach new heights; the infrastructure should stay in lock step with this evolution to ensure the development of the best product or system using the best available resources.

As the systems engineering process for product or system development is launched, the proper infrastructure should be established to support it efficiently. The infrastructure design should be a formal, guided process of integrating the people, information, and technology of an organization. It is used to match the form of the organization as closely as possible to the purpose that the organization seeks to achieve. Through this design process, organizations act to improve the probability that the collective efforts of their members will be successful.

7.3.7. THE FINAL PRODUCT

Operator involvement in the systems engineering process; human performance integration with system operational requirements and system testing, evaluation, and validation;

the implementation of a strong knowledge-based operator-training program, including a drill program; the generation of well-written and validated procedures; and the selection and cultivation of personnel aptly prepared for system operation—all these actions are connected with a common theme: the development of a well-qualified, capable, and equipped human operator for the given system. As a clear illustration, we can recall the swift, logical, reasoning used by an officer in the Soviet Air Defense System to save the United States from nuclear war.

On September 26, 1983, Lieutenant Colonel Stanislav Petrov of the Soviet Air Defense Forces was on duty at the command center of the Soviet early warning satellites. Petrov's duties included monitoring the satellite early warning system and informing his chain of command of any nuclear attack. If the early warning system indicated an attack, the Soviet Union's response would be an immediate counterattack. Close to midnight, the early warning system indicated five inbound intercontinental ballistic missiles from the United States. Petrov deemed the detection to be an error, since a first-strike nuclear attack by the United States, should one be mounted, was expected to involve hundreds of concurrent missile launches with the intention to incapacitate any counterattack. Additionally, the early warning system had been newly designed and installed. In his estimation, the system was not yet entirely reliable. Petrov also observed that the ground radar had failed to corroborate the indications of the early warning system. Petrov ultimately rejected the warning and classified it as a false alarm. It was later determined that the false alarm had been produced by an atypical orientation of sunlight on high-altitude clouds and the early warning systems satellites' orbits (Hoffman, 1999).

Imagine if the Soviet Air Defense System had been designed with little to no human interaction and had automatically initiated a counterattack based on the indication received by the system received and the Soviet Union’s established response strategy! This dramatic example emphasizes the importance of the human being within a system who is well trained and knowledgeable of the system that he or she operates.

7.3.8. WAYS TO MINIMIZE THE IMPACT OF HUMAN ERROR THROUGHOUT THE SYSTEMS ENGINEERING PROCESS

As this study has emphasized repeatedly, human error cannot be entirely prevented, but if proper tools and techniques are implemented early in the systems engineering process, it can be reasonably minimized. With this goal in mind, it is also important to establish a system to minimize the impact or potential impact of errors. Along with the steps discussed previously in this chapter, a human performance improvement (HPI) process should be established not only to remain cognizant of human performance during system design, but also to provide a means to evaluate human performance in operating the system at its various stages. This process incorporates HPI logic into system design and subsequent system operation and provides a mechanism to assess and mitigate potential impacts of human error during system design. This process should be established early in the systems engineering process to identify how human error affects plant systems and equipment; this information in turn will provide necessary feedback into system design process. This process is displayed by means of a use case model in Figure 19. The nucleus of this model is converging the efforts of all project entities on meeting the established design requirements comprised of safety, security, and customer requirements.

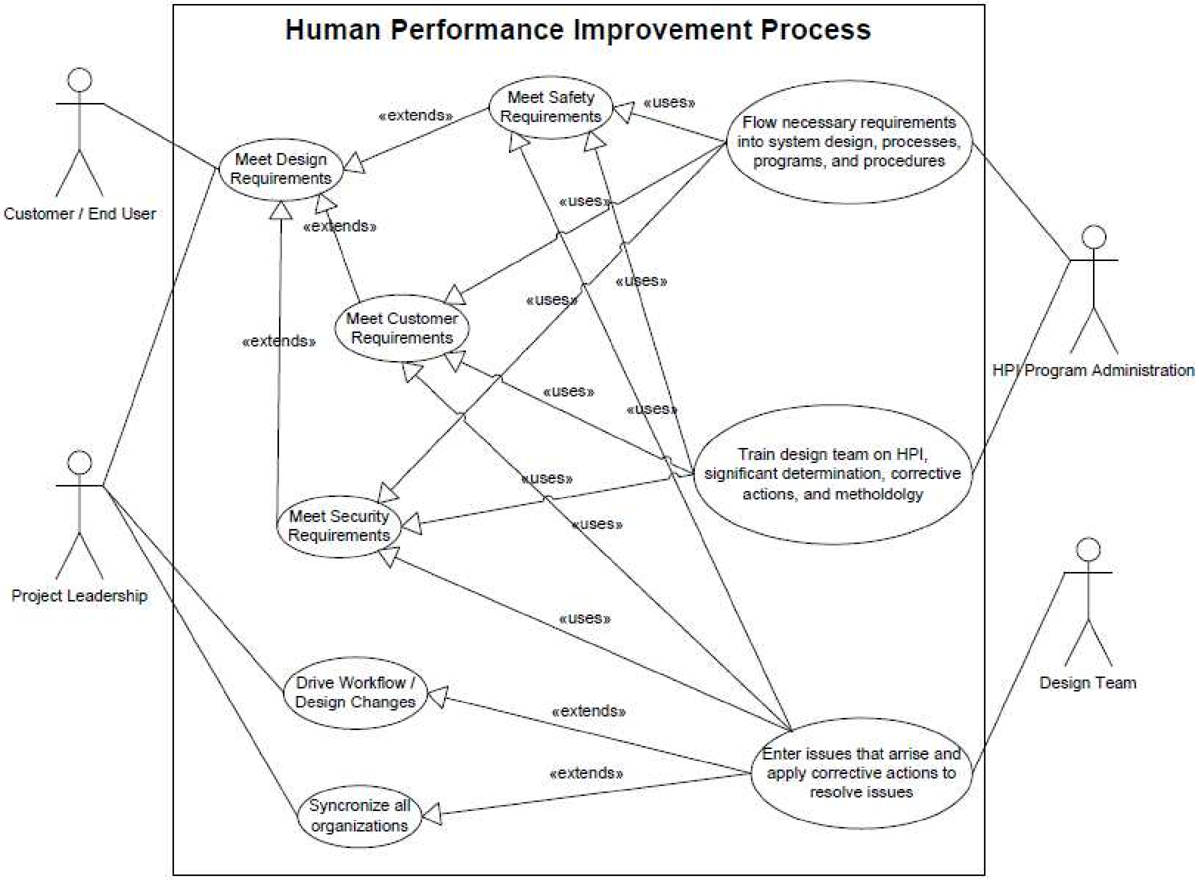

Figure 19. Use Case Model of the Human Performance Improvement Process

To institute this process in a manageable fashion, organizations should determine human error severity criteria and establish a tracking system to capture these potential human error–induced issues for consideration in developing engineered and administrative component features, human error prevention training and reinforcement, and lessons learned. These potential issues and incidents can be discovered at any stage of the systems engineering process, during the development of procedures for system operation, during training development, during FMEA, and during the design reviews conducted at the conclusion of each stage. Additionally, this information can be used to determine trend data and thereby predict negative behaviors before potential errors or adverse events can occur. These data can also provide a multitude of information to be used for other purposes across the company, industry, and systems engineering discipline. For example, they can be used to track and document trends in potential human errors during system design and actual human errors during system utilization, to provide feedback into the operator training program (for either continuing training or the qualification process), to generate reports for project and organizational management, to determine organizational goals, or to compare plant performance to that of other plants in a similar industry.

First, organizations should create a formal process to examine incidents and perceived vulnerabilities that occur throughout system development during the systems engineering process and, later, during plant operation. A methodical approach should be established to systematically examine the potential incident or vulnerability through a series of questions so as to determine regulatory impact and safety significance, determine which organization will perform the corrective action or causal analysis, and ultimately correct the deficiency. Figure 20 displays an example of a process chart exhibiting the progression from problem reporting to problem correction.

As displayed at the top of Figure 20, a determination of the significance level should be made. An example of the classification of severity criteria tailored for a nuclear facility is presented in Table 10 below where level 1 events are the most severe and level 3 are the least severe.

With the human error severity criteria determined, a tracking database established, and a formal process to collect and analyze the information, organizations now need to determine acceptable quantities of error within the established levels, so that this information can be fed into TPM quantitative measurement determination and assessment. The goal of this system

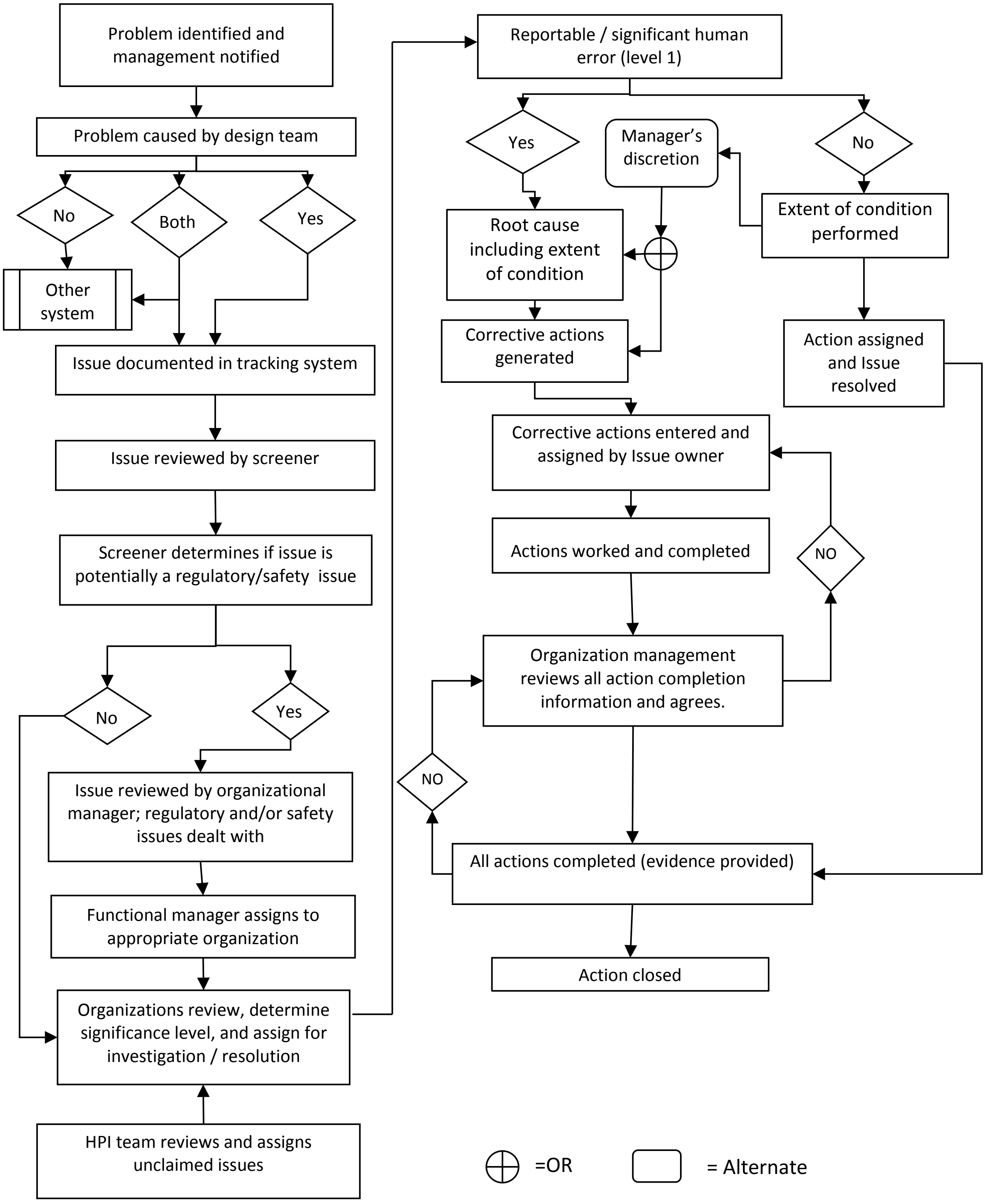

Figure 20. Human Performance Flowchart

Table 10. Severity Criteria Matrix

Incident Category	Level 1	Level 2	Level 3
Plant Transients	• Repeat occurrences of organizational or programmatic breakdowns that affect nuclear safety. (Level 1, 2, or 3) • Significant event requiring use of safety features • Multiple equipment malfunctions or human errors occurred that significantly increased the severity of the transient. • Significant operating/design violations of safety analysis	• Failures that could affect multiple safety systems or components • Misvalving operation or maintenance error on wrong equipment causing tripping or transient on operating equipment • NRC reportable event requiring a written response • Significant program weakness in design, analysis, operation, maintenance, testing, procedures, or training.	• Minor program weaknesses in design, analysis, operation, maintenance, testing, procedures, or training identified by independent or management assessors • An auxiliary plant transient • M&TE that fails calibration but does not cause operational impact to safety-related equipment • Safeguards/security issues that do not meet the regulatory criteria.
Incident Category	**Level 1**	**Level 2**	**Level 3**
Personnel Safety	• Death not due to natural causes • Major disability injury	• Injury or near miss with fatality potential • Work-related injury requiring inpatient hospitalization • Individual exceeds regulatory dose limits • Multiple or other substantial personnel contamination instances	• Personnel contamination events occurring from procedural violations or poor radiation worker practice. • Personnel contaminations due to human error and which result in dose assignment • Defeated or missing LOTO with no potential for exposure to hazardous energy
Incident Category	**Level 1**	**Level 2**	**Level 3**
Environmental Impact	• Releases resulting in significant threat to human health or environment • EPA violation or OSHA citation that results in enforcement action • Release in excess of radiological limits with actual or potential for off-site impact	• Immediately reportable spills with potential to harm environment • Release in excess of radiological limits with no potential for off-site impact • Repeated failures such as spills of chemicals or oil, improper storage, failed secondary containments.	• Permit criteria threatened by a discharge • Failure to maintain secondary containment for chemical/oil spills • Isolated nonreportable failures such as spills of chemicals or oil, improper storage, failed secondary containments, etc.
Incident Category	**Level 1**	**Level 2**	**Level 3**
Economic/ Operational Impact	• Missing business commitment	• Extensive equipment damage (e.g., required replacement or substantial repairs) • Conditions resulting in substantial outage delays or extensions • Lengthy unplanned outage or operation at substantially reduced production • Repeated failures to implement or maintain commitments to regulatory agencies	• Fire protection equipment unavailable when it was needed • Conditions detected by independent or management assessors that do not represent a substantial organizational or programmatic barrier breakdown • Adverse trends in equipment, programmatic, or human performance that do not directly challenge safety, regulatory compliance, or reliability

should be to keep potential errors at the lowest significance level. So how is this done? The answer is straightforward, but requires consistent attention. Due diligence, constant emphasis, and management support must be devoted to the identification and reporting of potential human errors and the corrective action processing of the problems as they are reported (per Figure 20). This processing will determine the significance level of the error and therefore the required amount of staff attention. Deployment of sufficient corrective actions will not only fix the immediate problem but will also prevent similar potential errors from occurring later in the systems engineering process. Depending on the significance level, a generic implications review could be conducted to determine the extent of the condition, the extent to which the actual condition or similar conditions exist in other plant processes, equipment, or human performance, and the extent to which the root cause and contributing causes of an identified problem could impact the same or similar plant processes, equipment, or human performance (both irrespective of severity level). Based on this review, the organization could put additional preventative actions in place to inhibit error-likely situations. This process, if effectively performed, will constantly reinforce good human performance practice, reduce human error in system design and potential human errors during operation, proportionally decrease the volume of potential problems at all levels, and continually drive errors to the least significant level. This concept is displayed visually in Figure 21.

In conjunction with a sound human performance improvement program, a management team should be established to ensure that the program is effectively and consistently implemented with a particular emphasis on evaluating significant issues, adverse trends identified, and ineffective corrective actions that were applied to conditions adverse to safety and security. This team could also incorporate all issues, not just human errors, into its engagement.

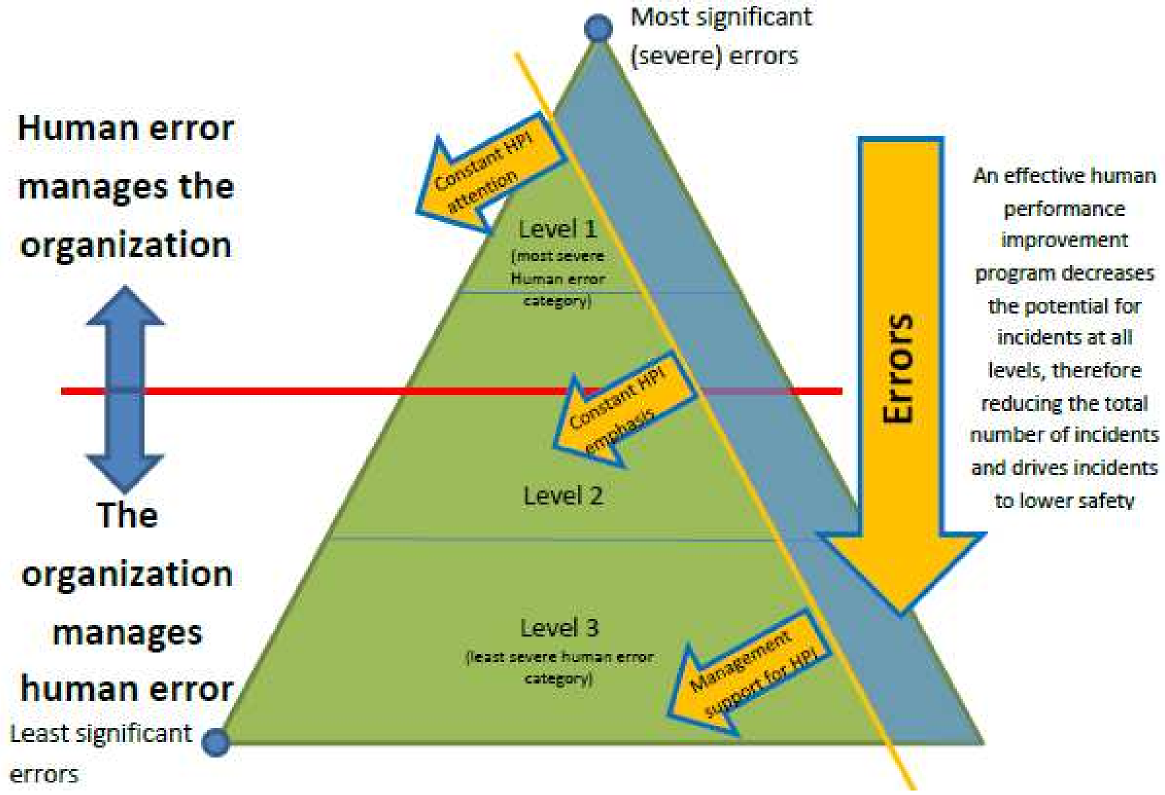

Figure 21. Human Performance Significance Level Triangle

Specifically, management oversight is required to ensure the following:

- Proper disposition of issues
- Application of the Proper significance level
- Proper trend identification
- Greater management intervention in certain issues
- Identification of issues that should be disseminated as lessons learned
- Proper application of corrective actions
- Periodic review of performance indicators
- Differentiation between corrective actions and process improvements
- Review of corrective action plans to ensure that they address previous ineffective corrective actions

- Review of root cause investigation results

The reporting of human errors should aim to produce a culture focused on safety and operational excellence. Employees should be not only encouraged but expected to make error incident reports. This should be a living part of the organizational DNA and “business as usual” for plant employees. Most importantly, employees must know that they will not experience retaliation for making reports. The generation of a positive nuclear safety culture and a safety-conscious work environment is a delicate and complex task, but once it has been established, it will improve morale, breed content employees, strengthen plant safety, and ultimately boost productivity.

7.4. DESIGN OF NEW SYSTEMS

While the focus of the previous section discusses human error reduction while improving or upgrading existing systems, technologically advanced systems and facilities of the future nuclear fleet need to keep a steady press to keep human error as low as possible. As the evolution of systems progress, the role of the humans within the system inevitably will continue to evolve as well. This evolution necessitates the continued drum beat of human performance improvement while keeping sights set on system efficiency and safety. Within this context, as new future systems are designed and the role of the human is transformed, human error should be architected for substantial reduction as compared to predecessor systems with an increase in system stability and safety. This necessitates a different focus appropriate for a new set of nuclear facility technology with new automation types and the roles of humans modified accordingly to accommodate. This focus should compel the optimization of human-machine roles to reduce human error and increase inherent stability of the system.

As new systems are designed, systems engineers must view the system with an open mind and must give consideration to various technology options, affordability, accept the fact that human interaction is inevitable, account for human limitations, and, ultimately, establish appropriate requirements for the system and for the human. The incorporation of these elements will appropriately balance the next-generation system and lead to an optimized human-machine system.

7.4.1. HUMAN-MACHINE SYSTEM OPTIMIZATION

Human-machine interaction is the boundary where interactions between humans and machines transpire. The objective of this interaction is to facilitate safe and effective operation and efficient control of the machine from the human end as the machine simultaneously feeds back information that aids the operators' decision-making processes. Generally, the intent of human-machine interface design is to produce a user interface that makes it straightforward, efficient, and manageable to operate a machine so as to attain a desired outcome. This generally means that the operator needs to provide a specific input to achieve a desired output, and also that the machine minimizes undesired outputs to the human. To achieve safe and reliable operation, this interface requires a practical balance between the human and the machine. The purpose of this section is to propose a methodology that optimizes the balance between the human and machine sides of the human-machine interface of a system at a nuclear facility.

7.4.1.1. BACKGROUND

The very detailed interaction between machines and humans in nuclear facilities is a changing technical matrix that is addressed by means of a human-machine interface. Studies of the interactions between machines and humans have been conducted for more than half a century. Effective models of human-machine interaction and matrices for numerous products can be found in the nuclear industry (Johannsen, 2009).

The interactions between humans and machines at nuclear facilities have been recognized as significant due to their safety implications; as a result, these interactions are handled with a high level of care. The entire system of the human-mechanical interface, the machine and the human user are described as the human mechanical system (HMS) and may include distinct user categories, such as managers, maintenance personnel, and operators, all of whom have distinct needs regarding information and control (Johannsen, 2009).

The term *mechanical* in HMS refers to any category of changing technical system, which can include the software and automation components as well as the mechanical components. The technical system's automation components are described as the administrative and control systems. These systems interact in a direct manner with the technical machine interface. The power generation process at a nuclear power facility is an appropriate example (Johannsen, 2009).

In a nuclear facility, the decision support systems are state-of-the-art, and the component machines are programmed with substantial knowledge and can provide advice to the user. The application domains of the human mechanical system include human users, the human-machine interface, and the mechanical components (Johannsen, 2009).

The context of automation in the administration of changing technical matrices has been significantly enhanced over the last several years. This statement is true for all the technical systems associated with nuclear facilities and products. Elevated levels of efficiency have been attained by means of the enhanced application of automatic administration. The requirement for communication between machines and humans increased with the augmented context of automation. Usually, enhanced automation does not replace the human's interaction with the machinery; rather, it transforms the location of the interface between the two (Rogers, 2011).

7.4.1.2. THE HUMAN-MACHINE INTERFACE

The bread and butter of nuclear facility operation is safety and efficiency. In the fulfillment of these essential elements, there is a recurrent concern for efficient human interaction with the machines being operated. Enhancement of this human-machine link is a necessary enterprise within the process management not only for the organizational overview, but also for the schematic placement of roles and specific defining variables for maintaining the interaction. The effort to reach a level of optimization where this human-machine synergy takes into account the human-machine interaction as part of routine operations during production, maintenance evolutions, and off-normal operations requiring emergency mitigation, such as the impact of natural phenomena or unexpected failures within the system. To operate effectively, each human-machine link must be well defined and specifically engineered utilizing the requirements established to fulfill the system purpose, which necessitates appropriate design decisions that meet this purpose and design that accounts for specific roles and processes remaining integrated and strong. This implies not only considering all the decisions, manipulations, and potential errors that can be made in the system under design, but also lessons learned from other similar systems.

To achieve safety and efficiency in operations, the human-machine interaction should be a focal point during system design. This interaction has many facets and factors to consider. An integrated approach to seeking further process dynamics remains defined by interaction and does not leave processes on their own to facilitate operations independently. Within the human-machine link, the machine is designed and installed to fulfill a specific purpose and, in doing so, must provide a mechanism to exhibit required system parameters so that the human can intervene to ensure that the machine is operating at the necessary capacity for efficient functionality and take necessary actions if an unsafe condition arises. Furthermore, conditional models for both emergency and nominal routines aimed at meeting safety and operating standards see a network of knowledge centered upon creating processes that diminish uncertainty and strive to define every contingency. Systems should be designed with machine monitoring in mind that allows the human activity to be fixed and defined by routine that eliminates much uncertainty in operation.

7.4.1.3. HUMAN ERROR AND THE HUMAN-MACHINE INTERFACE

This dissertation has repeatedly emphasized the considerable potential for human error, and this is especially true within the context of the human-machine interface. Specifically, there is a greater potential for errors in the case of information interpretation that requires both humans and machines to collaborate. The error emerges when erroneous information defines the process. Without the correct, most relevant system information, errors can arise both from the action of internal machine control mechanisms or human analysis and from the resulting actions based on wrong information. It is important to design the system for a stronger human-machine interaction with less censoring of human behavior and more mining of information for evaluation of processes; this allows the human to incorporate change in ways that the machine cannot. One must be wary, however, of too much ingenuity and flexible decisions as a means of deviating from the original purpose of operation. To redefine safety for the wrong needs also suggests that the wrong values are applied, which can result in human error; the resulting consequences, in the context of nuclear facility operation, can be detrimental.

Some errors happen because humans interact at a cognitive, rational level but also have emotion and conflict to consider when making choices. In some contexts, errors take place out of complacency or boredom regarding one's role in the system. For evaluation and redesign to take place, not only is it important for each member of the team to be cross-trained in some defined functions, information needs to be shared and new knowledge circulated to inspire new ideas for solving core capabilities of safety and efficiency. Roles are aligned with integration because knowledge is open, and this leads to systems that have flexibility and tolerance of the human factor of emotion. Design of the system should not be dependent upon freedom or correct roles but on how the process is defined to carry out the purpose. Roles fit into the process and so do human personalities for specific roles.

7.4.1.4. DECISIONS AND THE HUMAN-MACHINE INTERFACE

Decisions can be challenging for the human even if machines monitoring for system reliability show little change in data or information about the system. Decisions can be made for the wrong reasons based on limited information. The data may not match the task, or the outcomes may have limited validity. Data should reflect what the operator understands about the activity, behaviors, and resources that define the process. Unfortunately, at times incorrect observations, missing information, or misinterpretations of information can result in poor decisions. Additionally, operators may evaluate the data from the interface differently from each other, creating a lack of collaboration in optimizing the links in the system. The machine may offer valid knowledge, but its translation into human knowledge is uncertain, potentially reducing the information's value for making decisions. So even if there may be adequate monitoring systems, backup data systems, cameras, institutionalized protocols for data management, and suitable storage and handling, the information can be interpreted incorrectly, leading to poor decision making and reflecting weakness in design.

Taking into account the human element will permit use of decision-making systems to consider operational scenarios. Deterministic functions are not flexible and allow for the same variable to be inputted only to return the same outcomes. Non-deterministic functions allow for some flexibility in the sense that they can return different outcomes even with the same input. This allows for further dimensionality in modeling the various operational scenarios within the process to aid in redefining the human-machine interface, based on additional data that support the desired, optimal process outcome. Within the framework of safety, serious consideration must be given to situations where decisions are made quickly, under pressure, and with uncertainty. These operational scenarios exist for all industries, but from the perspective of nuclear operation, where the consequences of errors can be extremely severe, these scenarios should be identified in detail and the human-machine links to be analyzed should be defined.

Understanding how system capabilities can define risks to the system related to safety and performance involves a recognition that operators can and must learn from mistakes made and that designers must perceive opportunities from errors. Continued reassessment and an approach to redesigning human-machine links can create system resilience. Errors can be less costly in this context of specific redesign architecture. Learning from past errors can enhance anticipation and expectations with regard to future events in terms of technology control strategy, unleashing its full power usefully to address factors that create conflict or uncertainty. This is an avenue for innovation because it drives the forces of uncertainty away and allows for technology application for human benefit.

7.4.2. CONSIDERATIONS IN OPTIMIZATION

7.4.2.1. HUMAN INTERACTION IS INEVITABLE

Although it might seem that the best way to engineer fault-tolerant systems is to eliminate any potential for human error, this assumption could lead to the conclusion that anything that can be automated should be automated. An intrinsic flaw in that argument is that no matter how complex the system, humans still need to interact with it. As discussed previously, when human interaction with a system is reduced, degradation of human skills can result. As a clear example, consider the decline in children's handwriting skills. In the past, all elementary students learned cursive writing. Today, the emphasis has shifted toward computers, keyboarding skills have become more valued, and children are spending less time on handwriting, with a corresponding decrease in skill level. From a systems perspective, we can look at the Air Force as a model. When pilots started flying jets with increasing degrees of automation, researchers found that their overall flying proficiency was increasing but that they were losing their manual flight abilities (Orellana and Madni, 2012). As a result, pilot advisory boards started suggesting that pilots should fly more manual hours in order not to lose those skills.

The main focus of this dissertation has been on human error as a result of technological advancement associated with the upgrade of existing systems in existing nuclear facilities. Technological upgrades are unavoidable, so consistent efforts must be devoted toward keeping human error as low as possible amidst those changes. As the evolution of systems progresses, the role of humans within the system will inevitably continue to evolve as well. This evolution necessitates a continued emphasis on human performance improvement as part of maximizing system efficiency and safety. Within this context, as new systems are designed and the role of the human is transformed, human error should be targeted for substantial reduction relative to predecessor systems, with a corresponding increase in system stability and safety. For this purpose, the roles of humans and machines must be optimized in the design and implementation of new types of automation, but it must be understood that human interaction with systems is compulsory and of major importance.

7.4.2.2. THE ROLE OF COMPLEX SYSTEMS AND HUMAN ACTORS

From a systems engineering perspective, it is important to understand the precise role of complex systems in the interactions between human actors. In the past, computing and cybernetics systems were focused on extending the physical attributes of humans and doing things that humans could not safely do, such as interacting directly with highly radioactive materials. However, as computing power has increased as a natural result of Moore's Law, now systems are advancing into the realm of enhancing cognitive and mental capacities (Orellana and Madni, 2012). Reducing human error through system architecture is a very important goal, as was revealed by tragic failures in the use of Patriot missiles in 2003 during the Iraq war. The Patriot radar systems were engineered in such a way as to record false hits and false alarms without displaying any uncertainty regarding the target (Madni, 2009). The human tendency when working with automated systems is to trust the accuracy of the information provided. Unfortunately, because the systems were poorly engineered, the humans interacting with such systems took the blame for shooting down a British Tornado and a U.S. Navy F18/A, which were incorrectly identified as targets by the automated systems (Madni, 2009).

As this example illustrates, one crucial part of engineering human error out of systems designs is to make certain that the systems do not introduce their own errors. If humans interacting with engineered solutions are to be expected to operate consistently, the systems must provide sufficient information to the humans involved so that they can use their unique characteristics in analyzing the situation and making the proper decisions. A crucial responsibility of the system engineer in designing a human-machine interface system, therefore, is to properly articulate who makes the final call in crucial decisions. In some situations, the automated systems should never be overridden by the human operator—for instance, if doing so would expose the humans involved to unacceptable amounts of radiation exposure or automatic shutdowns due to low or high system pressure. Conversely, in other situations, such as normal or controlled operations, an automated system should not be able to override the human's judgment. A good human-machine interface achieves an appropriate balance between the skills of the operators involved in the particular situation and the inherent strengths of the systems involved.

Some areas where human errors can occur in integration with automation systems reflect a lack of knowledge in the area of human cognition and cognitive processes. Humans have amazing but still limited cognitive abilities, and systems designers must take those limitations into consideration. For example, it is known that excessive use of multi-windowed systems for monitoring can result in degraded human performance, because these systems overtax the operator's attentional capacity (Madni, 2009). Important alerts could be missed due to exceeding the human's cognitive processing abilities. Whereas an initial alarm can seize an operator's attention, repeated alarms (or so-called nuisance alarms) inevitably cause the operator to become habituated to them (like the classic fable about crying wolf too often). Thus, when a truly important alarm is sounded, the operator may tune it out and not attend to it. Excessive flexibility also presents a problem for human operators. A classic example is the smartphone: most users take advantage of only a small fraction of its functions, because most of them are too complex or take too much time to figure out. Therefore, for systems engineers to eliminate human error factors, they must fully understand the cognitive limitations of the users of such systems and compensate for them by designing systems that augment human capabilities of flexible thinking, while at the same time not presenting such an overwhelming variety of options that crucial indicators or tools are ignored because they overwhelm the humans whom they are designed to assist.

7.4.2.3. ACCOUNT FOR HUMAN LIMITATIONS

As technology advances, it becomes increasingly apparent that from a systems engineering perspective, systems have a (nearly) unlimited capacity whereas humans do not. Therefore, to create systems that reduce human error as much as possible, a respect for the limitations of the human brain and its processing capacity is necessary. As was mentioned earlier, the human brain has a limited processing capacity, because its processing activity occurs in the area referred to commonly as short-term memory (Richardson et al., 1996). The short-term memory circuit consists of sensory memory, which can contain a few seconds of data at most, and the short-term memory store. The complexity of designing with respect for this system lies in the fact that the attention capacities of short-term memory are divided between data just taken in, data retrieved from long-term memory for processing, coding procedures, and search strategies (Richardson et al., 1996). Therefore, when designing complex systems with many things that must be attended to, systems engineers must find a way to narrow the information presented to the most essential elements, so that the crucial information that must have the human operator's attention is front and center at all times.

An analogous system in which visual displays play an essential safety role is visual control systems for automobiles. Indeed, the so-called instrument cluster is a crucial part of the safe operation of a motor vehicle because it relays safety-related signals to the driver (Bellotti et al., 2004). As automobile safety systems become increasingly advanced, with more components designed to assist the driver in safe automobile operation (including collision detection, parking assistance, night vision assistance, adaptive cruise control, and more), the space available for displaying this information becomes a key limitation that must be overcome (Bellotti et al., 2004). To deal with the space limitations of automobiles, designers have turned to the novel solution of creating configurable dashboards. One of the salient points arising from this research is that all this additional information must be provided to the driver of the automobile without simultaneously distracting him or her from the primary goal, which is to safely operate the automobile. This is why human-machine interfaces in cars must be designed in a way such as to prevent human error (Bellotti et al., 2004). Research on automobile interfaces has found that customizable dashboard interfaces increased passive safety, as the ability to tailor the interfaces was correlated with significant improvements in users' attention and reaction capabilities (Lim, Benbasat, and Todd, 1996). One reason posited for this improvement in attention is that customized interfaces are closer to the real-world systems that they are supposed to support. Because the end user is directly involved in the customization, Lim et al. (1996) posited a reduction of the psychological distance between the user and the system, making it easier for the user to execute the needed tasks.

This insight can be directly applied to the arrangement and composition of nuclear facility control interfaces. Vital operational information should be maintained at the forefront (reactor power, core temperature and pressure, etc.), but other information can be managed and displayed at the operator's discretion or according to plant procedures. This arrangement combines the availability of vital information with operator knowledge, based on training and experience, as to what displays are necessary at different times without overwhelming the operator’s cognitive capacity.

7.4.2.4. APPLICATION OF THE DASHBOARD CONCEPT IN NUCLEAR OPERATIONS

Considerable data suggest that the use of a dashboard concept holds promise in the area of human-machine interface design. One of the most valuable aspects of dashboards is that they can improve decision making (or prevent errors) by amplifying cognition as well as making the most of humans’ limited perceptual capacity (Yigitbasioglu and Velcu, 2012). As Lim et al. (1996) suggested, flexibility in selection of dashboard formats aids in user response as well as in accurate use of the information. Additionally, dashboards can be an effective answer to the problem of memory overload, a key limiting factor that can contribute to human error in using human-machine interfaces.

Several elements of dashboard design must be taken into account when one is designing dashboard human-machine interface. The first factor is visualization. The information visualized within a dashboard design must actually amplify cognition. The visualization of data can be considered correct if the end users consistently decode the information presented properly. Again, respecting the limited cognitive capacity of short-term or processing memory, an effective dashboard design will strike an appropriate balance between visual complexity and the information utility required for the particular situation.

Other functions can be built into dashboards to reduce errors. For example, automated alerts (in limited fashion, because of the aforementioned problem of habituation) can be included in the dashboard design, along with theory-guided format selections that can help to lead an operator to the correct selections for a given scenario. Limiting the dashboard to a single page and a simple color scheme, along with links and grid lines for 2D/3D data graphs, is another research-supported way to improve the visual clarity of dashboard designs (Yigitbasioglu and Velcu, 2012).

Another important aspect of human-machine interface design is the affordance of information in a way that is consistent with the desired results. Affordance, in the context of human-machine interface design, refers to the features provided to the user (Hartson, 2003). One way in which affordance can reduce human error is in the proper presentation of choices or options. For example, shading a button or menu item in gray and making that choice inaccessible because it is a contextually inappropriate choice can guide the user toward making correct choices in the situation. There is, however, an accompanying danger that affordances can also misinform or misdirect a user into an incorrect choice or option. For example, a horizontal line on a scrolling page could lead the user into thinking that the page has ended when actually there is more content "below the fold." Improper or misunderstood instructions can introduce or increase the opportunity for human error in human-machine interface use.

7.5. CONFIDENCE IN PROPOSED APPROACHES

To assess experts' confidence in the proposed methods described in this chapter, a Likert-style survey was designed and administered to a group of systems engineers to gain their impressions of the methods proposed, whether the methods would be successful in reducing human error, whether the experts would be likely to use these methods, and issues affecting the implementation of these methods within the systems engineering process in the industry setting. The survey sample consisted of 40 system design engineers (age 25 to 65) of various backgrounds, locations, and disciplines (nuclear engineers, electrical engineers, mechanical engineers, etc.) who were knowledgeable regarding the systems engineering and design process.

The statements contained in the survey were extracted directly from the sections of this chapter. The respondents were provided with the chapter content and the questions and statements along with the five-point Likert scale. Depending on the question, the potential responses were labeled in one of two ways: (1) “never,” “occasionally,” “regularly,” “frequently,” and “always,” or (2) “strongly disagree,” “disagree,” “neither agree or disagree,” “agree,” and “strongly agree.”

The examination of the Likert-style quantitative rating questions indicated the following totals shown in Figure 22.

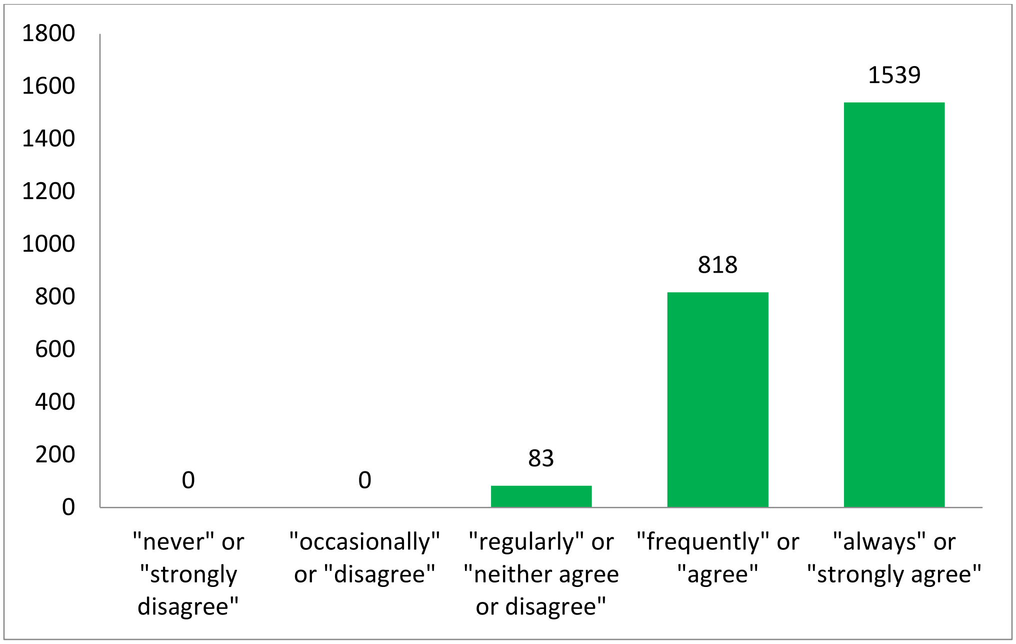

Figure 22. Human Performance Significance Level Triangle

As shown above, the totals are weighted to “always” or “strongly agree” with no responses indicating “never”, “strongly disagree”, “occasionally”, or “disagree”, therefore, the responses are largely favorable for the methods proposed in this chapter.

Additional analysis is shown in Table 11 below.

Table 11. Results of Survey Analysis

Analysis	Results
Percent Agree	96.6%
Top Box	63.1%
Net Top Box	63.1%
Z-Score to %	86%
Coefficient of Variation	12%

The percentage agreeing represents those who indicated “strongly agree” or “agree” (or “frequently” or “always,” depending on how the question was worded) on the 5-point Likert scale in response to each item. The top box represents only those responses of “strongly agree” or “always.” The net top box is found by counting the number of respondents who selected the top choice and subtracting the number who selected the bottom choice. The *z*-score to percentile rank converts the raw score into a normal score due to the fact that the rating scale means often follow a normal or close to normal distribution. The coefficient of variation is a measure of variability, unlike the first four which are measures of the central tendency (Sauro, 2011).

The quantitative results show that the respondents were strongly favorable regarding the value, usability, and likely industry acceptance of the concepts presented in this chapter.

In addition, the respondents were given the opportunity to offer open-ended comments on each section of the survey. All remarks expressed an appreciation of the concepts, an acknowledgment of the benefits of implementing such concepts, and expectations that future implementation would receive a positive industry reception. See Appendix C for a comprehensive explanation of the survey and additional details associated with the results and analysis.

7.6. CHAPTER CONCLUSION

This chapter has examined the impact of technology on present-day plant operators and discussed a way forward for industry to involve operations personnel involvement in the systems engineering process and maximize performance excellence. It entails the integration of human performance considerations into system operational requirements and system testing, evaluation, and validation; proper generation of procedures, processes, and programs; the implementation of a sound, knowledge-based operator training program; the creation of a robust plant casualty control drill program; the development of human error significance criteria; the establishment of a tracking database; the creation of a formal process to sort the information; and a method to keep errors minimized and at low safety significance. The final chapter will discuss the conclusions drawn from this dissertation and recommendations for further research.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1. CHAPTER INTRODUCTION

The systems associated with nuclear facilities are some of the most complex ever developed. As a result, it is important to consider whether the complexity and changing technologies used at nuclear facilities may exacerbate the cost of incidents caused by human error. This dissertation has investigated the relationship between human performance, technological advances, and the complex systems involved with nuclear facilities.

The primary research question driving this study was whether technological advances in the complex systems of nuclear facilities increase the severity, in terms of cost, of incidents caused by human error. This is an important question because most nuclear facilities continually update their technology for varying reasons. This continuous technological improvement can frequently require operators to change their routines and their method of interacting with the complex system and the new technology.

To answer this question, hypotheses were established and a study was conducted to determine whether technological advances affect the interaction between operators and the systems that they operate, resulting in an increased cost of incidents related to human error. The hypothesis was stated as follows:

H_1: Technological advances at a nuclear facility that affect how operators interact within the system **do** increase the cost of incidents caused by human error.

The null hypothesis was stated as follows:

H_0: Technological advances at a nuclear facility that affect how operators interact within the system **do not** increase the cost of incidents caused by human error.

8.2. CONCLUSIONS

The *t*-test was used to determine whether there was a statistical difference in the costs of nuclear incidents related to operator error when interacting with a system where recent technological advances have been installed, relative to other incidents. The *t*-test indicated a statistically significant difference between the two groups; therefore, the null hypothesis was rejected. The evidence indicated that, indeed, technological advances at a nuclear facility that affect how operators interact within the system do increase the cost of incidents caused by human error.

As a follow-up study, the question of whether organizations benefit overall by incorporating advanced technology at their facilities was analyzed. The data from this analysis indicated that spending more money on upgrades will increase a facility's capacity factor (i.e., the ratio between observed output and potential output if the facility were consistently running at its full capacity) as well as the number of incidents reported. However, the incidents in the randomly selected facilities for this study were relatively minor. Given that the nuclear facilities produce vast amounts of power and the upgrades significantly increase the capacity factor, there appears to be a financial advantage in conducting upgrades, but this benefit should be weighed against the increased rate of level 1 and 2 incidents observed.

Based on the information and analysis discussed above, there is evidence that technological advances at a nuclear facility are worth the risk, even though they may increase the cost of resulting incidents due to human error. Due to these findings, additional study was conducted on the impact of human factors (including human error) on plant operation and the phases of the systems engineering process. This was followed by a discussion of the impact of evolving technology on today’s facility operators and ways to overcome these challenges by utilizing the systems engineering process.

8.3. CONTRIBUTIONS OF THIS DISSERTATION

The primary contributions of this research are as follows:

- Discovered quantitative evidence that technological advances at a nuclear facility that affect how operators interact within the system can increase the cost of incidents caused by human error.
- Discovered quantitative evidence that spending more money on the incorporation of advanced technology into existing nuclear facilities can increase the capacity of the facility as well as the potential number of incidents.
- Performed an extensive examination of the impact of human performance on plant operation and the systems engineering process.
- Established a model to cultivate human performance–enhanced system design and operation via:
    - operator involvement in all stages of the systems engineering process,
    - iterative procedures and operator training development throughout all stages of the systems engineering process, and
    - early selection and cultivation of suitable operators chosen and groomed specifically for the systems being designed.
- Explored a methodology to optimize the balance between the human and machine sides of the human-machine interface in a system.

- Developed a novel method of incorporating human performance characteristics into the system design and development stages of the systems engineering process. Specifically, the study proposes the incorporation of human performance attributes into system operational requirements, TPMs, and system testing, evaluation, and validation.

8.4. RECOMMENDATIONS

This study resulted in a rejection of the null hypothesis. Therefore, there is evidence that changing the technology with which operators interact increases the cost of incidents resulting from human error. As a result of this conclusion, three recommendations are offered.

8.4.1. RECOMMENDATION 1: ADDITIONAL RESEARCH ON THIS TOPIC

Additional research on this topic is recommended. Specifically, a study could be conducted on the rate of small-scale incidents (i.e., those at level 1 or 2 of the INES). Many of these incidents are not as intricately studied as those that reach a higher level of severity. Instead of an in-depth analysis of each incident, a simple count could be made of the minor incidents that follow changes in technology. A similar procedure to the one used in this study could be used for data analysis. Instead of using the cost of the incident as the quantitative measure, the number of minor incidents could be used. This approach would eliminate the need to search for cost information on each incident or the details of the incident report other than the INES rating. (See Appendix D for a minor event study as described here.)

8.4.2. RECOMMENDATION 2: INTEGRATION OF OPERATOR PERSPECTIVES IN EARLY STAGES OF SYSTEM DESIGN

As broached in Chapter 7, the operator has a unique perspective relevant to the successful operation of the system or component, therefore, their input can result in appreciably less complication after a system or component is installed and operational. It is recommended that systems engineering process programmatic enhancements be considered to tap this resource more effectively and efficiently. Additionally, it is recommended that research be done to quantifiably determine the impact from harnessing operator perspectives in the early stages of the systems engineering process.

8.4.3. RECOMMENDATION 3: IMPROVE TRAINING, PROCEDURES, AND HUMAN PERFORMANCE AT FACILITIES IN CONJUNCTION WITH THE DEVELOPMENT AND INSTALLATION OF NEW TECHNOLOGY

Lastly, as examined in Chapter 7, it is recommended that the systematic and continuous improvement of training, procedures, and human performance be further researched, refined and evaluated to quantitatively demonstrate a decrease in human error and increase in plant safety.

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APPENDIX A: SPECIFIC INCIDENTS

Each of the nuclear incidents that occurred in the United States from 1955 until 2012 is briefly discussed below, with an attempt to determine whether new technology had been introduced shortly before the incident. The NRC was founded in 1974, and the IAEA scales came into existence in 1990. Most of the information on the older incidents comes from books on the topic. From this information, an estimate was made as to whether the incident warranted rating of 3 of greater on the IAEA scale. All monetary values listed in the table in chapter 4 were adjusted to 2005 dollar values.

November 29, 1955: Idaho Falls, Idaho

The experimental breeder reactor at Idaho Falls, Idaho is now decommissioned (Perrow 2011) and is now a national historic landmark. A wide range of experiments was conducted at this facility by the U.S. government as well as state governments and national laboratories. Several universities also conducted research at the facility. The area has been home to more than 50 reactors (Rogers, 2013).

In November 1955, a reactor entered into a partial meltdown during a test of the coolant flow (Sovacool, 2011). The use of a nuclear reactor to produce electricity was still relatively novel at this time. The construction of the breeder reactor had begun in 1949, and it was installed and began to produce power in 1951. Therefore, assuming normal staff turnover, the individuals working with the reactor had up to four years of experience with the equipment prior to the meltdown. For this reason, the incident is not categorized as not occurring due to human error related to novel technological advances (Krivit, 2011).

July 26, 1959: Simi Valley, California

The reactor in Simi Valley, California experienced a partial core meltdown in 1959 (Sovacool, 2011). The entire facility was an experiment in using a sodium reactor to produce electricity through nuclear power. The reactor was in use from 1957 until 1964 and is considered the first nuclear reactor to provide electricity within the United States (Rogers, 2013).

The 1959 meltdown involved 13 of 43 fuel elements melting, with the release of radioactive gas (Sovacool, 2011). The experimental facility's purpose was to construct a facility that would produce electricity from nuclear energy, allowing workers to gain experience with running this type of power plant. Therefore, throughout the facility's operation, new instruments and technologies were being introduced. One reason for the partial meltdown is that the individuals working at the facility were using new equipment and gauges with which they were not familiar (Perrow, 2011). Therefore, this incident is judged as attributable to human error when working with new technology.

January 3, 1961: Idaho Falls, Idaho

The experimental reactor at Idaho Falls was the site of fatalities due to an incident associated with the reactor core (Harrison and Hester, 2011). The primary nuclear control rod had been removed from the reactor. As a result, the reactor became supercritical and had a power excursion. Three people in the reactor room died due to exposure to radiation. In fact, 500 R per hour were still being emitted from the bodies when the rescue workers arrived. A rod ejection caused one body to be lodged in the ceiling of the reactor room, held there by the control rod that was launched during the reactor super-criticality. The individuals in the control room were so irradiated that they had to be buried in coffins made of lead (Perrow, 2011).

The investigation of this incident revealed that new equipment had been installed in the control room (Sovacool, 2011), including the gauges that indicated whether the control rods were in their proper location and orientation (Rogers, 2013). Therefore, this incident is deemed to have been due to human error when working with new technology.

July 24, 1964: Charlestown, Rhode Island

The facility in Charlestown, Rhode Island reprocessed highly enriched uranium in the form of scrap materials produced from fuel elements (Rogers, 2013). A worker was stirring up a tank that contained uranium within a sodium carbonate solution. This person was supposed to add trichloroethane to enable the removal of organic compounds. Instead, the worker added a uranium solution. This resulted in a criticality excursion as well as a bright flash of light. Roughly 20 percent of the contents of the tank, or 10 liters, splashed out of the container. The worker was exposed to an excessive amount of radiation and died two days later (Perrow, 2011).

The worker who made the error had done this procedure on several occasions (Sovacool, 2011). The labeling of the bottles had not been changed, and the individual was familiar with all the technology involved (Harrison and Hester, 2011). Therefore, this incident is not judged to have been due to human error when working with new technologies.

October 5, 1966: Monroe, Michigan

The Enrico Fermi nuclear power plant in Monroe, Michigan is operated by DTE Energy (Sovacool, 2011). Its first unit was constructed in 1963; a second unit was built in 1988 (Rogers, 2013).

The reactor unit, which was of the fast breeder type, suffered a partial fuel meltdown in October 1966 (Sovacool, 2011). The primary cause of the increase in temperature was determined to be blockage of a spigot needed for the liquid sodium coolant to enter the reactor. The blockage prevented sufficient coolant from entering the reactor, causing its temperature of rise slowly over several hours (Perrow, 2011).

The incident at the Fermi reactor could have been avoided if the operators had noticed that the reactor temperatures were rising (Harrison and Hester, 2011). However, they did not become aware of the problem until alarms sounded regarding the elevated core temperature. By this time, a partial fuel meltdown had already occurred. A number of the subassemblies for the rods reached temperatures over 700°F, causing the fuel to melt. It was later discovered that new gauges for reading the core temperature had been recently installed, and unfamiliarity with the instruments is likely to have led to the temperature change being overlooked (Rogers, 2013). Therefore, this incident is deemed to have been due to human error when working with new equipment.

July 16, 1971: Cordova, Illinois

An electrician died after coming into contact with a live cable at the reactor in Cordova, Illinois (Perrow, 2011). The electrician would not have been unfamiliar with the wiring or equipment. In fact, the electrician was doing routine maintenance of equipment on which he had worked previously (Sovacool, 2011). Therefore, this incident is not judged as due to human error associated with new technology.

March 22, 1975: Athens, Alabama

Both nuclear reactor units at the Brown’s Ferry facility in Alabama experienced a nuclear emergency in 1975 (Harrison and Hester, 2011). The problem began when two electricians were repairing ceiling air leaks within the room for cable spreading. Electrical cables controlling the reactors are routed to different tunnels of the two reactor buildings in this area. The electricians were using a spongy type of foam rubber to seal any leaks. They were using candles to determine whether the leaks had been plugged; if there was a remaining leak, the candle flame would flicker. One of the electricians placed a candle too close to the foam rubber and it ignited (Sovacool, 2011).

The resulting fire caused a number of the facility's safety systems to be disabled (Sovacool, 2011), including the emergency cooling system for unit one. This incident resulted from the misuse of candles, an outdated technology (Perrow, 2011). Therefore, it is not judged to be due to human error when working with new technology.

November 5, 1975: Brownville, Nebraska

The Cooper Nuclear Station is located near Brownville, Nebraska (Rogers, 2013). This facility is a boiling water reactor and the largest generator of electricity within Nebraska. It is owned and operated by the Nebraska Public Power District, a division of the state government, with support from Entergy Nuclear (Sovacool, 2011).

The Cooper Nuclear Station became operational in July 1974 (Perrow, 2011). The station is still in operation and provides roughly 800 MW of electrical power. The facility is outfitted with a Mark One containment system. In 1998, it became the first site within the United States to use nuclear fuel consisting of uranium taken from decommissioned nuclear weapons from the Soviet Union. The uranium from these nuclear weapons was down-blended to a uranium enrichment level for use as fuel (Sovacool, 2011).

In November 1975, a hydrogen gas explosion damaged an auxiliary building and the reactor (Harrison and Hester, 2011). The evidence for the cause of the hydrogen gas explosion is inconclusive. However, there is no indication that human error was involved (Perrow, 2011).

June 10, 1977: Waterford, Connecticut

The Millstone Nuclear Power Station in Waterford, Connecticut is the state's only nuclear power plant (Krivit, 2011). The first unit, which this incident refers, is no longer in operation, having ceased operations in 1998. The second and third units are still in operation, licensed until 2035 and 2045, respectively, with a combined power output of 2020 MW. This makes the facility the largest generator of electricity in New England (Perrow, 2011). The plant has a relatively good safety record; in 2004, it earned the top award from the U.S. Occupational Safety and Health Administration (OSHA) for a high level of workplace safety (Sehgal, 2012).

The 1977 incident involved an explosion of hydrogen gas (Rogers, 2013) that damaged three buildings on the premises and led to the shutdown of the Unit 1 reactor (Smith, 2012). Investigation into this incident led to the conclusion that it was not due to human error.

February 4, 1979: Surry, Virginia

An incident occurred in February 1979 at the nuclear power station in Surry County, Virginia (Perrow, 1999). This facility consists of two pressurized water reactors that became operational during 1972 and 1973. Each reactor can produce 800 MW of electricity. The condenser cycle uses the James River as a heat sink. This eliminates the necessity of cooling towers. Both reactors remain in operation (Krivit, 2011).

The 1979 incident involved a shutdown of the second reactor (Rogers, 2013), which was necessary because two tube bundles failed within the steam generator coupled to this reactor. The cause was determined to be due to faulty manufacturing of the materials involved (Smith, 2012). Therefore, the incident was not due to human error at the nuclear facility**.**

March 28, 1979: Middletown, Pennsylvania

In March 1979, the most expensive nuclear accident in U.S. history occurred at the Three Mile Island nuclear plant near Middletown, Pennsylvania (Krivit, 2011). The incident is also distinguished because it attained a rating of 5 on the INES (Perrow, 1999).

The problem began with a pilot-operated relief valve that became stuck open within the primary system, allowing a significant amount of coolant from the reactor to escape. The initial problem was a mechanical failure, but it was exacerbated by the plant operators' failure to recognize that the coolant was leaking. Control room indicators had recently been added to a new user interface for which the operators did not have adequate training. In fact, one of the operators was unaware of the placement of an indicator light and overrode the automatically operated emergency cooling system. The operator believed that an excess of coolant water within the reactor was causing the release of steam pressure (Perrow, 1999).

The incident at Three Mile Island led to an increase in U.S. government regulation of the nuclear industry (Krivit, 2011). The partial meltdown that resulted from the incident released radioactive iodine and gases of unknown quantities into the environment. Several epidemiologic studies have been conducted regarding the rates of cancer and other illnesses related to radiation in the area near the facility; no statistically significant increase in problems has been noted. The cleanup of the area began in 1979 and lasted for 14 years (Rogers, 2013).

The Three Mile Island disaster is especially important for this study as it had such a high cost and multiple in-depth investigations of the accident took place (Harrison and Hester, 2011), along with studies from the perspectives of human factors and user interface engineering. Essentially, the relief valve was stuck in the open position (Smith, 2012). The facility operators believed that a light on their control panels was indicating a closed valve. This was a misreading, as the light was indicating only the solenoid status and had nothing to do with the valve position. This relatively new control panel configuration had not been explained properly to the operators. Therefore, several hours passed before the operators could properly identify the problem (Marques, 2011). Accordingly, this incident is judged to be due to human error when working with new technology.

November 22, 1980: San Clemente, California

The San Onofre Nuclear Generating Station in San Diego County, California (Rogers, 2013) became operational in January 1968. It has been permanently shut down and will be decommissioned (Smith, 2012).

The incident that occurred at this facility in 1980 resulted in a worker’s death by electrocution (Krivit, 2011). The worker was cleaning the breaker cubicles. This is a routine maintenance procedure that the worker had performed previously, and he was familiar with the equipment. He came into contact with an energized electrical line (Marques, 2011). Although this was a human error, it was not due to working with a new type of technology.

January 25, 1982: Ontario, New York

The Ginna Nuclear Generating Station is located in Ontario, New York. As a result of the rupture of a steam generator tube, radioactive steam was released into the atmosphere (Harrison and Hester, 2011). The leak continued for more than 90 minutes, and more than 480 curies of radioactive gas were released as well as one millicurie of iodine-131. Additionally, nearly 1,700 gallons of contaminated water were lost from the reactor. This incident was due to a flaw in the design of the steam generator, so no employee error was involved. In fact, the steam generator tube design was based on an older design (Rogers, 2013).

February 26, 1982: San Clemente, California

In February 1982, San Onofre's reactor one was shutdown due to the possibility of an earthquake (Marques, 2011). This was a planned shutdown and not due to any type of human error.

March 20, 1982: Scriba, New York

The Nine Mile Point Nuclear Generating Station in Scriba, New York, has two units, o which unit one became operational in December 1969 and unit two in July 1987. This is one of the oldest reactors still operating within the United States. Unit one has a capacity of slightly over 620 MW; unit two can produce 1140 MW. The units are licensed until 2029 and 2046, respectively (Krivit, 2011).

In March 1982, the system piping failed in the recirculation system of unit one. As a result, the unit was closed for two years. The failure of the recirculation piping was due to human error when engineering the facility. The technology used in the plant was relatively new, and the engineers were unfamiliar with all of the systems. Additionally, they needed to use new types of equipment in facility design (Harrison and Hester, 2011). Therefore, this is judged to be an instance of human error when working with new technologies.

March 25, 1982: Buchanan, New York

Indian Point Energy Center is a nuclear power plant with three units in Buchanan, New York, approximately 38 miles from New York City (Harrison and Hester, 2011). The plant has an operational capacity of more than 2,000 MW. It supplies roughly one-third of the electricity needed for New York City and is operated by Entergy Nuclear Northeast, a subsidiary of the Entergy Corporation. The plant has two pressurized water reactors built by Westinghouse. Unit one of the two at the facility has been permanently shut down. Unit two was commissioned in 1974 and Unit three was commissioned in 1976 (Krivit, 2011).

Unit three was shut down in 1982 because of damage sustained by the main and steam generators (Marques, 2011). The steam generator tubes were damaged when the facility operators failed to notice warnings that it was not safe to use the section of the reactor that relied on these tubes. The interface that they were using had been installed only a few weeks before the incident occurred and the reactor personnel were not yet trained in their operation (Rogers, 2013). Therefore, this incident is judged to have been due to human error when working with new technology.

June 18, 1982: Seneca, South Carolina

The Oconee Nuclear Station is located on Lake Keowee near Seneca, South Carolina (Harrison and Hester, 2011). The plant has a capacity of 2,500 MW and is only the second nuclear facility within the United States to have had its operating license extended for an extra 20 years by the NRC. This facility has three pressurized water reactors designed by Babcock and Wilcox and is run by Duke Energy. According to the operating company, the facility has produced more than half a billion megawatt hours of electricity since it began operation in July 1973 (Marques, 2011).

In June 1982, the Oconee pressurized water reactor had a failure in a heat extraction line, causing damage to the thermal cooling system (Rogers, 2013). This failure was due to manufacturing problems with the materials used. No human error associated with the use of new technologies was suspected to have caused this incident.

February 12, 1983: Forked River, New Jersey

The Oyster Creek Nuclear Generating Station is located in Ocean County, New Jersey. Detection of a failure during a safety inspection resulted in the reactor being shut down for significant repairs (Salvendy, 2012). The Oyster Creek facility consists of one boiling water reactor capable of producing more than 630 MW of electricity. The facility has 800 acres dedicated to its operations. Oyster Creek, one of the oldest operating nuclear power plants in the United States, began operation in 1969 and has a license through the end of December 2019, at which point the plant is slated for permanent deactivation. The water to cool the plant is taken from a brackish estuary nearby, known as Barnegat Bay (Marques, 2011).

Although the shutdown due to the failed safety inspection carried an economic cost in excess of $30 million, it did not result in any damage to the facility or danger to those living near the plant (Smith, 2012). It was due to human error related to insufficient maintenance procedures, but not due to working with new technologies (Salvendy, 2012).

February 26, 1983: Fort Pierce, Florida

The St. Lucie Nuclear Plant has two pressurized water reactors of the combustion engineering type. The plant, operated by Florida Power and Light, began operations in 1976. Its first reactor unit's operating license has been extended to March 2036; the second reactor unit is licensed until April 2043 (Salvendy, 2012).

The St. Lucie unit one reactor was shut down for 13 months due to damage to the core barrel support and thermal shield (Krivit, 2011). This damage was judged to be secondary to a design flaw (Smith, 2012). There was no human error at the facility level, and the design engineers were not using new technologies (Marques, 2011). Therefore, the incident was not due to human error when working with new technology.

September 15, 1984: Athens, Alabama

The Browns Ferry unit two in Athens, Alabama was shut down in 1984 for a variety of safety violations, design problems, and operator errors (Smith, 2012) and remained out of operation for about six years, at a cost of more than $100 million. Although operator errors were involved in the events leading to the shutdown of unit two, these errors were not due to the use of new technology (Salvendy, 2012).

March 9, 1985: Athens, Alabama

A problem occurred during the 1985 startup of a reactor at the Browns Ferry plant in Alabama, due to a malfunction in the instrumentation system (Marques, 2011). Ultimately, the problem led to the suspension of operation of all three units. The instrument malfunction was due to an error in the manufacturing of the instruments and did not involve any type of mistake due to new technology (Salvendy, 2012). There were also problems with facility management, but these two were unrelated to new technologies.

June 9, 1985: Oak Harbor, Ohio

The Davis-Besse facility in Oak Harbor, Ohio (Krivit, 2011) has one pressurized water reactor that became operational in 1978 and has a license scheduled to expire in 2017. The owners of the facility are Toledo Edison and Cleveland Electric. The plant is operated by FirstEnergy Nuclear Operating Company, a subsidiary of FirstEnergy Corporation (Harrison and Hester, 2011). The reactor has a capacity of 889 MW and was designed by Babcock and Wilcox (Marques, 2011).

An incident in summer 1985 involved a shutdown of the primary feedwater pumps, which supply water for the reactor's steam generators (Smith, 2012). After the feedwater pumps had shut down, an operator in the control room tried to start the emergency feedwater pumps, but the emergency pumps entered an over-speed condition because of operator error. The human interface had been upgraded only one month prior to the incident (Salvendy, 2012). Therefore, this incident is judged to be due to human error when working with new technology.

April 11, 1986: Plymouth, Massachusetts

Boston Edison's Pilgrim Nuclear Power Plant is located in Plymouth, Massachusetts on Cape Cod Bay. It has a boiling water reactor produced by General Electric. The facility generates almost 15% of the electricity used in Massachusetts, or more than 5,100 GW per hour (Marques, 2011). This power plant has a capacity of 685 MW and is the sole nuclear power facility operating within Massachusetts. It commenced operations in December 1972 (Smith, 2012) and is licensed to operate until 2032 (Salvendy, 2012).

The plant experienced a series of equipment problems in 1986 that resulted in an emergency shutdown costing more than $1 billion (Marques, 2011). An investigation determined that the problem was not human error, but a design failure not associated with the use of new technologies (Krivit, 2011). Therefore, this problem was not due to a mistake when interacting with new technology.

March 31, 1987: Delta, Pennsylvania

The Peach Bottom Nuclear Generating Station is located in York County, Pennsylvania on the Susquehanna River. Its initial unit, one of the first active reactors in the United States, was commissioned in 1966 and decommissioned in 1974. Units two and three were commissioned in 1974 and are still in operation (Salvendy, 2012).

In 1987, the station experienced equipment difficulties and cooling malfunctions that resulted in an NRC-ordered shutdown of both units two and three (Marques, 2011). The reasons for the shutdown included corporate malfeasance, operator misconduct, and a general disregard for the safety and health of individuals living near the facility. The NRC found that the security guards were so overworked that they were often asleep on the job, and that 36,000 gallons of radioactive water had been released into the Susquehanna River. None of the errors that necessitated the 1987 shutdown were related to human error when working with new technologies. Poor management was the root of the problem (Smith, 2012).

July 15, 1987: Burlington, Kansas

The Wolf Creek Generating Station in Burlington, Kansas was commissioned in 1985 at a cost of over $3 billion (Salvendy, 2012). Construction began in 1977. The facility consists of a single Westinghouse pressurized water reactor that is rated for 1,170 MW. Installation of a new rotor in 2011 increased the electrical capacity to 1250 MW. The facility’s license has been extended to 2037 (Krivit, 2011).

Tragedy hit this facility in July 1987 when a safety inspector made contact with a mislabeled wire, was inadvertently electrocuted, and died (Smith, 2012). The electrical system in this part of the facility had recently been upgraded, and the worker doing the labeling had not been properly advised of the new wiring system (Marques, 2011). Therefore, this incident is judged as due to human error when working with new technology.

December 19, 1987: Scriba, New York

In 1987, Nine Mile Point’s unit one was shut down due to system malfunctions (Marques, 2011; Salvendy, 2012). An investigation revealed no human error related to new technologies.

The system malfunctions were due to design errors and lack of appropriate maintenance (Smith, 2012).

March 29, 1988: Burlington, Kansas

In 1988, the Wolf Creek Generating Station experienced its second fatality in less than a year (Sehgal, 2012). A worker fell into an unmarked manhole and was electrocuted while trying to escape. An investigation revealed that the manhole had recently been added as part of a facility update and renovations that were necessary due to new technologies associated with the power plant. During the renovations, the workers failed to label the manhole properly. Additionally, they were not familiar enough with the new system to understand the necessary safety measures to ensure that someone entering the manhole would not be electrocuted (Salvendy, 2012). Therefore, this incident is judged as due to human error when working with new technologies.

September 10, 1988: Surry, Virginia

Surry's unit two was shut down for 12 months (Krivit, 2011) because of the failure of a seal on a refueling cavity, which resulted in the destruction of an internal pipe system. An investigation revealed that both the internal pipe system and the cavity seal had been recently upgraded, but that the maintenance and inspection personnel at the facility were not familiar with the new systems (Salvendy, 2012). Therefore, this incident is judged to have been due to human error when working with new technology.

March 5, 1989: Tonopah, Arizona

The Palo Verde Nuclear Generating Station is located near Tonopah, Arizona, about 50 miles west of Phoenix (Sehgal, 2012). This facility, commissioned in 1988, has three pressurized water reactors that can generate a total of 3,875 MW, making it the largest power generation source in the United States. This nuclear facility is the only one in the world not located near a significant body of water. The plant uses a unique system for evaporating the water associated with treated sewage from towns and cities nearby (Harrison and Hester, 2011).

A 1989 incident at Palo Verde resulted from a failure of the atmospheric dump valves (Sehgal, 2012). Many of the maintenance and inspection personnel were not yet familiar with the unique cooling system associated with this facility. This unfamiliarity appears to have contributed to the valves' failure, an associated transformer fire, and an emergency shutdown of the facility (Krivit, 2011). Therefore, this incident is judged as having been due to human error associated with new technology.

March 17, 1989: Lusby, Maryland

The Calvert Cliffs Nuclear Power Plant near Lusby, Maryland was commissioned in 1975 and remains operational. In 1989, the facility was shut down after inspectors found cracks in the pressurized heat sleeves for units one and two (Sehgal, 2012). The cracks were attributed to design flaws and were not associated with the introduction of new technologies (Sehgal, 2012).

November 17, 1991: Scriba, New York

The FitzPatrick Nuclear Reactor was shut down for more than 12 months due to fire and safety problems (Krivit, 2011). This facility, commissioned in July 1975, consists of a single boiling water reactor supplied by General Electric, with a power generating capacity of 838 MW. The shutdown occurred after a discovery that several safety and fire procedures were not being followed. An investigation revealed that the fire and safety systems had recently been upgraded, but that the associated staff at the facility had not been properly trained on the new equipment (Harrison and Hester, 2011). Therefore, this incident is judged as having been due to human error when working with new technology.

April 21, 1992: Southport, North Carolina

Both units one and two of the Brunswick reactor in Southport, North Carolina were shut down in 1992 after a failure in the emergency diesel generators (Sehgal, 2012). The monitoring equipment used to ensure that the diesel generators were operating properly had recently been upgrade. The facility personnel working with this new equipment stated that they did not understand how to properly interpret some of the readings (Sehgal, 2012). Therefore, this incident can be attributed to human error when working with new technology.

February 3, 1993: Bay City, Texas

The auxiliary feedwater pumps at the South Texas Project’s units one and two in Bay City failed, causing both reactors to be shut down (Sehgal, 2012). The problem was associated with maintenance personnel not having proper training related to the newly upgraded reactor cooling systems (Sehgal, 2012). This incident was thus due to human error when working with new technology.

February 27, 1993: Buchanan, New York

The New York Power Authority (NYPA) voluntarily shut down Indian Point unit three to address problems with its AMSAC, or anticipated transient without scram mitigation system actuation circuitry. On March 26, the NYPA submitted its action plan for correcting conditions at unit three to the NRC. Plant workers and NRC inspectors identified numerous surveillance testing deficiencies, fire protection program deficiencies, and design errors. On June 17, 1993, the NRC issued a Confirmatory Action Letter, documenting the agreed-upon tasks for restart. It took the NYPA nearly two years to complete those items and restart unit three on July 2, 1995. Because the shutdown was controlled and voluntary, this incident is determined not to be due to human error when interacting with new technology (Cahill, 1995).

March 2, 1993: Soddy-Daisy, Tennessee

The Sequoyah Nuclear Plant, located near Soddy-Daisy, Tennessee (Harrison and Hester, 2011), is owned and operated by the Tennessee Valley Authority. The plant consists of two Westinghouse pressurized water reactors. In 1993, multiple equipment failures and broken pipes led to the shutdown of unit one. The problem was found to be caused by equipment failures resulting from improper maintenance as well as operator error when reading the instruments. Both the equipment and the instrument had recently been installed (Krivit, 2011). Therefore, this incident can be classified as due to human error associated with new technology.

December 25, 1993: Newport, Michigan

On Christmas day of 1993, Fermi unit two at the nuclear facility in Newport, Michigan was shut down due to a major failure in the main turbine (Harrison and Hester, 2011). It was later discovered that the turbine failure was caused by improperly performed maintenance. This was a case of human error, but no new technology was involved (Sehgal, 2012).

January 14, 1995: Wiscasset, Maine

The Maine Yankee Nuclear Power Plant in Wiscasset, Maine (Sehgal, 2012) was in operation from 1972 until 1996, when it was closed due to costly repairs. The plant was decommissioned and then dismantled from 1997 to 2005. Only stored nuclear waste now remains at the site (Sovacool & Valentine, 2012).

The plant was shut down for 12 months in 1995 due to a crack in the steam generator tubes (Smith, 2012). This shutdown was followed by an NRC investigation, which identified multiple problems too costly to repair. The problems at this plant were not due to technological advances; in fact, failure to update the facility led to its decommissioning (Krivit, 2011).

May 16, 1995: Lower Alloways Creek, New Jersey

The Salem Nuclear Power Plant is located in the Lower Alloways Creek area of New Jersey (Smith, 2012). The plant consists of two pressurized water reactors (Harrison and Hester, 2011), licensed until 2036 and 2040, respectively. It is owned by Exelon Generation, LLC and PSEG Nuclear, LLC.

In 1995, both reactors were shut down for 24 months due to unreliable controls and a leaky generator (Krivit, 2011). Neither of these problems was due to problems with an operator interacting with the system.

February 20, 1996: Waterford, Connecticut

In 1996, a leaking valve was found in Waterford's units one and two (Krivit, 2011), along with other equipment failures as well. As a result, both units were temporarily shut down. No human error or technology enhancements were involved.

May 15, 1996: Morris, Illinois

The Dresden Generating Station, located near Morris, Illinois (Sovacool and Valentine, 2012), is the first privately financed nuclear power plant in the United States. It is owned and operated by Exelon Generation, LLC. There have been three boiling water reactor units within the facility. Unit one became operational in 1960 and was decommissioned in 1978. Unit two was made operational in 1970 and is licensed to operate until 2029. Unit three was commissioned in 1971 and has a license to operate until 2031. Both operating reactors have a maximum capacity of 867 MW. The facility provides power for Chicago and roughly one-quarter of the state of Illinois. It generates enough electricity for approximately one million homes (Sovacool, 2011).

This facility has had a problematic operating history (Harrison and Hester, 2011). From 1970 to 1996, it accumulated fines of more than $1.5 million. In May 1996, the water levels surrounding the reactor core dropped to an unacceptably low level, forcing a temporary shutdown of the facility. Frequent changes were made at the facility prior to 1996 in response to the numerous NRC sanctions. It is likely that multiple changes in the technology prior to the 1996 incident contributed to the operators' inability to determine that the water levels were too low, but due to the lack of information about the specific event, this event was not included in the statistical categorization (Krivit, 2011).

September 2, 1996: Crystal River, Florida

The Crystal River Three Nuclear Power Plant in Crystal River, Florida was closed in 2009 (Sehgal, 2012). The plant was a pressurized water reactor owned and operated by Duke Energy. It was the third nuclear power plant located in the Crystal River Energy Complex, which also has four fossil-fuel plants in this complex. The plant was commissioned in 1977 and cost $400 million. It was capable of producing 860 MW (Perrow, 1999).

In 1996, equipment malfunctions at unit three led to the temporary shutdown of the facility for repairs (Harrison and Hester, 2011). There is no indication that this incident was the result of operators working on new technologies that adversely affected their interaction with the system.

September 5, 1996: Clinton, Illinois

The Clinton Nuclear Generating Station located near Clinton, Illinois (Smith, 2012), was commissioned in 1987 and has a license to operate until 2026. The cost of the facility was over $2.6 billion. It is operated by the Exelon Corporation and has a second-generation boiling water reactor produced by General Electric. The operational reactor has a capacity of 1,043 MW. The original owner of the plant was Illinois Power (Sovacool & Valentine, 2012).

In 1996, Illinois Power shut down the facility because a reactor recirculation pump failed (Sovacool, 2011). Although it was not generally made public at the time, Illinois Power suspected that many of the problems were due to operators’ unfamiliarity with how to run the facility and their general inability to use and understand the readings provided by the recently updated user interface. In fact, following the incident in 1996, Illinois Power sold the facility to Exelon Corporation at a substantial loss. The estimated loss for the temporary shutdown in 1996 was $36 million, the original construction cost of the facility exceeded $2.6 billion, and the facility was sold to Exelon for only $40 million (Perrow, 1999). Therefore, this incident can be classified as due to human error associated with new technology.

September 20, 1996: Seneca, Illinois

The LaSalle County Nuclear Generating Station near Ottawa, Illinois (Sovacool, 2011) provides power for Chicago and much of northern Illinois. The facility consists of two General Electric boiling water reactors. The first unit has an operational capacity of 1,138 MW; the second unit can produce up to 1,150 MW. Both units were commissioned in 1984, and they are licensed until 2022 and 2023, respectively. Exelon Corporation handles the operations at this plant. Overall, the facility has operated well. In fact, the two units set a world record for continuous boiling water reactors when they both operated for more than 700 successive days (Sehgal, 2012). In 1996, however, a failure of the surface water systems forced both units to be shut down for more than two years (Harrison and Hester, 2011). There is no indication that operator error related to technological changes was involved in the problem.

September 9, 1997: Bridgman, Michigan

The Donald C. Cook Nuclear Generating Station near Bridgman, Michigan (Krivit, 2011) is operated by Indiana Michigan Power, a subsidiary of American Electric Power (AEP), which owns the plant. The site sits on 650 acres and has two nuclear reactors. The plant was constructed for $3.3 billion and is licensed to continue operating unit one until 2034 and unit two until 2037 (Perrow, 1999).

On September 9, 1997, as a result of a NRC inspection in the engineering area, both units were shut down for approximately 3 years due to legal problems with licensing and design. Specifically, the NRC determined that it was unclear whether emergency core cooling systems could perform their intended functions in the event of a design basis accident (Harrison and Hester, 2011). No operator error was involved in this difficulty.

May 25, 1999: Waterford, Connecticut

In May 1999, a steam leak was detected in the feed water heater, resulting in a manual shutdown of the power plant (Sovacool & Valentine, 2012). The problem did not involve operators working with an updated interface.

September 29, 1999: Lower Alloways Creek Township, New Jersey

The Hope Creek Nuclear Generating Station is located on the same site as the Salem Nuclear Power Plant, in Lower Alloways Creek Township of New Jersey (Perrow, 1999). The Hope Creek facility has a single boiling water reactor, manufactured by General Electric and operated by PSEG Nuclear, LLC. It has a capacity of 1268 MW and took 12 years to construct. The plant was finished and commissioned in 1986 and is licensed to operate until 2046 (Sehgal, 2012).

In 1999, a major Freon leak led to the tripping of the ventilation train chiller (Smith, 2012), which caused toxic gas to be released into the cooling system and inflicted substantial damage (Sovacool, 2011). There is no indication that this problem was a result of human error.

February 15, 2000: Buchanan, New York

The Buchanan plant experienced a shutdown in 2000. It appears that the operators at the Indian Point Energy Center failed to read the system feedback properly and that a Freon leak was allowed to continue for a significant amount of time before it caused the ventilation train chiller to trip (Perrow, 1999). Furthermore, the plant had recently undergone changes to its computer system in anticipation of the new millennium, probably contributing to the operators' failure to fully understand the readings (Sovacool, 2011). This can be considered an example of technological advances negatively affecting operators' interaction with the system.

February 16, 2002: Oak Harbor, Ohio

In March 2002, the facility maintenance workers at the Davis-Besse nuclear plant discovered a football-sized hole located near the reactor vessel head (Sovacool and Valentine, 2012). No adverse incident resulted from this hole, but the NRC required the plant to close for two years while FirstEnergy completed necessary maintenance. The corrosion of the reactor head was attributable to boric acid. Abundant readings should have caused the operators to suspect that something was wrong. However, the facility had recently undergone numerous technological enhancements of the user interface in its main control center. When questioned, the operators admitted that they did not feel fully confident with the new equipment (Krivit, 2011). Accordingly, human error related to technological changes was definitely a factor in this incident.

January 15, 2003: Bridgman, Michigan

Unit two of the Donald C. Cook Nuclear Generating Station shut down automatically in January 2003 due to a failure of the DC power supplie~~s~~ for the reactor control and instrumentation system. This failure resulted in an automatic trip of the main transformer which resulted in the rupture of the transformer oil tank and resulting fire. The loss of the main transformer precipitated an automatic trip of the main generator and an immediate turbine and reactor trip. The main transformer fire was extinguished within 35 minutes with one minor reflash (Krivit, 2011). Accordingly, human error related to technological changes was determined not to be a factor in this incident.

June 16, 2005: Braidwood, Illinois

The Braidwood Generating Station near Braidwood, Illinois (Sovacool and Valentine, 2012) was constructed by Commonwealth Edison and later transferred to its parent company, the Exelon Corporation. This facility was under construction from 1976 until 1988 and cost over $5 billion. The plant uses two pressurized water reactors, both commissioned in 1988 and licensed until 2026 and 2027, respectively. The facility has an operational capacity of 2,330 MW (Sovacool, 2011).

During January 2003, a fault in the primary transformer at the station resulted in a fire that damaged the main generator and backup turbines (Smith, 2012). There is no indication that human error when dealing with new technologies was responsible for the problem. As a result of these problems, tritium and nuclear contaminants were released into the local water supply (Sehgal, 2012).

August 4, 2005: Buchanan, New York

In 2005, at the Indian Point Energy Center, workers digging at the facility discovered a leak in one of the spent fuel pools. Water containing strontium 90 and tritium had been leaking through a crack inside the pool building. There was also a report of strontium and radioactive nickel-63 in groundwater samples from the site. The operators at the plant were accused of allowing this leakage to occur from 1974 to 2005 (Sovacool, 2011).

The pool buildings used for storage are not directly connected to the everyday operational systems for the nuclear site (Harrison and Hester, 2011). Although staff can be blamed for not reporting the incident or checking the pools more frequently, there were no significant changes to the technology prior to this incident.

March 6, 2006: Erwin, Tennessee

Nuclear Fuel Services has been responsible for supplying fuel for the U.S. Navy’s nuclear-powered vessels for roughly 50 years (Smith, 2012). The company, a subsidiary of the Babcock and Wilcox Corporation (Perrow, 1999), is also involved in the reprocessing of weapons-grade uranium into a form that can be used as fuel for nuclear reactors. This process is often referred to as down blending (Sovacool and Valentine, 2012). The company’s gated complex of 65 acres is located in Erwin, Tennessee.

In March 2006, Nuclear Fuel Services was responsible for a spill of approximately 35 liters of highly enriched uranium (Krivit, 2011), which required a seven-month shutdown of the facility. The cost of this incident was reported at $95 million, but due to the sensitive nature of the company’s business relationship with the U.S. government, little information can be obtained on the specifics of this problem (Perrow, 1999). Therefore, due to the lack of information about the specific event, this event was not included in the statistical categorization.

September 10, 2009: Crystal River, Florida

The Crystal River Nuclear Power Plant's unit three has been closed since September 2009 (Sovacool, 2011). The facility was initially brought offline so that its outdated steam generators could be replaced. Progress Energy determined that it could save $15 million if it managed the project on its own rather than having outside experts manage the replacement. This approach had previously never been attempted by any utility company. A subsequent investigation revealed that the company found that it did not have the proper expertise or experience to undertake the task. As of this time, the reactor remains shut down due to cost overruns in the renovation. Although this shutdown has exhibited seriously deficient program planning and management, the problems were not due to any technological changes or interactions by operators within the system (Sehgal, 2012).

February 1, 2010: Vernon, Vermont

The Vermont Yankee Nuclear Power Plant was a boiling water reactor manufactured by General Electric is located in Vernon, Vermont (Sovacool, 2011). The facility was commissioned in 1972 and ceased operations in 2014. It had a capacity of 620 MW and was operated by Entergy (Sehgal, 2012). In 2008, the facility generated more than one-third of all electricity used by the state.

In February 2010, it was discovered that groundwater samples taken from the site of a newly dug well contained an amount of tritium 37 times higher than the permitted federal limit

(Sovacool and Valentine, 2012). The source of this tritium was traced to a leak in the steam pipes within the Advanced Off-Gas pipe tunnel. The pipes were repaired and the leak was contained (Harrison and Hester, 2011). No new technologies were involved in the checking of groundwater samples.

APPENDIX B: ERROR PRECURSORS

This listing of error precursors is extracted from DOE-HDBK-1028-2009, *DOE Standard Human Performance Improvement Handbook*, Volume 1: *Concepts and Principles* (U.S. Department of Energy, 2009), pages 2–35 to 2–37.

Task Demands

- Time pressure (in a hurry)
- High workload (memory requirements)
- Simultaneous, multiple tasks
- Repetitive actions / monotony
- Irreversible acts
- Interpretation of requirements
- Unclear goals, roles, or responsibilities
- Lack of or unclear standards
- Confusing procedure / vague guidance
- Excessive communication requirements
- Delays; idle time
- Complexity / high information flow
- Long-term monitoring
- Excessive time on task

Individual Capabilities

- Unfamiliarity with task / First time
- Lack of knowledge (faulty mental model)
- New technique not used before
- Imprecise communication habits
- Lack of proficiency / inexperience
- Indistinct problem-solving skills
- “Unsafe” attitudes for critical task
- Illness / fatigue / injury (general health)
- Unawareness of critical parameters
- Inappropriate values
- Major life event: medical, financial, and emotional
- Poor manual dexterity
- Low self-esteem; moody
- Questionable ethics (bends the rules)
- Sense of control / learned helplessness
- Personality type

Work Environment

- Distractions / interruptions
- Changes / departure from routine
- Confusing displays / controls
- Work-arounds / out of specification instrumentation
- Hidden system response
- Unexpected equipment conditions
- Lack of alternative indication
- Personality conflicts
- Back shift or recent shift change
- Excessive group cohesiveness / peer pressure
- Production overemphasis
- Adverse physical climate (habitability)
- No accounting of performance.
- Conflicting conventions; stereotypes
- Poor equipment layout; poor access
- Fear of consequences of error
- Mistrust among work groups
- Meaningless rules
- Nuisance alarms
- Unavailable parts or tools
- Acceptability of "cookbooking" practices
- "Rulebook" culture
- Equipment sensitivity (inadvertent actions)
- Lack of clear strategic vision or goals
- Identical and adjacent displays or controls
- Out-of-service warning systems
- Lack of procedure place-keeping

Human Nature

- Stress (limits attention)
- Habit patterns
- Assumptions (inaccurate mental picture)
- Complacency / overconfidence
- Mind-set
- Inaccurate risk perception
- Mental shortcuts (biases)
- Limited short-term memory
- Pollyanna effect
- Limited perspective (bounded rationality)
- Avoidance of mental strain
- First day back from vacation / days off
- Sugar cycle (after a meal)
- Fatigue (sleep deprivation and biorhythms)
- Tunnel vision (lack of big picture)
- "Something is not right" (gut feeling)
- Pattern-matching bias
- Social deference (excessive professional courtesy)
- Easily bored
- Close-in-time cause-effect correlation
- Difficulty in seeing own errors
- Frequency and similarity biases
- Availability bias
- Imprecise physical actions
- Limited attention span
- Spatial disorientation
- Physical reflex
- Anxiety (involving uncertainty)

APPENDIX C: SURVEY STRUCTURE, ANALYSIS, AND RESULTS

Survey Delivery Method

Interviews and questionnaires were used in combination as the survey delivery method. This approach not only obtains quantitative data, but also gives respondents the opportunity to express their qualitative thoughts, reactions, and feedback on the subject matter, which will help in assessing the confidence that experts in the engineering field have regarding the proposals in chapter 7.

Question Type Employed

To develop the question set for the survey, chapter 7 was parceled into subsets by discrete subject matter, and questions were written in such a manner as to determine a level of confidence that the concepts would be successful and that implementation would be feasible. Once the questions had been generated, they were revised based on several relevant concepts fundamental to survey design methodology. Both closed- and open-ended questions were used to ensure that the entire breadth of responses could be collected and to provide evidence of expert confidence regarding the concepts proposed in chapter 7. For the closed-ended questions, a Likert-type scale from 1 to 5 was employed to quantify results on a portion of the survey. Open-ended questions (including the opportunity to comment on answers to closed-ended questions) gave respondents the ability to elaborate on their numerical responses, with the purpose of obtaining evidence that the proposed concepts are sound or identifying where improvement is needed.

Design Biases Considered

As indicated above, the initial set of survey questions and iterations thereafter were reviewed relative to several common design biases: leading or loaded questions, overlapping response options, unbalanced response options (including floor and ceiling effects), and framing effects. The survey contained no emotionally charged questions, and the use of Likert-type questions with a neutral response option, along with permitting respondents to elaborate on their answers, made it easier to avoid most of these biases. To avoid framing effects, benchmarking was utilized to compare the present questions to those from a similar survey.

The respondents were advised that anonymity of all information provided on the survey would be maintained.

A pilot study was conducted with three individuals to gauge whether the questions were understandable, consistent, and reliable and that the concepts made sense, as well as to obtain opinions on specific wording and phrasing used.

Additional Considerations

Additional factors taken into consideration in question development were the avoidance of jargon, slang, and abbreviations in question content; ensuring that questions were written in such a way as to test hypotheses (not questions written *about* hypotheses); maintenance of realistic expectations as to respondent capabilities; and avoidance of negatively phrased questions.

Lastly, question ordering was accomplished by taking into consideration organizational concerns (e.g., choice of opening and closing questions, and smooth survey flow) and order effects (content relationships, contextual effects, and rating dependencies). Parceling the chapter content into manageable sections enabled the respondent to read the information on each specific topic and then answer a series of survey questions on that topic. This ensured that the respondent would not have to presume what the question was referring to and prevented frustration by not compelling the respondent to reread sections.

Survey Population and Personnel Selection

The survey sample consisted of 40 system design engineers (age 25 to 65) of various backgrounds and disciplines (nuclear engineers, electrical engineers, mechanical engineers, etc.) who were knowledgeable regarding the systems engineering and design process.

To select the personnel for the study, the engineering staff roster of my place of employment was first filtered to exclude staff who did not hold an engineering degree and those who had not been involved in systems engineering or design for at least five years. From this reduced listing, random selection occurred using a random number generator on Microsoft Excel. Thirty individuals were selected using this method, and then additional individuals who had expressed interest were added to the final sample. The solicitation letter, disseminated by email, included a brief explanation of the study, the estimated time required to complete the survey interview, and how the information would be handled and addressed within the dissertation.

Survey Administration

The statements contained in the survey were extracted directly from sections of chapter 7. The respondents were provided with the chapter content and the questions and statements along with the five-point Likert scale. Depending on the question, the potential responses were labeled in one of two ways: (1) “never,” “occasionally,” “regularly,” “frequently,” and “always,” or (2) “strongly disagree,” “disagree,” “neither agree or disagree,” “agree,” and “strongly agree.” Using two different scales not only allows for flexibility in questioning but also offers survey range and depth instead of repetition.

Additionally, as discussed above, the respondents could make open-ended comments on any of the closed-ended questions, and those comments were recorded in the appropriate box on the survey.

Human Subject Protections

The Colorado State University Institutional Review Board (IRB) coordinator declared the study exempt from the requirements of the human subject protections regulations with conditions as described in 45 CFR 46.101(b):

> Category 2 - Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

This determination is documented via IRB ID: 205-17H with a review date of September 26, 2016. The study authorization was valid from three years from the review date, and the study was completed within that time period.

All research participants signed a written consent form explaining their rights as a volunteer, the ability to withdraw their consent at any time during the study, the fact that no identifying information was collected or used in the analysis of the results, and reasonable assurance that the researchers had taken reasonable safeguards to minimize any known or potential but unknown risks and that there were no known risks.

Survey Questions

Table 12. Operator Involvement in the Systems Engineering Process

<table>
<tr><td colspan="7">Using a scale of 1-5 (1=Strongly Disagree, 2=Disagree, 3=Neither Agree or Disagree, 4=Agree, 5=Strongly Agree), please indicate your agreement with the following concepts:</td></tr>
<tr><th>#</th><th>Statement</th><th>Strongly Disagree</th><th>Disagree</th><th>Neither Agree or Disagree</th><th>Agree</th><th>Strongly Agree</th></tr>
<tr><td>1</td><td>Operations personnel should be involved in the systems engineering process from the onset.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>2</td><td>Because system utilization encompasses a large portion of the systems life, operations personnel participation in system design is necessary not only for system operational success and support, but also for human error reduction in the operation of new technologies.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>3</td><td>FMEA can and should be used during all stages of the systems engineering process.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>4</td><td>Operations personnel should play a role in FMEA during the design stages.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>5</td><td>Design criteria can come and should come from a number of diverse sources, but those that originate from the plant operations staff should be given elevated deliberation because they will become the system owner through the utilization phase of the systems life.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td colspan="7">Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:</td></tr>
<tr><th>#</th><th>Statement</th><th>Never</th><th>Occasionally</th><th>Regularly</th><th>Frequently</th><th>Always</th></tr>
<tr><td>6</td><td>Involve operations personnel in the systems engineering process from the onset.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>7</td><td>Utilize FMEA techniques during all stages of the systems engineering process.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>8</td><td>Involve operations personnel in FMEA during the design stages of the systems engineering process.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>9</td><td>Give design criteria that originate from operations personnel elevated deliberation in system design.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
</table>

Table 13. Human Performance Association with System Operational Requirements and System Test, Evaluation, and Validation

#	Statement	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
10	Embedded within the elements of system operational requirements should be specific, exclusive human performance system requirements that can be easily assessed and discernable in system design.	1	2	3	4	5
11	The creation of human performance TPMs that evaluate the integration of the human error reduction tools with the technology necessary to achieve functionality required for system purpose should be given sufficient attention.	1	2	3	4	5
12	Error precursors require systematic evaluation, logical selection or generation, and potential modification before adaptation into human performance TPMs.	1	2	3	4	5

Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:

#	Statement	Never	Occasionally	Regularly	Frequently	Always
13	Establish and incorporate human performance system operational requirements into system design.	1	2	3	4	5
14	Establish and incorporate human performance TPMs that evaluate the integration of the human error reduction tools with the technology necessary to achieve functionality required for system purpose.	1	2	3	4	5

Table 14. Procedure and Training Development in the Systems Engineering Process

Using a scale of 1-5 (1=Strongly Disagree, 2=Disagree, 3=Neither Agree or Disagree, 4=Agree, 5=Strongly Agree), please indicate your agreement with the following concepts:

#	Statement	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
15	The generation of operations procedures should begin at the conceptual design stage in the systems engineering process and then further developed and refined as the systems engineering process advances.	1	2	3	4	5
16	Proper application of human error prevention tools and techniques should be soundly intertwined into the framework of the operations procedures.	1	2	3	4	5
17	In the generation of operations procedures, every effort should be made to drive human performance into the skill-based mode.	1	2	3	4	5
18	When manipulating technologically advanced, complex systems, operators should be trained utilizing the knowledge-based training approach to ensure adherence to design boundaries, efficiency in operation, and an adequate margin to safety.	1	2	3	4	5
19	Operator training generation should begin at conceptual design and be further developed as the systems engineering process advances.	1	2	3	4	5
20	Included in a robust knowledge-based training program should be a vigorous plant casualty control drill program.	1	2	3	4	5
21	The drill program involving the system in design should be developed during the conceptual design stage and iterated as the systems engineering process progresses.	1	2	3	4	5
22	Drill scenario development can provide another avenue for system design review and evaluation by, potentially, an additional set of eyes viewing it from an alternant perspective.	1	2	3	4	5
23	The development of the drill program during the conceptual design stage and iteration through the remainder of the systems engineering process could provide feedback to system designers for desirable improvements and cultivates the continued development of operator training and procedures.	1	2	3	4	5

Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:

#	Statement	Never	Occasionally	Regularly	Frequently	Always
24	Generate operations procedures during the conceptual design stage in the systems engineering process further develop and refine the procedures as the systems engineering process advances.	1	2	3	4	5
25	Intertwine human error prevention tools and techniques into the framework of operations procedures.	1	2	3	4	5
26	Train operators utilizing the knowledge-based training approach to ensure adherence to design boundaries, efficiency in operation, and an adequate margin to safety.	1	2	3	4	5
27	Generate operator training during the conceptual design stage and further develop the training as the systems engineering process advances.	1	2	3	4	5

Table 14. Continued

28	Include a vigorous plant casualty control drill program within a robust knowledge-based training program.	1	2	3	4	5
29	Generate a drill program during the conceptual design stage and further develop the training as the systems engineering process advances.	1	2	3	4	5

Table 15. Operator Attribute Determination

#	Statement	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
30	The determination and development of necessary operator skills and training requirements should begin at the conceptual design stage in the systems engineering process and be refined as the systems engineering process advances.	1	2	3	4	5
31	Determined operator attributes can manifest as system requirements determined during requirements analysis.	1	2	3	4	5
32	Workforce planning should be built in all stages of the systems engineering process to ensure personnel with the necessary attributes are available when the system is deployed.	1	2	3	4	5
33	The development of the human should be as important as the design of the system.	1	2	3	4	5
34	As the systems engineering process progresses, management needs to be constantly assessing the connection between leadership practices, employee work passion, customer devotion, and the bottom line.	1	2	3	4	5
35	There is a clear connection between the quality of an organization’s leadership practices, as perceived by employees, and subsequent intentions by personnel to stay with an organization, perform at a high level, and apply discretionary effort.	1	2	3	4	5

Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:

#	Statement	Never	Occasionally	Regularly	Frequently	Always
36	Determine and develop necessary operator skills and training requirements at the conceptual design stage in the systems engineering process and refine them as the systems engineering process advances.	1	2	3	4	5
37	Build workforce planning into all stages of the systems engineering process to ensure personnel with the necessary attributes are available when the system is deployed.	1	2	3	4	5
38	Develop the human operator with the same rigor and attention as the design of the system.	1	2	3	4	5
39	Constantly assessing the connection between leadership practices, employee work passion, customer devotion, and the bottom line as the systems engineering process progresses.	1	2	3	4	5

Table 16. Systems Engineering Infrastructure

<table>
<tr><th>#</th><th>Statement</th><th>Strongly Disagree</th><th>Disagree</th><th>Neither Agree or Disagree</th><th>Agree</th><th>Strongly Agree</th></tr>
<tr><td>40</td><td>The design and development of a system necessitates an adaptive and unique systems engineering infrastructure.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>41</td><td>With respect to systems engineering infrastructure, it is important to remain apprised and parallel to the industry standard and best practices regarding utilization of organizational design, management processes, software development and functionality, and administrative methods.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>42</td><td>As the systems engineering process for product or system development is launched, the proper infrastructure should be established to efficiently support the system development.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>43</td><td>The infrastructure design should be a formal, guided process for integrating the people, information, and technology of an organization.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td colspan="7">Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:</td></tr>
<tr><th>#</th><th>Statement</th><th>Never</th><th>Occasionally</th><th>Regularly</th><th>Frequently</th><th>Always</th></tr>
<tr><td>44</td><td>Establish the proper infrastructure to efficiently support the system development as the systems engineering process for product or system development is launched.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
</table>

Table 17. Means to Minimize Human Error Impact throughout the Systems Engineering Process

Using a scale of 1-5 (1=Strongly Disagree, 2=Disagree, 3=Neither Agree or Disagree, 4=Agree, 5=Strongly Agree), please indicate your agreement with the following concepts:						
#	**Statement**	**Strongly Disagree**	**Disagree**	**Neither Agree or Disagree**	**Agree**	**Strongly Agree**
45	A human performance improvement (HPI) process should be established not only to remain cognizant of human performance during system design, but to provide a means to evaluate human performance of the system at the various stages.	1	2	3	4	5
46	The HPI process can and should be established early in the systems engineering process to identify the impact and extent to which human error affects plant systems and equipment, which will provide necessary feedback into system design process.	1	2	3	4	5
47	To institute the HPI process in a manageable fashion, organizations should determine human error severity criteria and establish a tracking system to capture these human error induced potential issues for engineered and administrative component features, human error prevention training and reinforcement, and lessons learned.	1	2	3	4	5
48	These potential issues and incidents can be discovered during the many steps of each stage of the systems engineering process, during the development of procedures for system operation, during training development, during FMEA, and during the design reviews conducted at the conclusion of the conceptual, preliminary, and detail design and development stages of the systems engineering process.	1	2	3	4	5
49	As a part of the HPI process, organizations should create a formal process to examine incidents and perceived vulnerabilities that occur throughout the development of the system during the systems engineering process and, later, during plant operation.	1	2	3	4	5
50	As a part of the HPI process, a methodical approach should be established to systematically direct the potential incident or vulnerability through a series of questions and facilitators to determine regulatory impact, safety significance, determine which organization will perform the corrective action or causal analysis, and ultimately correct the deficiency.	1	2	3	4	5
51	Due diligence, attention, constant emphasis, and management support needs to be given to the identification and reporting of the potential human errors and the corrective action processing of the problems as they are reported	1	2	3	4	5
52	This process, if effectively performed, will constantly reinforce good human performance practice, the reduction of human error in system design and potential human errors during operation, proportionally decrease the volume of potential problems at all levels, and continually drive errors to the least significant level.	1	2	3	4	5

Table 17. Continued

53	A management team should be established to help ensure that the HPI program is effectively and consistently implemented with particular emphasis on evaluating significant issues, adverse trends identified, and ineffective corrective actions that were applied to conditions adverse to safety and security.	1	2	3	4	5
54	Management should promote a culture focused on safety and operational excellence where employees should be not only encouraged to make error incident reports, but expected to make these reports in a retaliation free atmosphere.	1	2	3	4	5

Using a scale of 1-5 (1=Never, 2=Occasionally, 3=Regularly, 4=Frequently, 5=Always), please indicate your likelihood to implement or support the following concepts:

#	Statement	Never	Occasionally	Regularly	Frequently	Always
55	Establish a human performance improvement (HPI) process to not only to remain cognizant of human performance during system design, but to provide a means to evaluate human performance of the system at the various stages.	1	2	3	4	5
56	Establish an HPI process early in the systems engineering process to identify the impact and extent to which human error affects plant systems and equipment, which will provide necessary feedback into system design process.	1	2	3	4	5
57	Determine human error severity criteria and establish a tracking system to capture these human error induced potential issues for engineered and administrative component features, human error prevention training and reinforcement, and lessons learned.	1	2	3	4	5
58	Create a formal process to examine incidents and perceived vulnerabilities that occur throughout the development of the system during the systems engineering process and, later, during plant operation.	1	2	3	4	5
59	Establish a methodical approach to systematically direct the potential incident or vulnerability through a series of questions and facilitators to determine regulatory impact, safety significance, determine which organization will perform the corrective action or causal analysis, and ultimately correct the deficiency.	1	2	3	4	5
60	Establish a management team to help ensure that the HPI program is effectively and consistently implemented with particular emphasis on evaluating significant issues, adverse trends identified, and ineffective corrective actions that were applied to conditions adverse to safety and security.	1	2	3	4	5
61	Promote a culture focused on safety and operational excellence where employees should be not only encouraged to make error incident reports, but expected to make these reports in a retaliation free atmosphere.	1	2	3	4	5

Table 18. Survey Data

Respondent

Question

Q\N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	5	5	5	5	5	4	5	5	5	5	5	4	5	5	5	5	5	4	5	5	5	4	5	5	4	5	5	4	4	4	5	4	5	5	4	4	5	4	5	5
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36	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	5	5	5	5	5	4	5	5	4	4	4	4	4	5	5	5	5	5	5	4	4	4	5	4	4
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38	4	4	4	5	4	4	4	5	4	4	5	5	4	5	4	5	4	5	4	4	4	5	4	3	5	4	4	4	4	5	5	4	3	5	4	5	5	3	4	4
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40	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	4	4	4	5	4	5	4	5	4	5	4	4	5	4	4	4
41	5	4	5	5	5	5	5	5	3	5	5	5	5	3	5	5	5	5	5	4	4	5	4	4	4	5	5	5	3	5	5	4	5	4	5	4	4	5	5	4
42	4	4	5	4	5	4	5	4	4	4	4	5	5	5	4	5	4	4	5	5	5	4	5	5	5	5	5	4	4	4	4	4	4	4	4	3	5	5	4	5
43	5	5	5	5	5	5	5	5	5	5	5	3	5	5	5	5	5	5	5	5	4	4	4	4	4	4	5	5	5	5	5	5	3	4	4	4	4	4	5	4
44	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	5	5	4	4	4	5	4	5	4	4	4	4
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48	5	5	5	3	5	5	5	5	5	5	5	5	3	5	5	5	5	5	5	5	5	5	4	4	4	5	3	5	4	5	4	5	5	5	4	5	4	4	4	4
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51	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	4	5	5	4	5	5	4	4	4	4	4	4	5	5	4	5
52	4	4	5	4	4	5	4	4	3	5	5	4	4	5	5	4	4	4	5	4	4	3	4	4	5	4	5	5	4	5	4	5	5	4	5	5	5	5	5	4
53	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	5	5	4	5	3	3	4	4	4	4	4	4	4	5	4	4	4
54	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	4	4	5	5	4	4	5	5	5	3	5	5	3	5	5	5	5
55	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	4	5	4	5	5	5	4	4	4	5	5	5	4	3	4	5	4
56	4	4	5	4	4	4	4	4	5	4	4	4	4	4	4	5	4	4	5	4	5	5	5	4	5	4	3	5	5	5	5	5	4	5	5	5	5	5	4	5
57	5	4	4	5	5	4	5	5	4	4	5	4	4	5	4	4	4	5	4	5	5	4	3	4	5	5	3	5	5	4	4	4	3	4	4	4	5	3	5	4
58	4	4	4	4	4	5	4	4	4	4	4	5	4	4	4	4	5	3	4	4	5	5	5	3	5	4	4	4	4	5	5	5	4	5	5	5	4	4	5	5
59	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	4	5	5	5	5	5	5	4	5	5	5	5	5	4	5	5
60	5	5	4	5	5	4	4	5	5	5	4	5	5	4	5	5	4	5	4	5	5	4	4	4	5	4	5	4	5	5	5	3	5	5	5	5	4	5	4	4
61	5	3	5	5	5	5	5	5	4	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5	4	4	4	5	4	5	5

Overall Analysis of Survey Results

Quantitative Analysis

Ideally, responses can be compared to an industry benchmark, a competitor, or even a similar question from a prior survey. In most cases, however, such data do not exist because they are too expensive or too difficult to obtain. Because the questions in this survey were original to this study, there are no historical or comparative data. The following quantitative analyses were performed:

1. **Percentage Agreeing:** The percentage of respondents who indicated “agree” or “strongly agree” (or “frequently” or “always”) on an item.
    a. **Analysis yielded a score of 96.6% for percentage agreeing**

2. **Top box and top two box scoring:** The top box refers to responses of “strongly agree” or “always.” In this case of this data set and analysis, the top two box score is the same as the score reported in result 1 above.
    a. **Analysis yielded a score of 96.6% for Top Two Box**
    b. **Analysis yielded a score of 63.1% for Top-Box**

3. **Net top box:** Found by counting the number of respondents selecting the top choice and subtracting the number who selected the bottom choice.
    a. **Analysis yielded a score of 63.1% for Net Top Box**

4. ***Z*-Score to Percentile Rank:** This converts the raw score into a normal score, because rating scale means often follow a normal or close to normal distribution. Eighty percent of the number of points in a scale is a reasonable benchmark to compare the mean to. For this analysis, 4 is used (5 x .80 = 4). First, subtract the benchmark from the mean. Next, divide the difference by the standard deviation. This is called a *z*-score (or normal score) and shows by how many standard deviations a score falls above or below the benchmark.

Lastly, convert the *z*-score to a percentile rank by using the properties of the normal curve.

   a. **Analysis yielded a score of 86% for *Z*-Score to Percentile Rank**

5. **Coefficient of Variation (CV):** The standard deviation is the most universal way to communicate variability, but it is hard to translate. The CV makes inferring easier by dividing the standard deviation by the mean. Higher values indicate higher variability. The CV is a measure of variability, unlike the first four results which are measures of the central tendency, so it can be used in addition to the other approaches.
   a. **Analysis yielded a score of 12% for Coefficient of Variation**

Based on the results of the general analysis above, it is apparent that the respondents were favorable toward the concepts presented in Chapter 7, indicating a high level of confidence in industry acceptance and utilization (Sauro, 2011).

Qualitative Analysis

In addition to the quantitative analysis above, the respondents were given the opportunity to comment on the survey questions as a means of giving additional context to the confidence judgments made. As shown in the comments presented below, all remarks made during survey administration expressed an appreciation of the concepts, an acknowledgment of the benefits of implementing them, and belief in a strong likelihood of future implementation and industry reception.

- Most respondents indicated that, prior to this survey; they did not make a distinction between human performance and human factors in system or component design. Most found it rather novel to separate the two concepts and provide a design focus on each one separately as comprising separate elements with different emphases.
- All respondents considered it prudent to involve operations personnel in systems design early in the systems engineering process to reduce errors during the operation of new technologies.
- All respondents expressed a high level of interest and support for incorporating human performance TPMs that evaluate the integration of human error reduction tools with the technology necessary to achieve the intended functionality. Most had never thought of incorporating human error reduction techniques into system design in such a way.
- Most respondents commented that it would be practical and worthwhile to begin procedural and training development early in the systems engineering process, but some respondents expressed concern that the development of training modules may be difficult due to the limited amount of detailed information available early in system design. As a result, I provided the clarification that training and enabling objectives could be determined early in design and that specifics would flow from these objectives once further details became available later in the design process. All respondents seemed to be satisfied with this amplification.
- Most respondents agreed that operator attribute determination should be conducted early in system design and that these attributes are cultivated throughout system design to ensure that operators are capable of safety and efficiently operating the system upon deployment. Some respondents indicated that this had been a significant problem in their

past experience, and that needing to get operators up to speed following the system design completion and installation had a significant schedule and cost impact.

- All respondents commented favorably on the idea of establishing a robust Human Performance Improvement process to be utilized during system design and operations. They supported this process not only for the system design period and for those that would operate the system, but also for the staff as a whole and as an improvement of the system design and engineering process. Many respondents commented that assigning severity levels to issues is an effective way to appropriately allocate resources. A few respondents remarked that within the nuclear industry, where raising issues is part of the culture, this process would fit well, but that it may be less effective in other industries where raising issues is not necessarily expected or encouraged.

APPENDIX D: MINOR EVENT STUDY

This appendix is a follow-up to the recommendation made in chapter 8 that the rate of small incidents at nuclear power plants should be investigated. These are incidents that would be rated as level 1 or 2 on the INES. November 2013 was chosen as the reporting date, since this was the most recent month with complete information at the time of this study. The table below illustrates the number of events that occurred on each day. They are divided into those associated with technological advances (TA) and those not associated with TA.

Table 19. Minor Events on Each Day during November 2013

Day of Month (November 2013)	TA	no TA	Total # of Events
1	2	1	3
4	4	1	5
5	1	2	3
6	3	3	6
7	1	3	4
8	4	1	5
12	3	2	5
13	1	0	1
14	1	1	2
15	3	1	4
18	3	2	5
19	4	2	6
20	3	0	3
21	2	1	3
22	1	2	3
25	2	1	3
26	0	0	0
27	2	1	3
29	1	3	4

Sources: NRC.gov and NRC Agencywide Documents Access and Management System.

The data were subjected to a one-tailed *t*-test (Steinberg, 2011) with the assumption that the number of minor events associated with TA would be higher than that not associated with TA. The test was run with both assumptions of equal variance and of unequal variance. The results were as follows:

T-test, equal variance	0.022634
T-test, unequal variance	0.019539

The hypothesis is as follows:

H_1: Technological advances at a nuclear facility that affect how operators interact within the system **do** increase the number of incidents caused by human error.

The null hypothesis is as follows:

H_0: Technological advances at a nuclear facility that affect how operators interact within the system **do not** increase the number of incidents caused by human error.

Conclusions of the Follow-Up Study

The results of the *t*-test mean that the null hypothesis can be rejected at the $p < 0.05$ level (Steinberg, 2011). Therefore, technological advances at nuclear power plants are associated with a higher likelihood of minor incidents at level 1 or 2 on the INES. It should be noted that the results for this section were obtained simply by counting the number of incidents reported and determining if any significant technological advances were installed at these facilities in the three months preceding the incident. The incidents were not screened by type and by whether they would be obviously due to operator error. For example, one of the incidents involved the presence of an alcoholic beverage inside the plant near the operations center. Some would argue that this could have nothing to do with technological changes; others might assert that the additional anxiety created by having to deal with technological changes led to the aberrant behavior. Since the hypothesis is that advances increase the likelihood of incidents occurring, this is probably not an important consideration.

It appears that changes to the technology increase the number of minor incidents at levels 1 or 2 on the INES. However, they do not significantly increase the probability of more severe incidents, i.e., those at Level 3 or higher on the INES.

APPENDIX E: PAPERS

E.1. THE INTERSECTION OF ADVANCING TECHNOLOGY AND HUMAN PERFORMANCE

International Nuclear Safety Journal Review Article

This paper was accepted for publication in the peer-reviewed journal and is undergoing the final editing process.

E.2. IMPACT OF ADVANCING TECHNOLOGY ON NUCLEAR FACILITY OPERATION

International Nuclear Safety Journal Research Article

This paper was accepted for publication in the peer-reviewed journal and is undergoing the final editing process.

E.1 INTERNATIONAL NUCLEAR SAFETY JOURNAL REVIEW ARTICLE

THE INTERSECTION OF ADVANCING TECHNOLOGY AND HUMAN PERFORMANCE

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Note: This paper was accepted for publication and is undergoing the final editing process.

ABSTRACT

Today’s sensory and processing technologies are perceptive and precise. They can discern the environment, solve complicated problems, make assessments and learn from experience. Although, they don’t think the way humans do, they can replicate many human intellectual aptitudes. Throughout the last several decades, companies have implemented advanced technology and increasingly removed the human from many aspects of nuclear operation. There are many advantages to this transition, but, like any system modification, failures inevitably manifest. In the instance of this article, human errors have resulted and have accounted for several accidents at nuclear facilities in the United States due to this transition. The accidents at these facilities due to human error often result in plant shutdowns, unnecessary expenses, and have the capacity to be problematic for people, the facilities, and environments. This article explores the context surrounding the complexity of changing technologies at the nuclear facilities and the potential exacerbation of problems caused by human error when technology advancements concerning operator interaction with control systems are implemented. To understand the complexity surrounding the human interaction with advancing technologies, the concepts of human performance and human factors will be examined and then the impact of these concepts within the framework of advancing technology will be applied to the operation of nuclear facilities. This review will draw attention to the vulnerabilities due to human error at nuclear facilities within the context of continually advancing technology and shed insight on the role human performance and human factors has on system design and the resulting outcome.

Keywords: Human Error, latent error, active error, human performance, human factors, technology advances

1.0 INTRODUCTION

Each time there are significant technological developments promised to assist people, to some degree, failed systems and prototypes inevitably result [1]. When researchers examine the effects that the changes in technology have made, there are often effects which are substantially different from those expected. Individuals using these technologies frequently make performance errors because they must adapt to increasingly complex technology. When this occurs instead of assisting the user, these new technologies may add burdens, which are especially problematic during crucial phases of tasks [2].

The pattern of human performance degradation when novel technologies are introduced has been found to occur in a wide range of endeavors [3]. For example, when there are systems developed for airplane cockpit automation, there can also be an associated decline in the pilot performance; their reaction times and numbers of errors increase. The same is true for virtually all industries including that of nuclear operation. When one contemplates human errors occurring at nuclear facilities, there are, by the nature of the power generation means, a number of unacceptable outcomes [4].

Nuclear facilities represent some of the most complex systems which have ever been designed [5]. Most of these plants also use state-of-the-art technology and continually update their systems. Unfortunately, like any complex system, the systems of nuclear facilities are not immune to failure. This is particularly true with regard to human error. Since these systems are astoundingly complex, any changes made in the technology has the potential to confuse human operators and result in a reduction in performance when they interact with machinery or software [6].

Despite significant research being done on human-machine interface, a wide range of problems still exist [3]. There remains a disparity between the optimism of technology developers and of the realistic operational difficulties as these systems are being introduced. The developers nearly always claim that the new technology will result in performance improvements. However, due to the operational complexities introduced, the technology may actually decrease the performance of those interacting with the system. Unfortunately, more often than not, the complexities are difficult to predict for the design teams.

To understand the complexity surrounding the human interaction with advancing technologies, the concepts of human performance and human factors will be examined and then the impact of these concepts will be applied to the operation of nuclear facilities. This review will draw attention to the vulnerabilities due to human error at nuclear facilities within the context of continually advancing technology and shed insight on the role human performance and human factors has on system design and the resulting outcome.

2.0 HUMAN PERFORMANCE

Human performance is a field of study related to process improvement methodologies to reduce human errors. It is focused on improving performance at the societal, organizational, process, and individual performer levels [7]. In other words, it is a series of behaviors executed to accomplish specific results [8].

Human performance failures inevitably result in human error. Consequently, human error is an unfortunate, but realistic aspect of any engineered system operated by humans. The number of human errors can be minimized and affects caused by human error can be reduced, but human error can never be completely eliminated and must continue to be a design consideration and an anticipation during system operation. Human error manifests in many forms, but the most prevalent and most easily classified categories are active error and latent error. To understand the impact advancing technology has on human error, a review of human behavior models and the human error classifications of active and latent are necessary to frame the problem and chart a course to overcome these challenges.

2.1 HUMAN BEHAVIOR MODELS

In order to understand human performance, there must be a basic understanding of human behavior. An organization of the different types of information processing involved in industrial tasks was developed by Jens Rasmussen of Denmark. This pattern provides a useful framework for identifying the types of errors likely to occur in different operational situations, or within different aspects of the same task where different types of information processing demands on the individual may occur. The classification system is known as the Skill, Rule, Knowledge based approach. The terms skill, rule and knowledge based information processing refer to the degree of conscious control exercised by the individual over his or her activities [9].

In the knowledge-based mode, the task is carried out by the human in an almost totally conscious fashion. This would occur if a beginner (e.g., an operator in training) is performing a task, or if an experienced individual encounters a completely novel situation. In either of these circumstances, substantial mental exertion would have to be asserted to evaluate the condition, and his or her responses would likely be slow. In addition, after each action, the person would need to evaluate its effect prior to taking additional action, which would probably further slow his or her responses to the situation. Knowledge-based performance results in a nominal error rate of 1:2 [9].

In the skill-based mode, efficient performance of well-practiced, mainly physical actions of which practically no conscious reasoning occurs. Skill-based actions are normally commenced by an explicit occurrence, such as the requirement to operate a valve, that may arise from an alarm, a procedure, or an indication from another individual. The well-practiced task of opening the valve will then be executed largely without conscious thought. The skill-based performance mode results in a nominal error rate of 1:1,000 [9].

The last category involves the use of rules. These rules may have been learned as a result of interacting with the plant, through formal training, or by working with experienced process workers. The level of conscious control is midway between that of the knowledge and skill based modes. The rule-based performance mode results in a nominal error rate of 1:100 [9].

Next, it is important to describe and distinguish between slips and mistakes. Slips are defined as errors in which the intention is correct, but a failure occurred when carrying out the activities required. For example, a worker may know that a receptacle needs to be filled but instead fills a similar receptacle nearby. This may occur if the receptacles are poorly labeled, or if the worker is confused with regard to the location of the correct receptacle. Mistakes, by contrast, arise from an incorrect intention, which leads to an incorrect action sequence, although this may be quite consistent with the wrong intention. An example here would be if a worker wrongly assumed that a reaction was endothermic and applied heat, thereby causing overheating. Incorrect intentions may arise from lack of knowledge or an inappropriate diagnosis [10].

Slips can be described as being due to misemployed aptitude because they are examples of the highly skilled, well-practiced activities that are characteristic of the skill-based mode. Mistakes, on the other hand, are largely confined to the rule and knowledge based performance modes.

In the skill-based mode, the individual is able to function very effectively by using pre-programmed sequences of behavior that do not require much conscious control. It is only occasionally needed to check on progress at specific points when operative in this mode. The consequence for this efficiency is that strong habits can take over when attention to checks is diverted by distractions, and when unfamiliar activities are embedded in a familiar context [9].

With regard to mistakes, two separate mechanisms operate. In the rule-based mode, an error of intention can occur if an improper diagnostic rule is utilized. For example, a worker who has considerable experience in shutdown, stagnate power plant chemistry may have learned diagnostic rules which are inappropriate for operational, dynamic, and volatile power plant chemistry. If he or she attempts to apply these rules to evaluate the cause of a continuous process disturbance, a misdiagnosis could result, which could then lead to an inappropriate action. In other situations, there is a tendency to overuse diagnostic rules that have been successful in the past. Such sound rules are usually applied first, even if they are not necessarily appropriate [9].

In the instance of knowledge-based mistakes, other factors are important. Most of these factors result from the substantial demands on the information processing abilities of the individual that are needed when a situation has to be assessed from conditions he or she is unaccustomed too. Given these demands, it is not a surprise that humans do not execute tasks very well in high stress, unfamiliar situations where they are required to “think on their feet” in the absence of rules, routines, and procedures to manage the situation. For example, operators may only utilize information, which is readily available for evaluation of the situation. Operators may also become over-confident in the correctness of their knowledge. A typical behavior that occurs during knowledge-based problem solving is insisting that one course of action is correct where the individual or the operating team become tangled in one aspect of the problem and exclude all other aspects that should be considered (the Three Mile Island accident is a prominent example). The opposite form of behavior is also observed, where the burdened worker gives his attention hastily to one problem after another, without solving any of them [11].

In the skill-based mode, recovery is usually prompt and effective, because the individual will have familiarity with the expected outcome of his or her actions and will therefore get timely feedback with respect to any slips that have occurred which may have prevented this outcome from being reached. This highlights the role of feedback as a significant aspect of error recovery. In the case of mistakes, the mistaken intention tends to be very resistant to non-endorsing evidence. People tend to ignore feedback information that does not support their expectations of the situation [9].

2.2 ACTIVE ERRORS

Simply by the nature of this error type, active errors have effects which are noticed immediately and can occur across the spectrum of human behavior modes. Active errors are usually associated with individuals in frontline operations of a system. Examples include officers of ships, air traffic controllers, pilots, or control room operators in a nuclear facility. When examining active errors, it is important to take into account the complexity associated with human nature [12].

Human nature includes all the emotional, mental, social, biological and physical characteristics which define the limitations, abilities, and tendencies of people [13]. An important aspect of human nature relevant to this study is the innate tendency toward imprecision. While machines tend to be precise, people are usually imprecise. This can be especially true in certain situations. For example, people tend to make more mistakes when they are under time pressures or in stressful situations. Due to the fallibility of people, they can get into situations which are beyond their abilities. Logically, complex systems intensify a person’s susceptibility to make mistakes [14].

2.2.1 CAUSES OF ACTIVE ERRORS

Because active errors are all too common in the realm of human error, the most prevalent causes of active errors should be understood in order to reduce them. One tendency of most individuals is to overestimate their abilities to maintain control at their work station [12]. In this instance, the maintenance of control means that the task occurs as it is supposed to with the person performing in the appropriate fashion. There are at least two reasons that this overestimation occurs. Consequential error is rare and many times an error occurs with no adverse result. This means that people conclude that errors will be caught unless they are inconsequential. The second factor is that people don’t know or acknowledge their own capabilities. For example, most people can function on insufficient sleep or work during times of distraction. They can also perform work duties during poor environmental conditions such as extreme cold, heat, vibration, or noise. People can become accustomed to these conditions. However, if the limits of the person’s capabilities are exceeded, the chance of them making errors increases. There are a number of factors related to human nature, which can be especially problematic when work is being performed within a complex system [13].

One important factor for active errors is stress [15]. Stress is not always a problem. Sometimes it is healthy and normal. Stress can focus attention and can aid an individual’s performance. However, elevated stress can overpower an individual. When this occurs, stress is detrimental to performance. Stress can be understood as the body’s physical and mental response to perceived threats within the environment. The important word in this case is “perceived.” It is the perception of the individual which leads to their adaptation to cope with a threat. Stress tends to increase according to a lack of familiarity with the situation. Extreme stress can lead to panic. This will inhibit the ability of the person to act, sense, recall, and perceive essential elements of a situation. Fear and anxiety often follow when an individual believes he or she is unable to respond appropriately to a situation. Along with this fear and anxiety, there is frequently a lapse of memory. This is frequently followed by an inability to perform certain actions and to think critically [16].

Another factor which is important to consider when looking at active errors is the tendency for people to avoid mental strain [12]. Most people will only reluctantly engage in long periods of concentrated thinking. They also tend to avoid situations in which they must display heightened levels of attention for an extended period of time. Thought can be a slow and laborious process that requires significant effort. Therefore, people often seek familiar patterns and tend to apply solutions with which they are already knowledgeable. This is a type of mental bias, which can be understood as a shortcut. The goal is to reduce the cognitive effort required to decide [16].

One of these mental biases is assumptions [17]. People frequently accept as true certain conditions which are not verified. Another bias is habit. This is an unconscious pattern for their behavior which has been acquired often due to frequent repetition. Confirmation bias can be problematic and is exemplified by a reluctance to abandon solutions which already exist. Individuals will be reluctant to change their way of thinking or behaving. This is true even when there is conflicting information for better solutions [14]. This leads people to support their position and ignore blatant evidence to the contrary. Frequency bias refers to an individual's gamble that a familiar solution will work. It can also lead to people viewing information as more important when it has occurred more frequently. Finally, people often suffer from availability bias. This refers to the tendency for people to use solutions which immediately come to mind. It is also associated with greater importance being placed on facts which are readily available [13]. Limited working memory can be a factor in active errors [18]. A person's mind has a short-term memory which is used to make decisions and solve problems. This short-term memory can be understood as a storeroom which demands attention and is temporary. It is used to recall new information and is actively involved with recall, storage, and learning. When the limits of this memory are exceeded, errors can result [15].

2.3 LATENT ERRORS

With active errors fully expounded, the next tier human error category involving latent errors can be defined with the intent to understand the distinctions and influences they have on active errors, the vulnerabilities that result from them, and a general comprehension of them in order to reduce their occurrence. Like active errors, latent errors may also have adverse consequences, but may lay dormant within a complex system for a significant period of time before they manifest [18]. They often become evident only when they are combined with factors which lead to a breach of the system defenses. Latent errors are frequently committed by individuals whose activities are removed in space and time from the direct human system interface. For example, latent errors may be committed by maintenance personnel, managers, construction workers, high-level decision-makers, or the system designers well before manifestation [18].

An analysis of significant accidents such as Chernobyl or Three-Mile Island found that latent errors frequently pose the most important threat when people interact with a complex system [14]. Traditionally, accident investigations and reliability analyses have concentrated on the direct equipment failures and operator errors [16]. While the operators do make mistakes such as those discussed in the section on active errors, many of the mistakes have an underlying cause connected to a latent error. This error can be exemplified as when an operator of a complex system inherits the mistakes made by the designers or installers [14].

A 21st century understanding of human error in the context of operators interacting with complex systems occurs when an awareness is made that the study of latent failures may be more beneficial than a focus on operator mistakes [14]. Unfortunately, most of the work which has been done on human factors has concentrated on the improvement to the human-machine interface, which, if an error occurs, results in an active error. While this is an important aspect of the study of human error, the latent errors which are inherent within the system have a broader range of possible problems. In other words, the active errors may only be the outcome of problems which are embedded within the system [15].

Latent human error comes into play when an individual's propensity for error is enhanced by the environment they work in and the systems with which they interact. According to James Reason, there are two adverse effects which can result from latent conditions. The first of which is the ability for latent conditions to provoke errors. The second being the impact the conditions have upon the long term health and welfare of the system which created them [19]. These conditions do not have to contribute to the possibility for error immediately. Rather, they can rest hidden within a system, until the correct elements align and cause the latent error to activate and cause an error to manifest [19].

2.3.1 TECHNOLOGICAL ADVANCES AND THE SUSCEPTIBILITY FOR LATENT ERROR

The fairly rapid growth of technological advances across all industries has generated additional focus on latent error [18]. Many of the 21st century complex systems have operators who are remote and removed from the processes which they control. As the systems have become more complex, they can intervene between people and the physical tasks involved. When this technology was initially introduced, operators still employed direct manipulation and sensing of the systems they were operating. They still had the ability to touch and see the system which they controlled. As this technology continued to advance, the remote manipulation of devices and sensing emerged, further removing the human from the process under their charge [12].

The most significant changes in how humans interact with complex systems came about due to the decreased cost of powerful computing [13]. Many system operators are now separated from the process by more than one component of a control system. At a lower level, there is the task interactive system which controls the detailed parts of an operation. There is an intervention between the specialized system and the operators due to the necessity of a human system interface. This involves the control system presenting pieces of information to the operator. However, the interface only allows a prescribed degree of interaction between the person and the remote process. This creates the situation of supervisory control. The person adjusts, monitors, and initiates processes and systems, which are also automatically controlled [15].

However, it is worth noting that the stimuli contained within the environment are impacting these remote operators at all times, and while they may not be in direct proximity to the site, there is still the possibility for errors to occur. Nuclear facilities are often comprised of individuals deemed the best in their field, and those who are the best, unfortunately, may be prone to making the worst mistakes [19]. While the focus may be placed upon these operators, there is an error being made when the systems themselves are not scrutinized for their own propensity to cause errors [19].

The increased computerization of nuclear facilities has led to installations which are progressively complex [14]. This added complexity on an already complex process results in latent errors being more difficult to detect which can lead to increasingly problematic results [18]. For example, in the case of a semi-automated control processes, if an operator would detect that there was a problem they would then begin to take the necessary actions to correct the problem. However, if due to a latent error embedded in the system, the control processes do not respond appropriately to the operator's actions, an event could result [17].

3.0 HUMAN FACTORS

With human behavior and the fundamental human error categories practically understood, systems designers endeavor to incorporate these human considerations into the design of the system and strive to reduce the likelihood of active and latent errors. In the design field of human factors engineering, designers are concerned with designing products, systems, or processes to take proper account of the interaction between them and the people who use them. In substance, it is the study of designing equipment and devices that fit the human body and its cognitive abilities [20]. In other words, it is the study of how human beings function within various work environments as they interact with equipment in the performance of various roles and tasks (at the human-machine interface) [8]. Common human factors considerations include anthropometric factors, human sensory factors, physiological factors, and psychological factors.

As alluded to above, human factors is concerned with the smooth interaction between the people using the technology and the environment within which they are working. When this is considered from the micro-ergonomic level, the focus is on the level of the human and machine [1]. Here the focus is the design of the individual control panels, workstations, the visual displays, and the ergonomically fitted seats upon which the nuclear facility operators spent the majority of the time. Problems which can arise at this level may be due to improperly designed displays and workstations and result from new technology being installed that had not been designed well in ergonomic terms. For example, in a minor incident, an operator reported that the display was too bright and after three hours working at the station, they were unable to clearly see the display. This resulted in the operator not noticing that the plant was operating outside its normal parameters [21].

The building blocks for technological systems of nuclear facilities include the people as well as the engineered components [22]. However, the organization, as well as its structure, can also be important. This is referred to as macro-ergonomics. In the example previously discussed, the operator had reported the problem to their supervisor several times [21]. If this supervisor would have followed up on the complaint of the operator, an incident may have been avoided. Therefore, it is crucial that systems be in place so that operators working with new equipment can alert their supervisor if there are difficulties. With regard to human factors, it is usually only the operators of the facility who can gauge the success of the new system. Often, any problems related to human factors engineering are not evident until a complaint or concern is raised or an incident occurs [22].

It should be recognized that performance and the inherent potential for mishaps of complicated technological systems is usually a function of the human and engineered subsystems [23]. The engineering will include items such as workstation design and the appearance of control boards. The human engineering refers to organizational and personnel systems while many systems failures are traditionally attributed to errors of the operator; this is often an oversimplification [22]. It is estimated that over 70% of all nuclear plant incidents can be attributed to operators. However, this is likely to be an overestimation as it does not take into account that the failure can be attributed to the effect of various factors beyond the control of the operator. For example, response systems that are ineffective, organizational designs that are not adaptable, and unresponsive managerial systems result in many problems which are attributed to operator error. There can also be ineffective training and operational processes that are overly complicated. This is especially problematic when new equipment has been installed [22].

4.0 HUMAN FACTORS IMPACT ON PLANT OPERATION

With an understanding of human performance and human factors, the complexity surrounding the human interaction with advancing technologies can now be appropriately explored. In order to recognize design considerations necessary to combat human error during system design and integration, it is important to first understand human factors impact on plant operation. As one can imagine, the reason for accidents occurring at nuclear facilities due to human error is complicated [2]. Both the human mind and the systems with which it is interacting at these facilities represent high levels of sophistication which can be challenging to understand individually, much less apprehending their amalgamated composite function. However, progress has been made toward determining the root causes of the problems that are likely to arise. A close investigation into the human errors indicates that there are both micro-ergonomic and macro-ergonomic reasons [22]. The accidents are nearly always the result of the way in which the systems operate and how humans interact with them. Many of the errors are an attribute as well as an effect of the complicated operational processes involved. They may also include managerial systems which are not responsive, ineffective training, organizational designs which are not adaptable, response systems which are poorly designed and environmental disturbances of a chronic nature [1].

4.1 COMPLEXITY OF THE SYSTEM INTERFACE AND HUMAN FACTORS IMPACT

The complexity and adaptability of the system interface plays a considerable role on the impact to human factors concerns. The common application of sociotechnical systems illustrates the necessity of thorough system design and full deliberation of human factors considerations during design. These systems also illustrate the intricacy associated with human-machine interface of complex systems.

Sociotechnical systems must often reside in complex contexts to deal with situations that are unexpected and can lead to errors [24]. This means that the behaviors of these systems are deeply interwoven with multiple parameters, which are determined as part of the external environment. An important case of this contextual dependency is the ever-increasing significance of the human-machine interaction. Pervasive applications that are advanced and include multimodal interfaces now have a need to maintain several complex hypotheses regarding the users and the situation in which the system is interacting to be of a practical value. These types of applications must provide behavior that is more flexible than a traditional computerized system. To explain, these systems need to be contextually aware of the situation and knowledgeable of the people with which they are interacting. Specifically, the system must understand the user's plans, goals, capabilities, and identity [25].

When considering the situation of complex human and machine interactions from an engineering perspective, the interaction of the machine and human must be understood as a systemic aspect that has considerable relevance [25]. Furthermore, since the aspectual interweaving of concepts is becoming more intensive with regard to human error modeling, new concepts and terms must be developed. Once the terms and concepts have been fully developed and are understood, the compatibility of the complex interactions occurring in the systems involving both machines and people can be analyzed for performance and errors [26].

Sociotechnical systems will generally reduce the information-processing load using vague concepts [25]. In other words, human experts do not use precise mathematical expressions. Instead, they prefer vague expressions, which have been developed through natural languages. This results in a vagueness that is an important part of the system robustness and safety. This is because the vague specifications can provide the system with the ability to change according to the context and become more robust. Furthermore, the humans interacting with the system often must deal with incomplete specifications. Many times the complete situation relevant information cannot be accessed by the human. As a result of situational time pressures, the person must make decisions which are uncertain and may be based on incomplete information [24].

An important aspect of sociotechnical systems is their level of structural dynamism [26]. The internal structure of these systems must often rapidly change from one phase of operation to another to meet environmental demands. For the structural dynamism to be properly described, ideas related to active architectures must be used. Transformation rules prove crucial for dealing with these system necessities [24].

The specification of the transformation rules defines the possible configurations that may be involved with the changing conditions within the context of operation [26]. Therefore, the transformation rules serve to describe the adaptive behaviors of these complex sociotechnical systems. They specify the way in which the systems can react to environmental changes through the use of structural mutations [26].

The sociotechnical systems have distinct qualities with regard to their adaptive potentials [25]. This means that their ability to maintain stability during adverse environmental conditions or events, which are unexpected, is larger than that of the behavior of more traditional systems, which are component-based. This also means that a richer understanding of an activity of the sociotechnical processes is likely to contribute to a more robust and flexible system [24].

As can be gathered from the description of sociotechnical systems, complexity resides at all levels of design and operation and requires thorough, detailed design attention to combat human error.

5.0 HUMAN ERROR REDUCTION IN PLANT OPERATION

Reducing the negative impact of technological advances on human error consists of improving human performance [23]. This type of performance improvement is a systematic process. The process is used to analyze and discover performance gaps, monitor performance, determine the desired level of performance, and develop effective interventions. Once the interventions have been developed, they must be implemented and continually evaluated with regard to their results. The ultimate goal for human performance is to have the nuclear facility be as close to event free as possible. This can be achieved by proactive management of human performance. It is also necessary to strengthen the facility defenses as well as the performance of the operators. Once the organization and processes are optimized, the errors can be reduced to a minimal level [1].

It should be remembered that even the best operators of nuclear facilities who are well trained and motivated will still make mistakes [27]. There is no amount of training or coaching which can prevent all errors. It is important for the managers as well as the operators at the facility to understand that the organization, workplace, and tasks interact with the operator to provide a potential for errors. The first step in preventing further problems is to understand why and how they occur [28].

The systemic errors at a nuclear facility can be reduced through using self-checks and specific tools [1]. Human errors can never be eliminated, but they can be reduced. For example, a maintenance professional at the facility may tighten a valve. No matter how well trained the individual is there is always a chance that a mistake will be made when this task is performed. The valve may be too tight or not tight enough [23]. The question is why the individual has made the mistake and what can be done to prevent future occurrences. After a mistake is made, there should be multiple barriers that prevent system failure. This serves to minimize ultimate consequences of any state. There will always be the chance that human error can occur. It is essential that there be organizational infrastructure in place which both identifies errors and protects the operators from negative consequences. This creates a situation in which more significant problems can be avoided [21].

While it is inevitable that people working at nuclear facilities will make errors, there are measures that can be taken to manage, predict, and prevent these errors [27]. One beneficial approach to human error reduction is to recognize the error traps and communicate them to others in order to proactively manage problem situations and minimize errors [2]. The work environment can be changed in order to lower, prevent, or remove conditions which lead to errors. Individual factors and tasks can be altered within the work environment in order to minimize future errors [28].

It is important to understand that the organizational values and processes significantly influence the behavior of an individual working at a nuclear facility [21]. The values and processes of the organization can be developed in a manner that fosters individuals taking actions which increase the chance for achieving the organizational goals. In the case of a nuclear facility, the values of the organization may focus on precision, accountability, and excellence for all employees of the facility [27]. This would encourage safe behaviors that decrease the number and severity of errors. The management of the facility can direct the behavior of workers and produce results that are more desirable and contain fewer errors. These improvements are achieved through increasing the performance of the staff. They also require excellence with regard to management systems, culture, and organizational processes. It is the societal factors involved with the work at a nuclear facility that can significantly decrease the chance of errors [28].

The improvements in human performance can be achieved through taking corrective actions after analyzing problem reports and events [23]. These types of corrective actions are a reactive method for learning that occurs after a problem. Nevertheless, they are important for improving the systems and technology involved. This is the reason that continual improvements and changes in technology are inevitable. Combining the reactive and proactive methods of learning allows for the anticipation of problematic events and the prevention of errors. This is often more cost-effective than only using the reactive approach [1].

It is the collective behaviors of the people at all levels in the facility that determine the performance outcome achieved [23]. The individual work is a product of the mental processes of the person that has been influenced through a variety of factors and demands which are present in the work environment. The work is also a function of the capabilities of each of the people involved. When the facility achieves high performance, the individuals will nearly always be taking responsibility for their own behaviors [27]. They will also be committed to making improvements to themselves as well as the work environment and tasks. Individuals working in a high-performance facility will exhibit certain behaviors. These behaviors include improving their personal capabilities, confirming the integrity of the facility defenses, anticipating situations that are likely to precipitate errors, and communicating with others in order to create a shared understanding of the facility and work to be done [21].

6.0 CONCLUSION

Since the nuclear industries founding, advancing technology has driven development and innovation to make nuclear power safe, secure, and reliable. Today’s advancing technologies have shaped the dynamics of the industry. These technologies can discern the environment, solve complicated problems, make assessments, and learn from experience. Although, they do not think the way humans do, they can replicate many human intellectual aptitudes. Although technological advances are beneficial in many respects, there should be a continuous striving for a balance between advancing technologies integrated into plants and the interaction humans have with these new technologies. New technologies should be designed and incorporated into existing systems to keep the human operator in the decision cycle, which consists of an ongoing process of action, feedback, and judgment. This will ensure operators remain attentive and engaged and promotes the kind of challenging practice that strengthens skills. Technology should play an essential, but secondary role. It should assume functions that a human operator has already surmounted, broadcast warnings when parameters are exceeded, provide vital information that enhances the operator's outlook and opposes the biases that often alter human thinking. The technology will then become the operator's partner, not the operator's replacement. This approach to technology application will not stifle technological progression. It only requires a shift in priorities and a rekindled emphasis on human strengths and weaknesses.

Incorporating advances in technology is a wonderful and necessary enterprise, but must be properly balanced within the confines of the system. It is often forgotten that humans are a vital part of this system. Technology is strongly suited to perform many functions, but it lacks in the ability to rationalize. Decisions concerning incorporating new technology into a plant must consider the human. Even the smartest software lacks the common sense, ingenuity, and vitality of the skilled operator. In the control room, human experts remain indispensable. Human insight, imagination and perception, enhanced through hard work and experience, cannot be replicated by the most cutting-edge technologies. If we let our own skills fade by relying too much on the technology crutch, we are going to render ourselves less capable, less resilient and more submissive to our machines.

Being cognizant of these realities is imperative during system design. The human, including the human's propensity for error, should be considered a vital element of the system that requires substantial design consideration. Engaged human participation is compulsory to successful system operation, but like all systems, has its failure modes. The human's natural susceptibility for error in system operation needs to be combated from multiple fronts.

It has been expressed multiple times throughout this paper that human error cannot be entirely prevented, but with proper tools and techniques, it can be reasonably minimized. With this in mind, it is important to establish a system to minimize error impact or potential impact regardless of the scale and complexity of operation. Based upon the work of Reason and Rasmussen, it can be seen that human models of behavior and their understanding are critical to the study of human performance systems. While errors and incidents are unavoidable, especially within the environment of a nuclear facility, there are ways to minimize these errors. Errors are going to be made, but the minimization of these errors is reliant upon a system which understands human behavior, and accommodates it, rather than attempting to compensate for errors after the fact.

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E.2 INTERNATIONAL NUCLEAR SAFETY JOURNAL RESEARCH ARTICLE

IMPACT OF ADVANCING TECHNOLOGY ON NUCLEAR FACILITY OPERATION

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Note: This paper was accepted for publication and is undergoing the final editing process.

ABSTRACT

Many unfortunate and unintended adverse industrial incidents occur across the United States each year, and the nuclear industry is no exception. Depending on the severity, these incidents can be problematic for people, the facilities, and surrounding environments. These incidents occur for a number of varying reasons, but more often than not, human error is an accomplice. This article explores whether the complexity and changing technologies which affect the way operators interact within the systems of the nuclear facilities exacerbate the severity of incidents caused by human error. A review of nuclear incidents in the United States from 1955 through 2010 reaching Level 3 or higher on the INES scale was conducted. The cost of each incident at facilities that had recently undergone technological changes affecting plant operator’s jobs were compared to those facilities which had not undergone changes. A t-test was applied and determined a statistically significant difference between the two groups. This affirmed that technological advances at nuclear facilities that affect how operators interact within the plant system increase the severity of resulting incidents. Next, a follow-on study was conducted to determine the impact from the incorporation of new technologies into nuclear facilities. The data indicated that spending more money on upgrades increased the capacity of the facility as well as the number of incidents reported, but the incident severity was minor.

Keywords: *Human Error, Human Performance, Nuclear Operation, Technology Advances, IAEA, INES, NRC*

1.0 INTRODUCTION

The operational life of nuclear reactors is measured in reactor-years [1]. One reactor year is equivalent to a reactor operating for one complete year. There are roughly 440 nuclear power plants that have been in operation for over 14,700 reactor-years. During this time, there have been 23 reactor core meltdowns. This is equivalent to one major nuclear accident for every 640 reactor years. However, according to the international design requirements for nuclear facilities, a reactor core meltdown should only occur about once every 20,000 reactor years. This means that the incidence of reactor core meltdowns is been 32 times higher than theory would predict [2]. This significant departure from the theory indicates additional unaccounted factors are violating the base assumption of the model.

Nuclear facilities represent some of the most complex systems which have ever been designed [1]. These plants use state-of-the-art technology and continually update their systems to remain safe, regulatory compliant, and economically sound. Unfortunately, like any complex system, the nuclear facilities are not immune to failure. This is particularly true with regard to human performance. As one can presume, many of these incidents have been the result of human error in one form or another. Since these systems are astoundingly complex, any changes made in the technology has the potential to confuse human operators and result in a reduction in performance when they interact with machinery or software [2]. The complexity and changing technology of the intricate systems involved with the operation and management of a nuclear facility may be part of the problem resulting in increased severity of human errors [1].

Of the 23 nuclear reactor meltdowns mentioned above, 17 were caused by some type of human error [3]. While it has been argued that this is difficult, if not impossible, to accurately predict, human error will endure necessitating relentless attention and continuous opposition. This being the case, there has been a great deal of literature devoted to the safety procedures used by nuclear facilities [2]. There has also been research performed explaining the effect that new technologies can have on human performance, especially when complex systems are involved. This leads to the question of whether the complexity and changing technologies of the nuclear facilities may exacerbate the severity of incidents caused by human error. This is an important question because most nuclear facilities continually update their system technology. This continuous technological improvement can create a situation where the operators must change their routine and method of interacting with the system.

2.0 RESEARCH METHODS

2.1 RESEARCH DESIGN

The research design used in this investigation is that of an observational study [4]. In the case of this research, the nuclear facilities are grouped into those which have had accidents and those which have not [5]. The facilities that had accidents are considered the treatment group, while the incident-free nuclear facilities are the control group. The variable affecting these plants, the treatment, is advances in technology. While the groups are categorized into those that have had incidents versus those which have not, the treatment variable is not categorical. Instead, it can be considered as existing on an interval scale [6].

2.2 METHODS

The International Nuclear Event Scale (INES) was used to determine if an event at a nuclear facility reaches a significance level that is noteworthy for this study. The INES has eight levels ranging from zero to seven (see figure 1). The International Atomic Energy Agency (IAEA) adopted the INES as a method for quickly and efficiently communicating the safety significance of incidents occurring at nuclear facilities. Because nuclear facilities are man-made, unique, and vastly different in design, the incidents that result are subject to certain interpretations when estimating the magnitude of the problem [5].

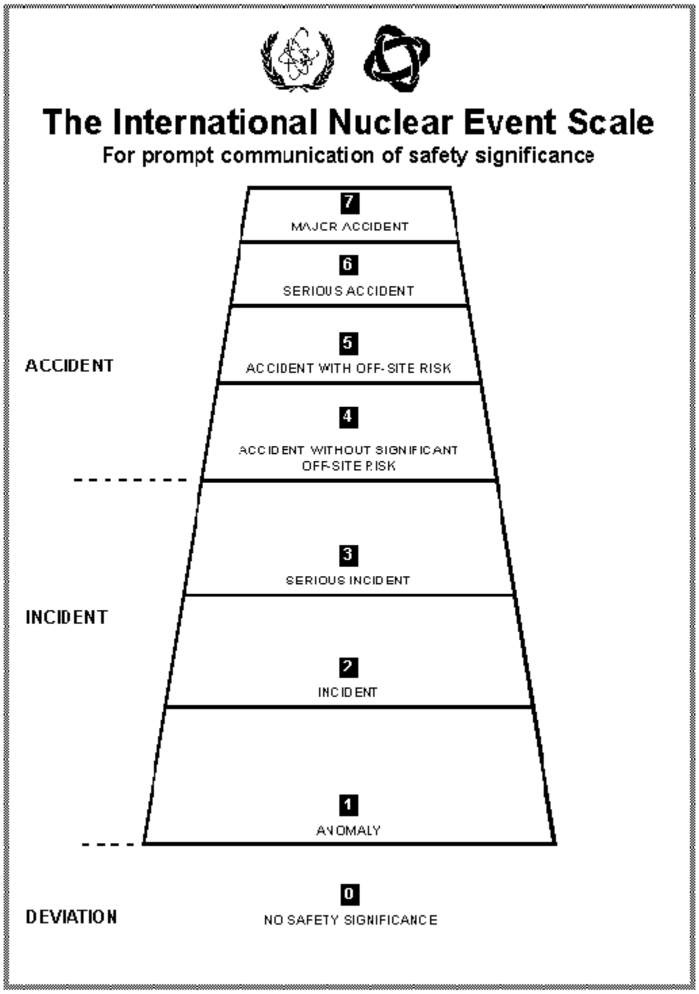

Figure 1 – INES Scale [7]

2.3 MATERIALS AND INSTRUMENTS

The IAEA and the U.S. Nuclear Regulatory Commission (NRC) both record events which they have been reported and investigated [8]. However, possibly due to the diverse nature of their cultures, their policies, and their laws, the IAEA data is not as complete or detailed as that of the NRC. The NRC uses a nuclear event scale that is similar to that of the INES and is transferred to the international scale for reporting purposes. While the NRC is responsible for nuclear safety in the United States, it cooperates with the IAEA and converts its events to the INES [5]. This is also true of the predecessor nuclear regulatory agencies of the US. This study used the event notification reports of the NRC and predecessor US regulatory agencies prior to the formation of the NRC [5]. This provided an opportunity to use a standardized level system to judge the severity of the nuclear event while taking advantage of the more detailed reports of the NRC. The information on incidents of INES severity level 3 or higher was collected and data from the plant where the incident occurred was gathered to determine if technological advances impacted the operators at the facility to cause the incident.

Incidents that reached the INES severity level 3 and above criteria were utilized in this study for three reasons. The first and most important reason is that any incident that does not reach the level 3 criteria was unlikely to cause a person to be permanently injured. It is improbable that radioactive material released at this level of an incident would even temporarily harm an individual, though this is possible. The second reason is related to the number of incidents. As one decreases the incident level, the occurrences increase exponentially. Therefore, using incidents that are below level 3 would yield an overwhelming amount of data. This is due to the thorough daily reporting criteria of the NRC. In fact, most days contain multiple reports, which are below the level 3 threshold. The third reason is that different countries require the reporting of a level 0 and level 1 incident in an inconsistent manner and it that it has been determined that there are varying levels of reliability with the interpretation and reporting of level 2 incidents. Therefore, these minor instances were not used for this study [9].

2.4 DATA COLLECTION, PROCESSING, AND ANALYSIS

The data collection for this study began with an examination of the event notification reports provided by the NRC and predecessor regulatory agencies. The researcher noted which events had an INES severity level of 3 or higher. This was done for the years 1999 to 2010. For information on events that occurred prior to 1999, the information on the incidents was taken from books addressing the topic. After the incidents with INES severity level of 3 or higher were identified, additional information was sought regarding technological changes that may have occurred in the plant. The events were then sorted according to those that followed no technological changes and those which followed technological changes. Only the technological changes that affect how the personnel of the facility interact with the systems were considered. For example, if there were changes in the speed with which information is passed between computers, but this is not likely to be something that a human operator would be aware of, this would not be a consideration for this study. However, if the change in the speed with which information is passed between the computers modifies the way in which the operators interact within the system, then this would be a consideration. An attempt to reduce bias in this aspect of the study was made through recruiting colleagues of the researcher to rank the technological changes that have occurred at the plants with incidents. If there were occurrences that were different from group consistency, they were not used for the study. This decreased the likelihood that the researcher could inadvertently influence the outcome of the study by selectively placing incidents into the three groups of technological change.

Because the INES is a logarithmic scale, each of the levels is roughly 10 times as severe as the previous one. This means that an accident with local consequences having an INES level of four will be about 1000 times as problematic as an anomaly having an INES level of one. The statistical analysis on the data made use of a t-test. This type of analysis is sensitive to the type of data used. If the INES level was used as a measure for the problem created by an accident, the accuracy of analysis would be impaired due to the logarithmic nature of the number. Therefore, an alternative numeric measure, the cost of the incident, was used to determine incident severity and maintain the integrity of the t-test [4]. The cost of the incident in terms of US dollars was used since the reports from incidents in the US already indicated the cost estimation. They only needed to be normalized to a specific year for consistency in accounting for inflation. This is an appropriate type of data for conducting a t-test [10].

The specific statistical test chosen to determine if a significant difference between the two groups existed (incidents caused by human error as a result of technological advances vs. incidents caused by human error *not* due to technological advances) was an independent samples t-test. An independent samples t-test determines if two independent groups are different from each other and if the two groups are not related. Before conducting the test, since the t-test is a parametric test and requires normally distributed data, the outcome variable, costs of incidents, was checked for normality and homoscedasticity of variance by examining the distribution of the data using histograms and Q-Q plots. After normality was established, the independent samples t-test was conducted.

3.0 RESULTS AND DISCUSSION

3.1 DATA ANALYSIS

From 1955 to 2010, 53 incidents were determined to meet the INES Level 3 and above criteria and had an average incident cost of $190,518,900 (SD = 461,511,400). 31 of the 53 were determined *not* to be due to human error as a result of technological advances whereas 22 of the incidents were determined to be due to human error as a result of technological advances. Of the 31 that were determined *not* to be due to human error as a result of technological advances, the cost of the incidents ranged from $1,000,000 to $695,000,000. The average cost of these incidents was $54,274,200 (SD = 142,559,800). The other 22 incidents were determined to be due to human error as a result of technological advances. The cost of these incidents ranged from $2,000,000 to $2,483,000,000. The average cost of these incidents was $382,500,000 (SD = 657,543,610). See Table 1.

Table 1 – Category Incident and Average Cost

Category of Incident	Mean	SD	Median
No Human error as a result of Technological Advances (n =31)	$54,274,200	$142,559,800	$9,500,000
Human Erroras a result of Technological Advances (n=22)	$382,500,000	$657,543,610	$61,500,000

** All of the monetary values were adjusted to 2005 dollar values.*

As discussed previously, to examine whether incidents *not* caused by human error as a result of technological advances cost more than incidents caused by human error as a result of technological advances at nuclear facilities, the independent samples t-test was conducted to examine the average cost differences of incidents between those two groups. To test the first assumption of the t-test, normality of data, the Kolmogorov-Smirnov test was used to compare the scores in the sample to a normally distributed set of scores. The Kolmogorov-Smirnov test was significant ($p < .001$), the distribution of scores of this sample is significantly different from a normal distribution of scores, and thus, the first assumption of the t-test was violated.

A Q-Q plot of the scores also indicates that the data is not normally distributed (see figure 2). A histogram (see figure 3) reveals that the data is positively skewed. Thus, the data was log-transformed, making the skewed data more normally distributed (see figures 4 and 5). A Q-Q plot is a form of scatterplot created by plotting two sets of quantiles against one another to assess normality of the data. Quantiles are not the same as the actual observations and different ranges of values can be presented compared with histograms. When the data contains extreme values, as is the case in this study, these may not be rendered in the graph as seen in the histogram (as displayed in figures 4 and 5). Thus, it is not expected to have the exact ranges of values between histograms and Q-Q plots since they plot different factors: quantiles for Q-Q plots and actual values for histograms.

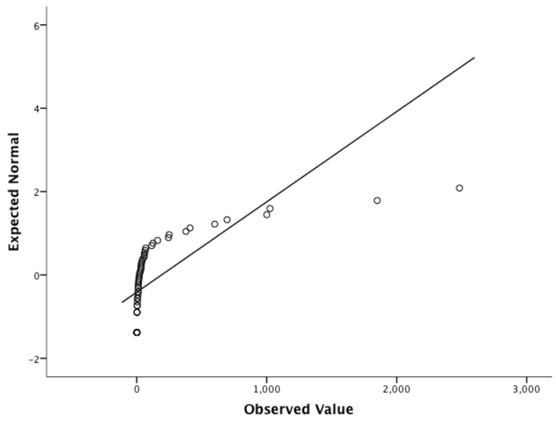

Figure 2 – Q-Q Plot of Cost

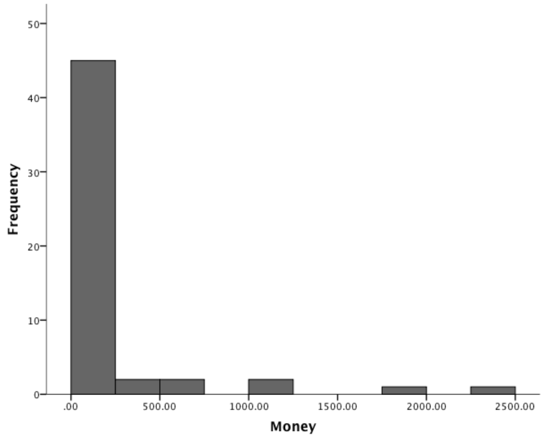

Figure 3 – Histogram of Cost

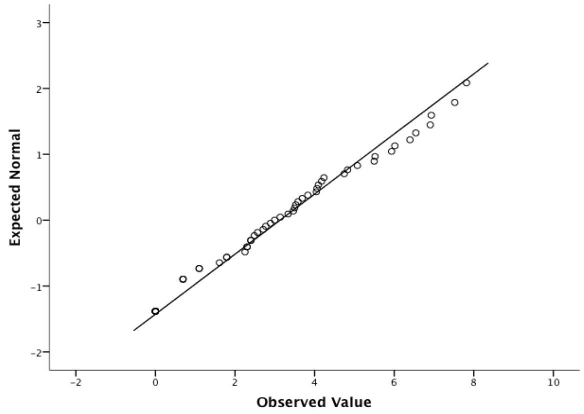

Figure 4 – Q-Q Plot of Log-Transformed Cost

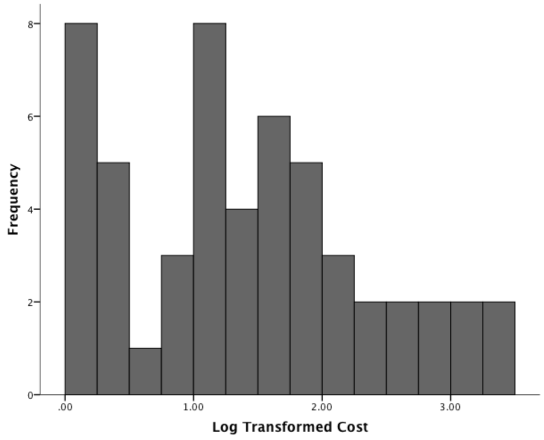

Figure 5 – Histogram of Cost (Log Transformed)

Now, using the log-transformed data, an independent samples t-test was conducted. Once again, normality of data was checked using the Kolmogorov-Smirnov test. The test was non-significant ($p = .200$), indicating that the distribution of the log-transformed cost scores are not significantly different than a normal distribution. To test the second assumption of the t-test, homogeneity of variance, the t-test was conducted and Levene's test was used to see if the variances of the groups are equal or unequal. Levene's test was non-significant ($p = .953$) and so it can be assumed that the variances are equal and the assumption was not violated. On average, the log-transformed costs of incidents due to technological advances were lower ($M = .92$, $SD = .81$) than the log-transformed costs of incidents caused by human error (M= 1.99, SD = .78), and this difference was significant, $t(51) = -4.81$, $p <.001$, one-tailed. The difference between the log-transformed means of cost between the two groups represent a large-sized effect, $d = 1.34$. Thus, incidents caused by human error as a result of technological advances, even though there are fewer, are more costly than incidents not caused by human error as a result of technological advances. Based on this analysis, there is evidence that technological advances at a nuclear facility which affect the way operators interact within the system does increase the severity of incidents caused by human error.

3.2 THE ECONOMIC AND SAFETY FACTORS INVOLVED WITH TECHNOLOGICAL IMPROVEMENTS

If there is evidence that incorporation of advanced technologies in nuclear facilities increases the severity of incidents caused by human error, then why incorporate advanced technologies into existing nuclear facilities? Many organizations find technological advancements necessary for three applications: replacing obsolete technology or equipment, regulatory reasons, and economic motives. Therefore, the outcome of technological advancement can be observed as two pronged: from a safety standpoint and from an economic standpoint. The question now becomes, are organizations better off from incorporating advanced technology at their facilities?

In order to determine the economic and safety factors involved with technological improvements, the information for 12 nuclear facilities for the 2008 through 2013 years was collected. For the aspect of safety, the number of reported incidents was used as an independent variable. For the economic aspect, the capacity factor, ratio of the observed output for a given period of time versus the potential output if the facility were consistently running at its nameplate capacity, was used as the independent variable. The cost of the upgrades was used as the dependent variable. An analysis of variance (ANOVA) and a regression analysis were performed on the data. The ANOVA was used to indicate the significance of the results. The regression equation indicates how much, and in what way, the upgrades affected the capacity and number of reported incidents [11]. Results are displayed in tables 2-4 below.

Table 2 – Regression Statistics

Regression Statistics	
Multiple R	0.926410175
R Square	0.858235811
Adjusted R Square	0.854126705
Standard Error	2.717930638
Observations	72

Table 3 – Analysis of Variance Data

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3085.7869	1542.89343	208.861884	5.35853E-30
Residual	69	509.71314	7.38714695		
Total	71	3595.5			

Table 4 – Regression Statistical Data

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-32.835	4.137640	-7.9357	2.6E-11	-41.089	-24.581	-41.089	-24.581
Capacity Factor	0.59165	0.051067	11.586	7.6E-18	0.48976 9	0.69352	0.48977	0.693522
Incidents	0.07526	0.017708	4.250	6.6E-05	0.03994	0.11059	0.03994	0.110593

There were 12 facilities in the sample and the information was collected over 6 years. This yielded 72 data points for the ANOVA. The F-test yielded an F statistic of 208.86. This is significant at the p <0.01 level. The regression analysis indicated that the regression coefficient for capacity factor was 0.592. The coefficient for incidents was 0.075. Both of these coefficients indicate that increased levels of upgrades will result in a higher capacity factor for the facility [6]. However, the number of incidents will also increase. The relationship of these factors is shown in the figures 6 and 7 below:

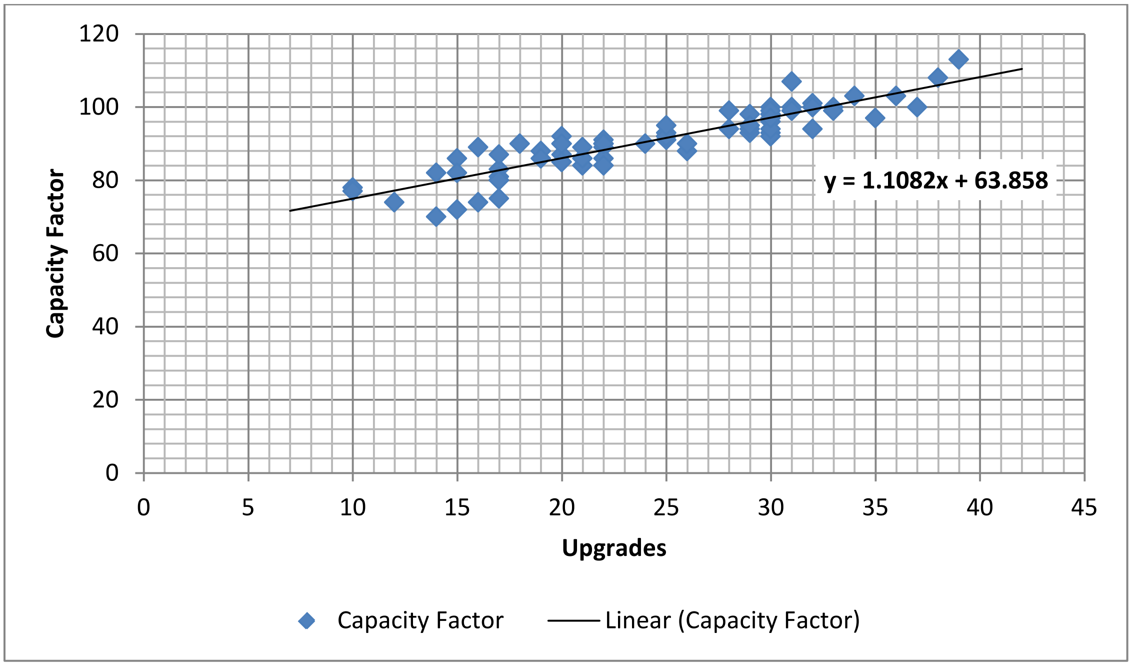

Figure 6 – Upgrades versus Capacity Factor

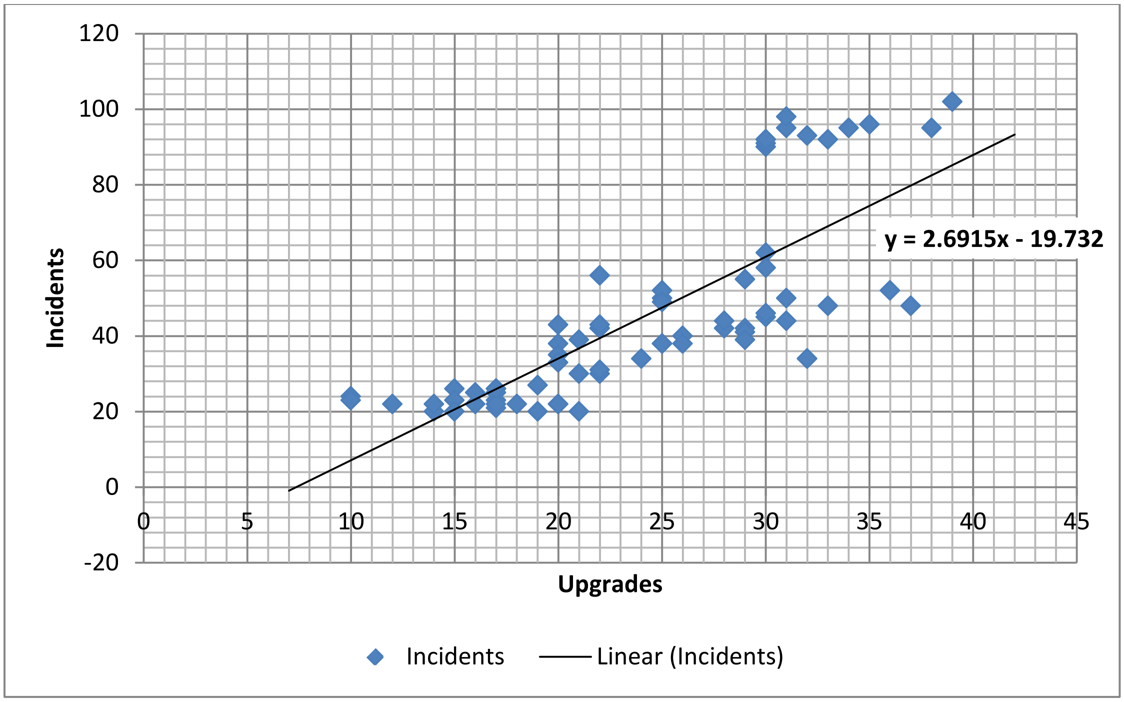

Figure 7 – Upgrades versus Incidents

An examination of figures 6 and 7, as well as a consideration of the regression coefficients reveals that increasing the level of upgrades is associated with a higher capacity factor and more incidents being reported. The capacity factor would generally be seen as a positive outcome, while the increased number of incidents would be negative.

The number of incidents was recorded as a way of measuring the safety associated with the upgrades. As the amount of money spent on upgrades increased, the number of incidents rose as well. However, these were only incidents which were at a INES severity level of 1 or 2. None of the 12 facilities randomly chosen this specific analysis had a major incident during the 6 years of the data being collected.

The data indicates that spending more money on upgrades will increase the capacity of the facility as well as the number of incidents reported. However, the incidents in the randomly selected facilities for this study over the 6-year period of time were relatively minor. Given that the nuclear facilities produce vast amounts of power, and the upgrades significantly increase the capacity factor, there appears to be a financial advantage in conducting upgrades however, this should be weighed against the increased rate of INES severity level 1 and 2 incidents observed. It should also be remembered that many of the major incidents at an INES severity level 3 or higher, were probably associated with human error while working with new technological advances. Since it does not seem likely that nuclear facilities can be fully automated anytime in the near future, engineers must continue to increase facility capacity factors with upgrades while minimizing human errors.

4.0 CONCLUSION

As discussed previously, over the years there have been numerous costly incidents at nuclear facilities in the United States [12]. In nearly every incident, the cause has been isolated and steps have been taken to alleviate problems and prevent future incidents. However, there are thousands of upgrades to various pieces of equipment over the lifetime of a nuclear facility. Since changing the technology associated with nuclear facilities is an ongoing and necessary process, based on the information and analysis presented in this article, there is evidence that technological advances at a nuclear facility which affect the way operators interact within the system does increase the severity of incidents caused by human error. Additionally, the economic impact of incorporating advanced technologies into facilities is advantageous to offset the risk. This situation creates the necessity to continually optimize operator performance and investigate new methods or enhance existing methods to reduce human error resulting in a decreased number of incidents or reduced incident severity.

Unfortunately, human error reduction and system design and deployment are often treated as two separate subjects with their own distinct processes that commonly intersect upon conclusion of design, prior to operation. This traditional approach to system design may have been successful for the antiquated, obsolete technologies of the past, but is proving to be problematic for the design of the more complicated systems of the present. As the complexity of advancing technologies crescendos, human-system interaction warrants a more prominent role in system design and therefore compels early consideration, deliberation, and integration in the beginning stages of the systems engineering process. Incorporation of human error prevention means into the system design process harvests the sound development of systems with an improved probability of successful, error-reduced operation.

Whether a system is being newly created or an existing system is undergoing a minor modification, plant operations personnel should to be involved in the design process from the onset. Operators are a significant system stakeholder and not only bring a unique yet vital perspective to the design team, but will eventually inherit the system being designed. Operators bring an essential perspective from the field, understanding the environment the system will operate in, the operator interface the system will undergo, and the robustness and redundancy the system will need to possess to successfully operate as required.

Achieving balance of innovation and practicality often yields difficulty, as designs are conceptualized, iterated, and deployed. The resulting product often requires a return to portions of the design stages for necessary alterations. In most cases, some of this duplication of effort can be avoided by simply appointing members of the operations staff to the system design team and leveraging their experience into the needs identification through system design and development for the system life-cycle.

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