Human-System Interface Complexity and Opacity Part I: Literature Review

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HAL2010-01

March 2010

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ABSTRACT

The nuclear power community in the United States is moving to modernize aging power plant control rooms as well as develop control rooms for new reactors. New generation control rooms, along with modernized control rooms, will rely more heavily on automation and computerized procedures. Of particular importance to the Nuclear Regulatory Commission (NRC) is the impact such modernizations or new technologies will have upon operator performance and reliability in these safety-critical control room environments. One specific area of interest is the effect that various complexities in the control room have on operator performance and reliability. This report identifies various definitions of complexity and characterizes complexity in the nuclear power plant (NPP) domain, focusing on the common complexity dimensions of number, variety, and interconnections. Based on this characterization of complexity, a comprehensive list of complexity sources within the NPP control room is presented, along with a novel approach to describe complexity source interconnections. Understanding the sources of complexity in advanced NPP control rooms and their effects on human reliability is critical for ensuring high and safe performance of both operators and the entire system. Without proper management, information representation and required operator-system interaction could exceed operator information processing capabilities. This report provides an initial step in assessing the sources of complexity in the NPP control rooms and introduces a systems-theoretic descriptive model of these sources of complexity leveraging network theory.

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Part I: Literature Review of HSI Complexity and Opacity

INTRODUCTION

Understanding complexity in a complex socio-technical system like Nuclear Power Plants (NPP) has been the overarching goal of different scientific disciplines. Although several rich interpretations of complexity in different disciplines have been offered, it is still unclear what exactly makes a system "complex" and how this complexity could be measured. Rosen (1977) claims that different perspectives on the topic of complexity tend to be as richly varied as complexity itself. This is, in part, due to oversimplification of scientific or philosophical explanations of real world phenomena or the so called "complexity science" (Dent, 1999). The complexity science approach to understanding complexity could be categorized as computational which suggests that complexity science researchers are more interested in finding the objective complexity as the inherent property of systems. This approach might be problematic, since humans perceive complexity differently. Therefore, understanding the way humans process perceived information seems vital, especially for systems in which safety is considered a critical objective in system operations. Moreover, modeling complexity as a quantitative attribute means that rich and critical information is lost that could be used to develop interventions to mitigate systems complexity. Underestimating complexity in terms of human factors in designing NPP systems may result in catastrophic events. The most notable event, in the context of NPPs, is the Three Mile Island (TMI) incident.

The nuclear power industry in United States has declined in terms of growth after the TMI incident in 1979 (Campbell, 1988). In order to increase efficiency and enhance safety, the nuclear community in United States is now at a stage where existing NPP control rooms are undergoing extensive modernization. Modernization in other supervisory control domains, such as air traffic control and cockpit design, shows an increasing trend in the adoption of advanced display technologies, such as digital displays.

Although advanced technologies may enable a more efficient working environment and provide more functionality, they may introduce additional complexity to the NPP operations in general. Investigating the effects of control room modernization is important since personnel in such environments must deal with increasing amounts of advanced technologies, such as large screen and multiple displays. Unfortunately the literature in the fields of Human-Computer Interaction (HCI) and Human Factors (HF) lacks a clear prescription of ‘how’ and ‘what’ information should be visualized in these new displays. Modern and computerized control rooms of the future may challenge human operators’ cognitive abilities by presenting information in complex ways. Without proper understanding and management of the sources of complexity in these control room environments, such sources of complexities may degrade human performance. It is vital to understand the effects of complexity that exist in the NPP control room which negatively impact human performance, as human errors are not affordable in the NPP operations due to the safety-critical nature of such operations.

This report investigates important sources of complexity in the NPP control environment and their impact on human performance. Interconnections between sources are reviewed to further the understanding of the overall complexity of the NPP systems. In addition, different categorizations of complexity are introduced, with the goal of isolating important aspects of complexity.

Background

This research is part of the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) project to promote research in the area of Human Factors in Nuclear Reactors. The post-TMI era saw a decline in the development of new nuclear reactors in the United States. After almost 30 years since the TMI incident, the nuclear community in the US is at a stage where the need for more advanced and modern reactors is apparent. In addition, the U.S. government has committed to building 6-10 new nuclear reactors in the next few years (Schmidt, 2010), so it is critical that new reactor control rooms are designed and built with the cognitive needs of operators at the forefront. These new and advanced reactors will have different tools with different functionality. As a result, it is vital to provide the NRC staff with a technical basis to understand the negative human performance effects of such changes and enable them to assess the acceptability of new designs in terms of safety.

One of the most important research topics identified both by previous NRC research (NUREG/CR-6947) and the Organization for Economic Cooperation and Development Work Group of Human and Organizational Factors (WGHOF), is "Human-System-Interface (HSI) complexity and opacity". These efforts identified the need for further investigation of the limitations of human cognitive abilities and information overload and in particular understanding the sources of complexity as an essential factor in predicting human reliability in HSI of NPP control rooms. Although research in other similar domains such as aviation (e.g. Xing, 2004; Cummings & Tsonis, 2006) shed some light on possible sources of display complexity, the exact nature of these sources in the NPP domain needs further investigation.

Research Objectives

The overall objective of this research is to identify factors that contribute to the complexity in new and advanced nuclear power plant systems and Human-System Interactions (HSI). More specifically, a main objective of this report is to discuss the sources of complexity as perceived by operators. The addition of new computerized systems to the NPP operations environment may have negative effects on human performance due to added complexity. This report could be used to facilitate NRC's human factors engineering reviewers in their safety and licensing activities for new and advanced control rooms by providing a technical basis to understand the nature of complexity in the NPP control rooms.

Document Organization

This document is organized into three main sections. In the first section, the methodology used to create a technical basis for complexity in NPP control rooms is described. The second section introduces several definitions of complexity and discusses different categorizations of complexity relative to the context of NPP control rooms based on an extensive literature review of different disciplines. Next, several important sources of complexity in the NPP operating environment are introduced, which should be considered in both the design and evaluation of control room systems. Finally, the last section discusses the effects of complexity on human performance and possible design techniques to mitigate the negative effects of complexity on human performance.

METHODOLOGY

In this section, we discuss the methodology used to develop a technical basis for understanding complexity in NPP control rooms. A literature review of previous work that concentrated on identifying complexity was conducted. The results of the review were analyzed to determine the applicability to NPP control room evaluation and design. In addition, several qualitative methods were used to gather practical information about the NPP control environment and to obtain expert opinion, as discussed below. Finally a conceptual understanding of NPP control rooms was developed and used as a basis for a qualitative framework of design and evaluation of NPP control rooms.

Understanding complexity is a challenge due to many interpretations of complexity in different situations and contexts. In order to provide a technical basis to understand complexity in the context of NPP control rooms, an extensive literature review of different disciplines was conducted. Chapter 3 (Characterization of Complexity) includes various intellectual perspectives on the topic of complexity, which enables a better understanding of the connection between complexity and the design and evaluation of NPP control rooms as complex systems.

Identification of Complexity Sources

One of the most important goals of this research is to identify the factors that contribute to complexity in NPP control rooms. Reviews of previous research in the aviation and process control environments, as well as preliminary field studies and operator interviews, led to the initial identification of important sources of complexity in NPP control rooms. In addition, extensive interviews were conducted with personnel in the Massachusetts Institute of Technology (MIT) research reactor in order to gather domain information. Plant operations at several different facilities were observed, including the NRC Technical Training Center (TTC) simulator and the New York Independent Systems Operator (NYISO) electricity distribution control room. Additionally, the NRC-maintained Human Event Repository and Analysis (HERA) database was parsed for complexity-related operator mistakes and errors. The review of the HERA database revealed several additional important sources of complexity

In order to verify and validate the identified sources of complexity in the NPP domain, several domain experts were asked to review the complexity sources. In addition, a questionnaire was designed to obtain data from operators in terms of what they perceived as contributors to their job complexity (Appendix A). The design of the questionnaire was informed by the work done by Xing (2008) that evaluated display complexity in air traffic control displays. The questionnaire was tailored to better understand complexity in the NPP environment, and was used to gather data from operators in different control rooms around the world. The questionnaire is a combination of close-ended (e.g., Likert-scale) and open-ended questions to enable both quantitative analysis and subjective opinion gathering. This data collection effort is still underway.

Guidance Development

The analysis of gathered data using the qualitative techniques mentioned above led to the generation of an initial list of complexity sources. These complexity sources will be used to create systems-theoretic models describing complexity in NPPs. This systematic generation of theoretical models based on available data is an important methodology called "Grounded Theory" (Martin & Turner, 1986). Grounded Theory is a popular qualitative analysis framework in social science research. It consists of finding patterns and relationships from loosely connected data gathered, and then generating knowledge about the behavior and actions of those under study. In addition, a NPP domain analysis will be used to develop a functional map of NPP operations, focusing on the sources of complexity.

Descriptive models of complex systems could be used to guide knowledge acquisition about system properties. As an important first step, a network model of complexity in NPP was developed to demonstrate the interconnections between the identified sources of complexity. Additionally, a normative and descriptive model of a NPP control system connected to states in Sheridan's (1992) supervisory control model was constructed. Such a descriptive model could be used to understand and visualize the structure and behavior of NPP subsystems including human operators' information processing and could also be used to establish preliminary goals (Sussman, 2003). The descriptive model is the important first step to generating guidelines for NRC safety personnel to evaluate existing or new control rooms.

CHARACTERIZATION OF COMPLEXITY

The term "complexity" comes from the Latin word "Complexus", which means, "to twine" as defined in the *Merriam-Webster* dictionary. In general, complexity refers to the difficulty of understanding a phenomenon in the environment. More specifically, we are concerned with complex systems, which include complicated interactions between different system parts. Complexity is defined in various ways across diverse disciplines and in relation to various systems. Although there are many convincing definitions of complexity, there is little consensus on the exact meaning of the term (Edmonds, 1995). Some of the most-used definitions of complexity are often tied to a collection of interconnected parts, or so called "systems". Some give emphasis to the complexity of a system's behavior, while others focus on the internal structure of the system. Simon argues that understanding complexity is only achievable by explaining the system as a tree-structured hierarchy (Simon, 1996).

In many of these definitions, however, complexity in human-system interfaces (HSI) contains several common components. In particular, complexity has been defined in terms of three separate dimensions within a particular system: quantity, variety, and interconnections (Xing and Manning, 2005; Xing, 2007). Quantity refers to the number of items in a certain part of the system. This quantity could be, in the context of HSI in NPP control rooms, the number of displays in the control room, the number of buttons on a control panel, number of icons on a particular display, or the number of sub-systems within an overall system. Variety is the number of different components in the system. Variety could refer to the number of different kinds of buttons on an NPP control panel, the number of different colors in a particular display, the number of different size displays, or the number of different types of pumps in a system. Interconnections describe the links between components of a system. These interconnections can be difficult to quantify in a given system, unless all system states are known. For instance, increasing the temperature of water in a holding tank could cause an automatic increase in the flow rate from the tank to a heat exchanger. This "cause and effect" type of interconnection is just one example of the various couplings and links that can occur in a given system.

This generic description of complexity is useful to understand the basis of the variety of complexities that have been identified in the literature. Nearly all the complexities in the literature are defined in terms of quantity, variety, and interconnections, though the measurement of these components is highly dependent on the domain. Furthermore, another important aspect of complexity namely the "temporal" aspect of complexity is underestimated in these investigations. Understanding the effects of time-on-task and duration of cognitive modes on perceived complexity of the control room is missing from these efforts. The following sections will review some of the complexity literature in relation to plant systems, functional tasks, human-system interfaces, and operator processing and shows the lack of temporal information in the respect to complexity.

Design Complexity and Flexibility

There is usually a tradeoff between added functionality and complexity in complex systems. The more functionality we add to a system, the more interconnections is being added between the parts of the system; hence the system becomes more complex. The same tradeoff could be explained between efficiency and complexity. A careful initial design with inherent flexibility allows the addition of more functionality in a later stage. This makes the relationship between complexity and flexibility in complex system worthy of investigation (Moses, 2003).

Perceived Complexity

Broadly stated, complexity could be explained as the inherent property of systems or the environment surrounding the system. Complexity could also be explained as the intrinsic property of an occurring social or natural phenomenon. This is referred to as "objective complexity" or "descriptive complexity" (Schlindwein and Ison, 2004). This objectivist view of complexity is dominant among scientific communities, and most of the quantitative attempts to measure complexity could be categorized under this type of complexity. Proponents of this ideology argue that the characteristics of complex systems are not merely what humans perceive; there exists an objective reality for each system independent of the observer (Cilliers, 1998; Rescher, 1998).

An alternate explanation of complexity describes it as the unique understanding of a phenomenon by a human observer. In other words, complexity is dependent on human perception and hence, each person has a different interpretation of complexity. This epistemological view of complexity is known as "perceived complexity" or "subjective complexity". For proponents of this view (e.g. Le Moigne, 1990; Casti, 1995; Martinez, 2001), complexity is an inherently subjective concept. Understanding the human's biological cognitive structure, such as cognitive information processing, is an important aspect of understanding complexity in an interactive system, exemplified by NPP control rooms. Intuitively, perceived complexity of a complex environment, such as a NPP control room, is correlated with operator performance and could affect their course of action. Perceived complexity may be affected by many factors, including the characteristics of a particular task, organizational factors, automation, and the environment.

A historical analysis of complexity literature done by Schlindwein and Ison (2004) shows that strategies of studying complexity are not comprehensive enough and complexity distinctions are, in some sense, biased through the objective or subjective outlook of the researchers in regards to complexity. A more systematic approach, which takes into account the interconnections between the observer and the observed, is missing from existing approaches. As Schlindwein and Ison argue, defining complexity should not be limited to just the specific attribute of biological, physical or social phenomena. Instead understanding complexity should involve a trans-disciplinary investigation of both system properties as well as the human's cognitive mechanisms. A complete separation of object and subject will result in an inconclusive complexity knowledge base (Ciurana, 2004). According to Morin (1983), complex thinking requires the reintegration of the observer in her or his observation. In that sense, Rescher's (1998) approach in defining modes of complexity to be *epistemic (*i.e. human understanding of complexity grows hierarchically and mirrors the real world), *ontological* (i.e. entities or processes in the real world have organizational or structural complexities) and *functional* (non-scientific and common sense knowledge of the real world) is considered an appropriate line of thought which acknowledges both subjective and objective nature of complexity.

Complexities in Plant Systems

Objective complexity can be quantified in terms of the systems and system interconnections making up a plant. In a plant system, the number of individual systems can be quantified, along with the connections between systems. These components can be evaluated according to the more generic previously discussed definition of complexity, in terms of quantity, variety, and interconnections. These components can also be evaluated in terms of alternative measures of plant complexity, such as situational complexity.

Papin and Quellien investigate what they refer to as "situational complexity", which aggregates several factors, including specific work situations, operator competencies, available tools, specific plant states, and plant dynamics (Papin and Quellien, 2006). Human operators perceive situational complexity in a subjective manner. However, situational complexity has some objective components, including the specific plant states and plant dynamics, referred to as *operational complexity*. The authors argue that the subjective nature of the remaining aspects is the source of human error in plant control. There are two possible methods for reducing the negative effect situational complexity has on human performance: mitigating the subjective components of situational complexity, or reducing the operational constraints of the plant to reduce operational complexity (Papin and Quellien, 2006).

Operational complexity consists of the functional and dynamic characteristics of each individual component in the plant environment, along with the various interconnections between components (Papin and Quellien, 2006). There are four types of interconnections: physical dependencies, side effects, utilization constraints, and technical dependencies. Each of these interconnections plays a role in the Operational Complexity Factor, which is essentially a global measure of plant complexity. A lower Operational Complexity Factor is a result of a less complex plant, which should reduce an operator's overall perceived complexity. Reducing operational complexity obviously requires a significant investment in design and construction. New advanced reactors have the ability to make reductions in operational complexity as a mitigation of perceived complexity. Updating currently operating reactors to reduce operational complexity, however, could be an extremely expensive or even impossible approach (Papin and Quellien, 2006).

Perrow (1999) explains complexity in terms of interactions among subsystems (from linear to complex) and coupling of parts (from loose to tight) (Figure 1). Perrow argues that our systems have become so complex and tightly coupled that accidents are inevitable and are considered "normal". He defines linear systems as systems in which interaction between the parts are expected in a sequence. This is in contrast with complex systems in which the interactions between the parts are unexpected. Table 1 summarizes Perrow's proposed characteristics of complex and highly coupled systems. Based on this categorization, power plants are identified as an example of a complex and highly coupled system.

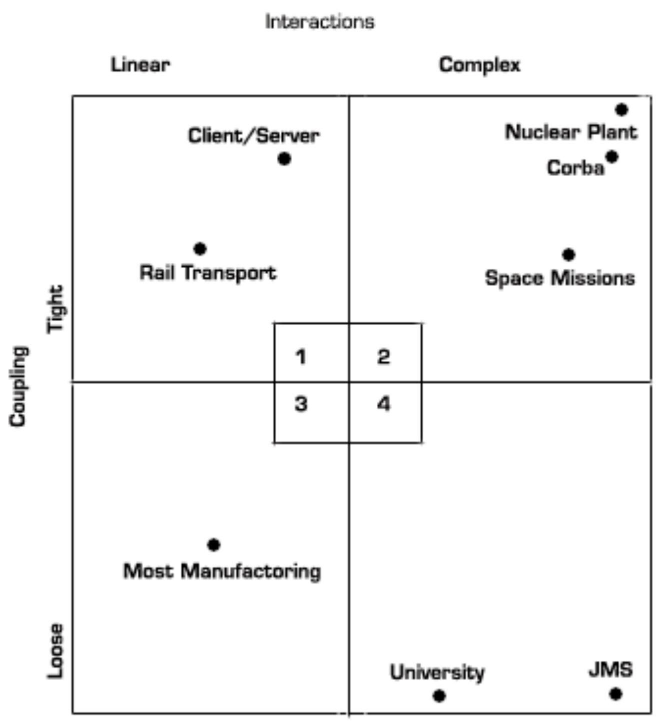


Figure 1. Perrow's (1999) model of complexity.

Table 1. Characteristics of complex and tightly coupled systems (Perrow, 1999).

Complex Systems	Tightly Coupled Systems
• Proximity of components • Too many control parameters with interconnections • Limited understanding of some processes • Propagation of failure through "common mode" connections between parts • Unfamiliar of unintended feedback loops • Indirect or inferential sources	• Delays are "not possible" • Sequence of events are invariant • Alternative paths not available • Little opportunity for substitution or slack • Redundancies are designed in and deliberate

Complexities in Human-System Interfaces (HSI)

Human-system interfaces (HSI) take many different forms, including digital displays, analog gauges or readouts, auditory signals, or tactile controls. Much of the research conducted on human-system interfaces focus on digital displays and the associated effects of display complexity on human performance. Display complexity has been defined in terms of the display type (visual, auditory, haptic), the number of menus or decision points, and the links among the menus or decision points (Li and Wieringa, 2000). Understanding display complexity is of great importance, due to the growing complexity of computer applications and the increasing importance of human-computer interaction in complex systems.

Interface design has been studied heavily in the past and a large number of recommendations and guidelines have been produced, however, these studies are extremely dispersed and the findings are sometimes in contradiction. Maguire (1982), who consolidated a large number of interface design recommendations, argues that these differences are due to task-dependency, which results in low external validity of such recommendations. With respect to complexity, it is important to investigate these recommendations in order to identify those interface design variables and information representations that may affect perceived complexities. Previous research has shown a number of such variables (e.g. DeSanctis, 1984; Powers et al., 1984; Benbasat et al., 1986; Te'eni, 1989) such as mode of presentation (e.g. tabular vs. graphical) and the number of windows as factors that contribute to the perceived complexity.

Operator Information Processing

Understanding how humans process information is an important condition for designing efficient and easy to use interactive NPP control systems and is the key to understanding complexity, particularly perceived complexity, and its effects on human performance in such environments. To this end, Card, Moran, and Newell (1983) introduced a *Model Human Processor* (MHP), which consists of three interacting systems, namely perceptual processor, cognitive processor and motor processor. The MHP could be used to calculate the time it takes to perform a task using the perceptual, cognitive and motor processes, which are associated with different types of memories, namely Visual Short Term Memory (VSTM), Working Memory (WM) and Long-Term Memory (LTM). Based on MHP model, Card et al. (1983) suggested that for supervisory control tasks with more intense stimuli, perceptual processor cycle time is faster than the tasks with weak stimuli. MHP has been widely used in cognitive psychology and was the basis for the creation of GOMS (Goals, Operators, Methods, and Selection Rules) technique (Card et al., 1983) to describe and model human task performance. However, MHP model has been criticized for its overly simplistic explanation of human behavior and its focus on a single person and hence ignoring other factors such as environment and other people (Meyer and Kiera 1999).

Wickens and Hollands (2000) introduced a model that explains how humans process information by illustrating the perception and cognition mechanism, their relation to short and long-term memories, and the response creation (Figure 2). Working memory (attentional enhancement of short-term memory) has been studied heavily as an important factor in perceptual mechanisms and several working memory theories have been proposed (e.g. Cowan, 1995; Eriksson and Kintsch, 1995; Badelley, 2000; Guida et al., 2005). In the context if supervisory control domains similar to NPP control rooms, limitations of working memory, such as limited capacity and its relation to long-term memory, have been studied (Anderson, 1995; Lycan, 1999; Coren et al., 1999; Altman and Trafton, 2002), as has been attention (Shiffrin and Schneider, 1977; Wickens, 1984; Altmann and Steedman, 1988; Desimone and Duncan, 1995), vigilance or sustained attention (Ruffle-Smith, 1979; Davies and Parasuraman, 1982; Carter and Beh, 1989; Lavine et al., 2002) and change blindness (Pashler, 1988; Grimes, 1996; Rensink et al., 1997; Silverman and Mack, 2006). Change blindness occurs when people miss changes in a scene (e.g. displays) usually caused by visual disruption (e.g. eye movement), among others.

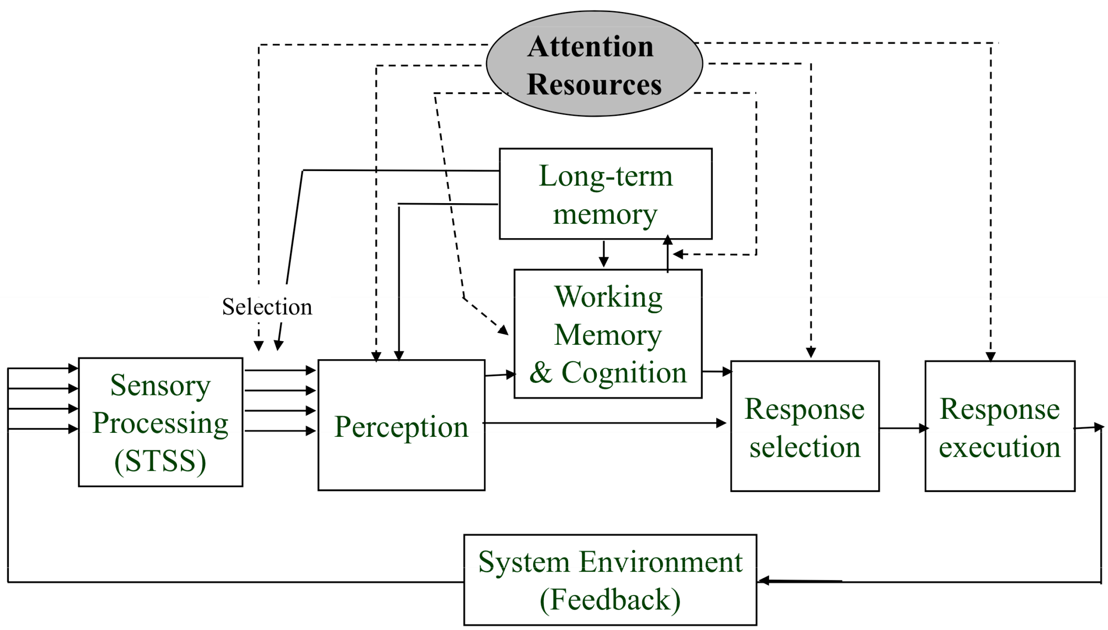


Figure 2. Modified from Wickens and Hollands (2000, p.11).

Sources of Complexity in Human Supervisory Control Systems

The term "Supervisory Control" is also referred to in the literature as "Human-Supervisory Control (HSC)", which is the process of controlling or monitoring the state and behavior of system's components by individual operators (Sheridan, 1992). In practice, supervisory control is usually a mixture of both human and automation control of several system components (i.e. controllers) that provide feedback regarding the operational state of the system under supervision. These controllers or control loops could be human operators or automated systems (Ferrell and Sheridan, 1967; Sheridan and Hennessy, 1984). However, even when systems are fully automated, human supervisors' judgment is used to handle the unresolved problems. Sheridan (1960) defined this higher-level control as "metacontrol."

Sheridan (1992) defined five generic supervisory of functions planning, teaching (or programming the computer), monitoring, intervening and learning. Sheridan argues that these functions operate within three nested control loops (Figure 3). Sheridan's abstract model has been widely used to explain human supervisors' behavior in several different settings such as commercial aviation (Wiener and Curry, 1980; Sarter and Amalberti, 2000), nuclear and process control (Moray, 1997; Mumaw et al., 2000; Guerlain et al., 2002), air traffic control (Endsley and Kriss, 1995; Wickens et al., 1997; Morphew and Wickens, 1998; Metzger and Parasuraman, 1999), medicine (Leape, 1994; Helmreich, 2000; Guerlain et al., 2005), automobiles (Sheridan, 1992; Fong and Thorpe, 2001) and more recently military applications (Amalberti and Deblon, 1992; Cummings and Mitchell 2006; Crandall and Cummings, 2007; Cummings et al., 2007). Figure 4 depicts human supervisory control in the NPP system. While automation is increasingly being used in process control domains, particularly for increased precision and productivity, operational safety still remains as the most important consideration in design and evaluation of new NPP plants.

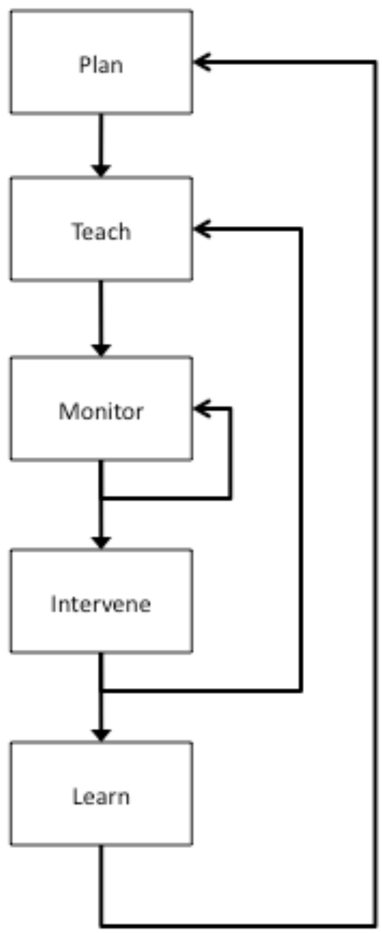


Figure 3. Sheridan's (1992) Supervisory Control Model.

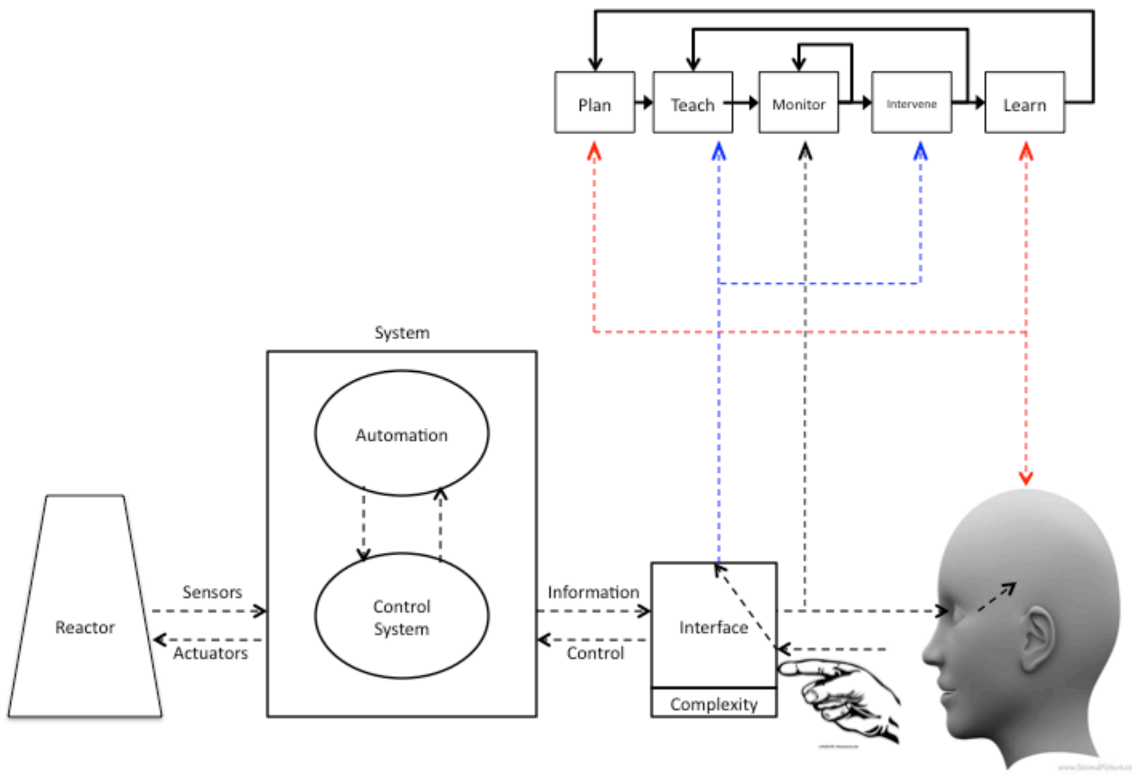


Figure 4. Human supervisory control in NPP context.

NPP control rooms have many elements in common with other human supervisory control systems, thus it is conceivable that complexities in NPP control rooms may share commonalities with sources in other supervisory control systems. Cummings and Tsonis (2006) proposed a Human Supervisory Control (HSC) complexity chain in an effort to isolate specific categories of complexity sources within HSC socio-technical systems, in particular the air traffic control domain (Figure 5). The HSC complexity chain identifies environmental complexity as the objective state of complexity that exists in the world and cognitive complexity as the complexity perceived by a human operator. In the case of a complex environment (NPPs, for example), perceived complexity could be quite high, potentially negatively impacting safe operator performance. For example, many NPPs have redundant systems for safety reasons. However, including a redundant system could double the amount of information available to the operator (including displays and controls), which could increase an operator's cognitive complexity. To mitigate cognitive complexity, organizational policies and procedures along with information representations in the form of interfaces and displays, can be introduced into the system. However, the introduction of these mitigations and devices can also add to the overall perceived complexity of the operator.

Organizational complexity represents the additional constraints placed upon the system by operational requirements, such as the number of crewmembers in the control room, emergency procedures, or shift length. The original HSC complexity chain contained a display complexity category, which considered the complexities offered by visualizations found in the display. This interpretation only recognizes the output to the operator, with no consideration of input from the operator to the system, which is required to close the supervisory control loop. Thus, we propose to change the “display complexity” nomenclature in the original HSC complexity chain (Cummings & Tsonis, 2006) to “interface complexity”, to reflect this two-way communication. Interface complexity is thus the complexity derived from controls and displays, which could include display font size, number of colors used in the display, or numbers and variety of buttons, levers, etc.

Though this complexity model is representative of many types of complexity within HSC systems, it does not specify the sources of complexity within these systems. The following section identifies and discusses sources of complexity, relating each to the context of nuclear power plant control.

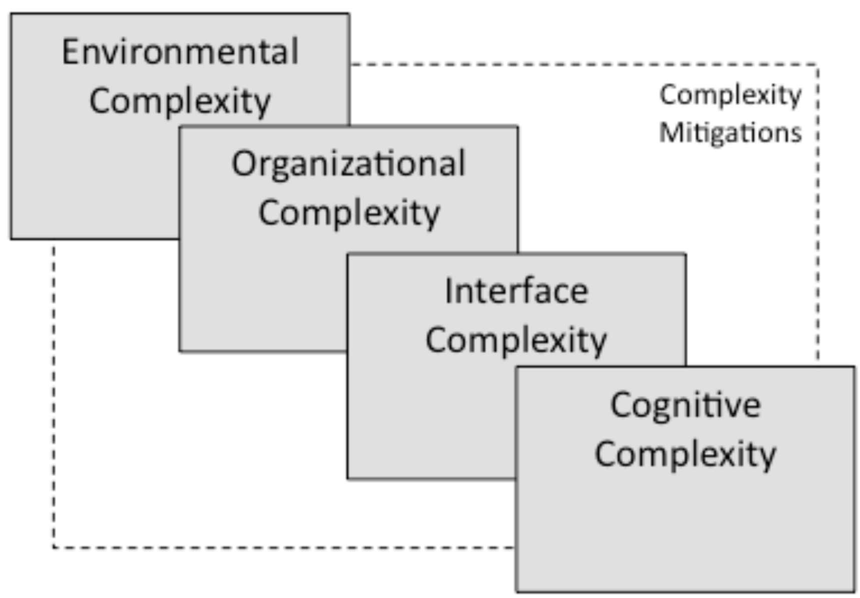


Figure 5. The modified Human Supervisory Control Complexity Chain (Cummings and Tsonis, 2006, p.2).

COMPLEXITY AND HUMAN PERFORMANCE

In safety-critical work environments, such as aviation and process plants, in which humans are at the sharp end of interaction with the underlying process, human error is identified as the cause for system failures (Woods and Cook, 2003). A closer investigation of these systems shows regularities and factors that make certain kinds of erroneous actions and their assessment predictable (Hollnagel, 1988). The objective complexity of the system is one of the main factors to consider, mainly because humans cognitive capabilities are limited. When dealing with a problem like an emergency alarm in a nuclear power plant, the rationality of human problem solvers is exercised relative to the complexity of the environments in which they function (Klein et al., 1993; Klein, 1998). In other words, human rationality is bounded (Simon, 1957) as local rationality, which is based on a subset of available information and cognitive resources in a specific situation (Woods et al., 1995).

Empirical research provides evidence that humans are error-prone in their decisions, especially in complex systems where decisions are being made under pressure (e.g. Allnut, 1982; Reason, 1990; Li et al., 2001). Hollnagel (1993) estimated that human errors account for 60-90% of incidents in complex systems. Gopher et al. (1989) shows that in one single intensive care unit (ICU) study, doctors and nurses made an average of 1.7 errors for each patient a day. This research motivated a body of scholarship to understand what causes human error in supervisory control and how to avoid these errors, especially in safety-critical supervisory control tasks such as NPP control (e.g. Swain and Guttman, 1983; Roth et al., 1994; Leiden et al., 2001; Deustch and Pew, 2002). Johnson-Laird (1983) and Gentner & Stevens (1983) introduced mental models as a way humans simplify the cognitive handling of information by encoding a certain image of the world. Traditionally human error researchers addressed error as delays in reaction time (e.g. Pachella, 1973); however, more recently, cognitive psychologists and human factors practitioners have revisited other classes of errors, such as skill-based mistakes and rule-based mistakes or slips (Rasmussen, 1983). The study of these other classes of errors has resulted in different frameworks to analyze human error and to prescribe solutions. One such framework was developed by Reason (1995) that shows the anatomy of incidents in an organization (**Figure 6**).

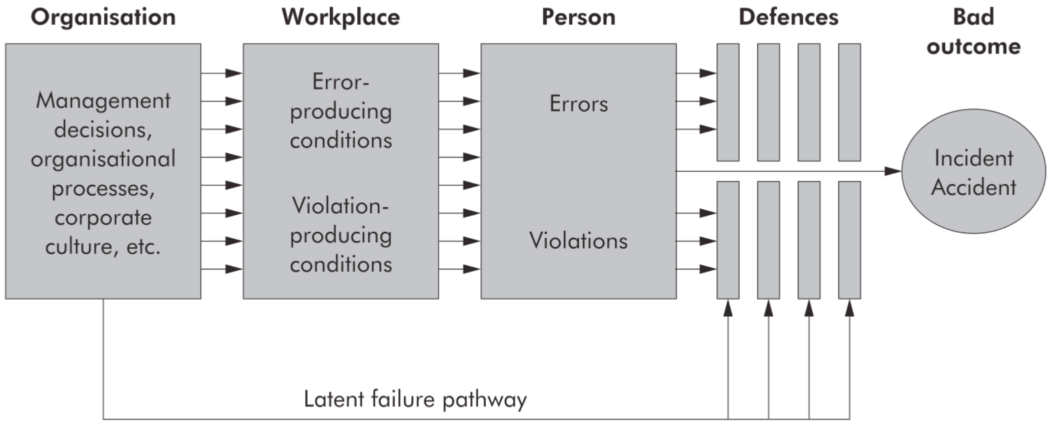


Figure 6. Stages in the development of an organization accident (Reason, 1995).

Reason (2000) takes two different approaches in dealing with errors. The first approach, which is the human's approach, focuses on human error. The second approach, which is the system's approach, focuses on the conditions under which human works and tries to mitigate the effects of errors by designing error-tolerant systems. In general, literature in the field of supervisory control provides evidence that poor system design or poor organizational structure are responsible for many of the errors, which are incorrectly seen as irresponsible human action (Norman 1988; Reason, 1990; Woods and Cook, 1999). Reason (2000) using his "Swiss Cheese Model" argues that even multiple levels of defenses and barriers (slices of cheese) may be penetrated by an accident trajectory (Figure 7). He argues that the holes in the defenses (slices) arise for two reasons: *Active failures*, which are errors that are committed by people who are directly in contact with the system (e.g. slips, lapses, mistakes etc.) and *Latent Errors* (or "resident pathogens") which arise from decisions made by designers, builders and high-level decision makers. The supervisory control literature provides several prescriptions to remedy errors arisen from both active and latent errors. These prescriptions include minimizing the likelihood of errors by carefully designing systems with safeguards and barriers, awareness interfaces, and training as well as prescribing ways to tolerate errors.

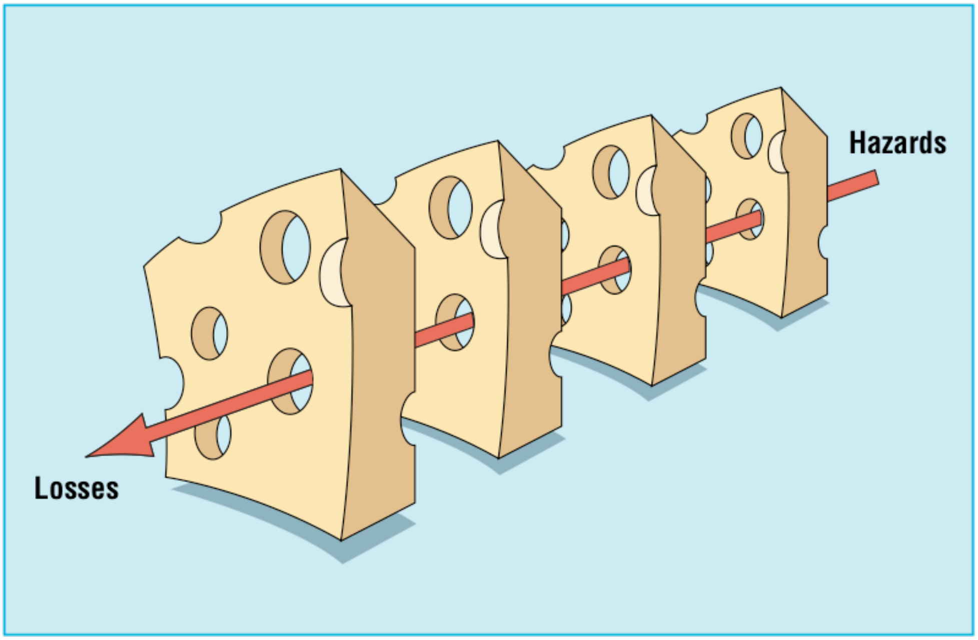


Figure 7. Swiss cheese model (Reason, 2000).

Functions of NPP Controllers

The first step to understand human performance in NPP control is to identify the particular functions that NPP operators must complete to do their job properly. Identifying particular functions will allow further analysis concerning the specific points within each function that are susceptible to potential operator errors. Additionally, each function can be associated with particular sources of complexity, which informs the identification of interrelations between these sources in CSN. By cross-referencing functions and complexity sources, specifically focused mitigations or designs can be developed to increase human reliability and reduce human errors. Figure 8 presents the major functions of NPPs, which can be extended to the high-level operator functions.

The function map in Figure 8 identifies two specific goals within NPPs: maintaining plant safety and maintaining plant availability. Though the NRC regulatory practices focus on safety, it is important to understand that particular aspects of plant availability are related and even reliant on plant safety.

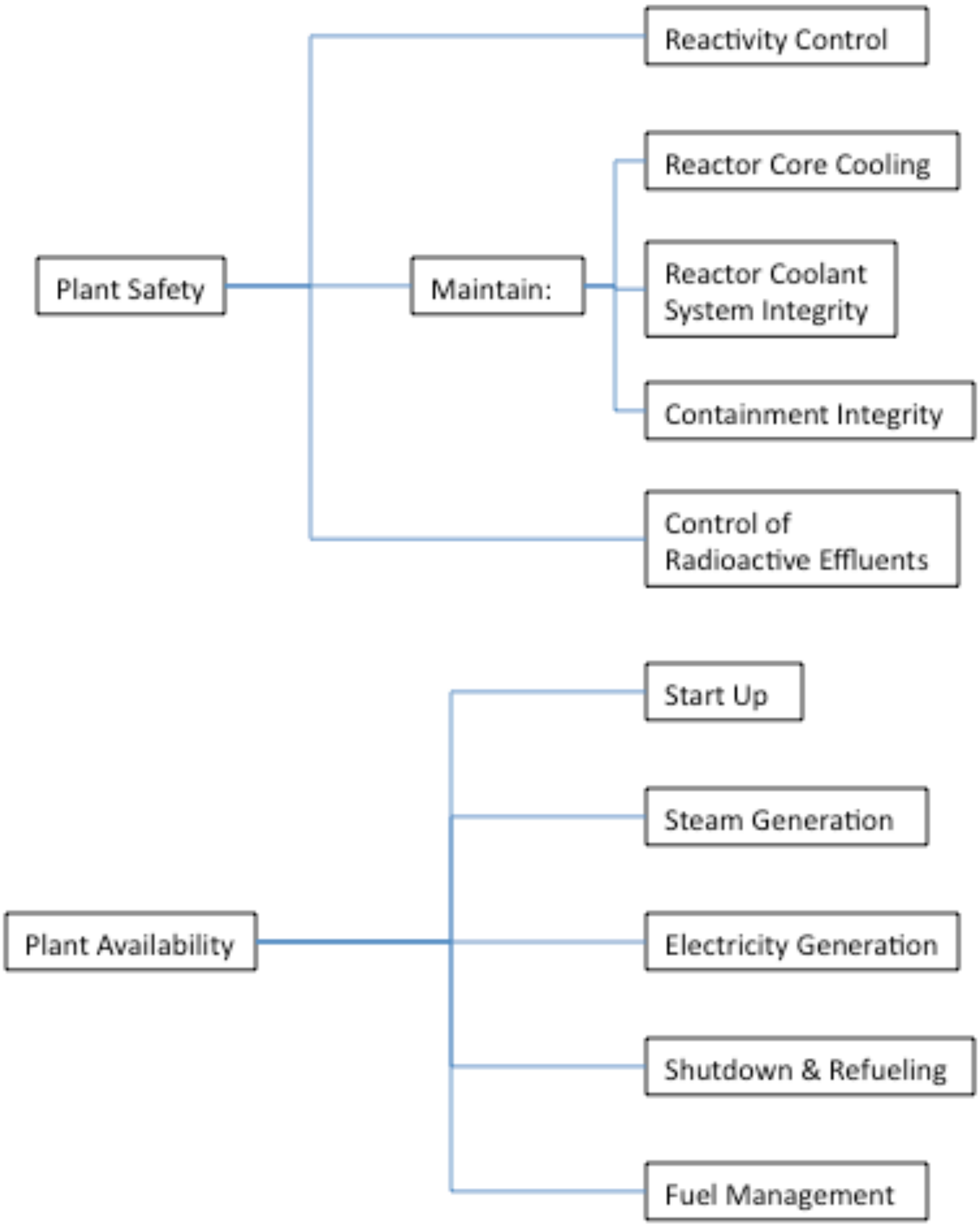


Figure 8. High level functions of NPPs (IEC, 2000).

SOURCES OF COMPLEXITY IN NUCLEAR POWER PLANT CONTROL ROOMS

Identifying sources of complexity in NPP control rooms is an important first step in understanding the effect (both positive and negative) that particular complexity sources have on control room operation and safety. These sources of complexity can be identified through a series of qualitative methods, including interviews with control room operators, control room observations, field studies, ethnography and cognitive task and work analyses. Our approach focuses on identifying particular sources of complexity within each of the complexity categories described in the HSC complexity chain.

Reviews of previous research in the aviation and process control environments, as well as field studies and operator interviews, led to the initial identification of important sources of complexity in NPP control rooms. In addition, extensive interviews were conducted with personnel in the Massachusetts Institute of Technology (MIT) research reactor in order to gather domain information. Plant operations at several different facilities were observed, including the U.S. Nuclear Regulatory Commission (NRC) Technical Training Center simulator and the New York Independent Systems Operator (NYISO) electricity distribution control room. Additionally, the NRC-maintained Human Event Repository and Analysis (HERA) database was parsed for complexity-related operator mistakes and errors. The review of the HERA database revealed several additional important sources of complexity.

In the HERA database, there are 22 events: near misses (narrowly avoided catastrophic situations) or minor events, such as a small atmospheric release of radioactive effluents. Each event was carefully examined and parsed, resulting in a large collection of individual actions taken before, during, and after the event. Each particular action was coded according to conventional probabilistic risk assessment (PRA) methods (Halbert et al., 2006). Each of the 22 events in the HERA database was examined for the performance-shaping factor (PSF) class of complexity. Each of the PSFs that were coded as a human error (XHE) or human success (HS) due to complexity were examined and recorded (Appendix B). Two particular factors occurred quite frequently: "Simultaneous tasks with high attention demands" and "Problems in differentiating important from less important information". These factors translated to sources of complexity concerning parallel tasks and procedures and can also be related to several sources within the interface complexity category.

In order to verify and validate the identified sources of complexity in the NPP domain, several domain experts were asked to review the complexity sources. In addition, a questionnaire was designed to obtain data from operators in terms of what they perceived as contributors to their job complexity (Appendix A). The design of the questionnaire was informed by the work done by Xing (2008) that evaluated display complexity in air traffic control displays. The questionnaire was tailored to better understand complexity in the NPP environment, and was used to gather data from operators in different control rooms around the world. The questionnaire is a combination of close-ended (e.g., Likert-scale) and open-ended questions to enable both quantitative analysis and subjective opinion gathering. This data collection effort is still underway.

The qualitative analysis of gathered data led to the generation of an initial list of complexity sources in the NPP control rooms, within the complexity categories of environmental (Table 2), organizational (Table 3), interface (Table 4), and cognitive (Table 5). It is notable that the majority of sources can be categorized under *quantity* and *variety*, which represent two dimensions of complexity (Xing and Manning, 2005). The third dimension of complexity, interrelationships, is addressed in the next section.

Table 2. Sources of environmental complexity in NPP control rooms.

Environmental Complexity	
• Control room size	• Control room layout
• Operational mode duration	• Ambient noise level
• Frequency of operational mode transitions	• Number of critical events in previous shift
• Number of operational mode transitions	• Number of external interruptions

Table 3. Sources of organizational complexity in NPP control rooms.

Organizational Complexity	
• Number of procedures	• Number of crew members
• Variety of procedures	• Number of team hierarchy levels
• Number of steps in procedures	• Number of collaborative procedures
• Number of procedure switches	• Number of crewmembers required for each procedure
• Number of dependent procedures	• Number of information sources per inference
• Number of parallel procedures	• Procedure durations
• Number of required inferences per procedure	• Duration between procedures
• Shift length	

Table 4. Sources of interface complexity in NPP control rooms.

Interface Complexity	
• Number of displays • Display size • Information amount • Variety of fonts • Font size • Number of icons • Variety of icons • Variety of colors • Number of alarms • Variety of alarms • Alarm duration • Display resolution • Number of shared control devices • Number of shared displays • Display luminance • Clutter	• Real-time update rate • Number of animated display features • Number of required unit conversions • Variety of displays • Number of redundant displays • Number of control devices • Variety of control devices • Number of redundant control devices • Distance between control devices • Distance between displays • Distance between control devices and displays • Distance between controls and their associated displays • Text to graphic ratio • Refresh rates

Table 5. Sources of cognitive complexity in NPP control rooms.

Cognitive Complexity	
• Cognitive fatigue • Number of years of experience in other control rooms • Number of years of experience in same control room	• Number of years of working with same crew (team familiarity) • Number of simulator hours completed per operator • Boredom

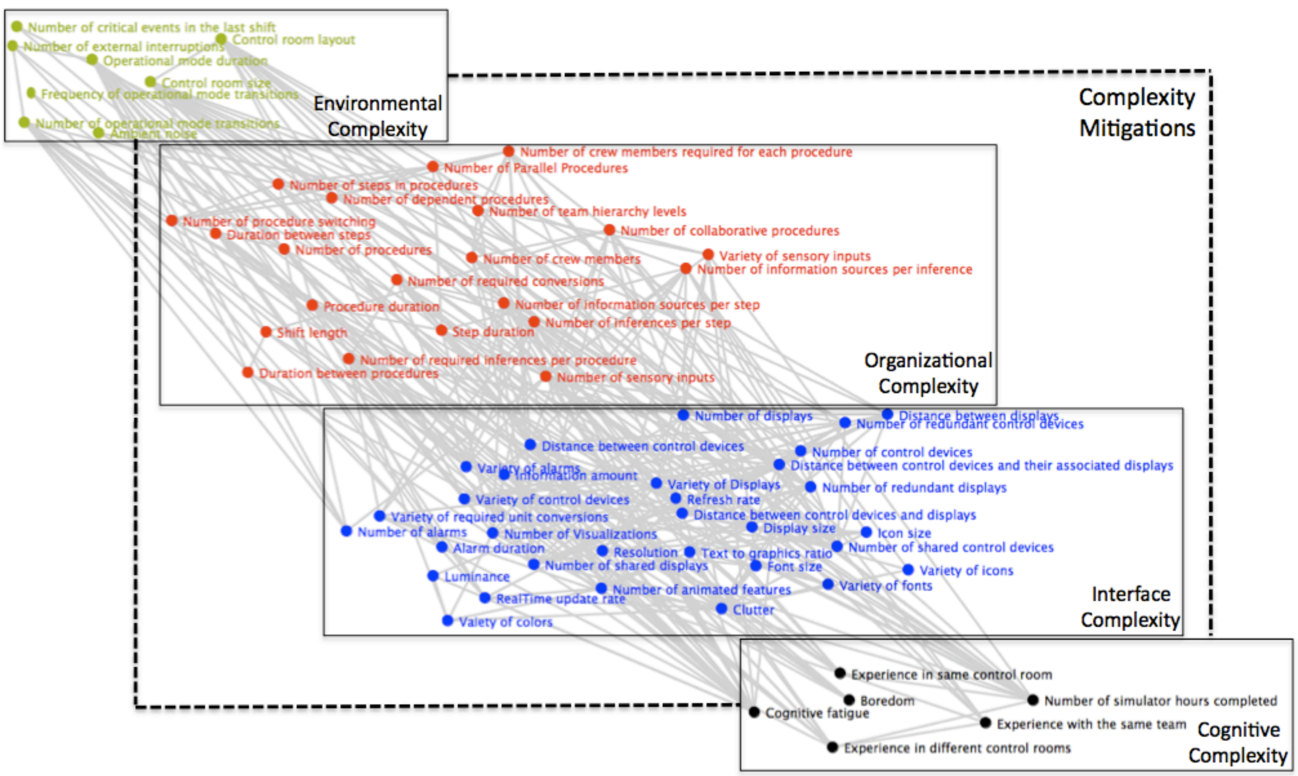
Some of the identified sources in Table 2 are associated with operational modes. An operational mode at any given time could be defined in terms of the reactor's status. Through operator interviews and observations, four modes were identified: monitoring, normal, urgent and emergent. The monitoring mode exists when the reactor is in fully autonomous operation, requiring the operator to monitor the situation. A normal mode exists in the situation in which the operator is performing a task or procedure that is related to maintenance, such as refueling or fuel rotation. Urgent and emergent modes exist in abnormal plant states, where operators are required to access emergency procedures and time pressures exist. Broadly stated, the monitoring and normal modes are associated with low cognitive workload whereas urgent and emergent modes usually involve high cognitive workload. In addition, monitoring and normal modes are related to boredom, which is due to under-arousal, caused by insufficient workload (Pattyn et al., 2008). Although fatigue and boredom are highly interconnected, cognitive fatigue, which is caused by high mental effort, could be associated with urgent and emergent modes. The mode-related sources of complexity highlight the importance of the temporal aspects of complexity, especially when operators transition from a monitoring or normal mode state to an urgent or emergent mode. Studies show that this "cognitive context switch" could negatively affect operator's performance (e.g., Mackworth, 1948; Fruhstorfer and Bergstorm, 1969; Beaty et al., 1974). It is widely accepted among researchers who study vigilance that maintaining a constant level of alertness is almost impossible for operators who perform monotonous monitoring tasks (Mackworth, 1948). In the context of NPP control, human errors resulting from such mode transitions may be explained through an increase in the perceived complexity of the control room immediately after the mode transition.

Complexity Source Network

One problem that can be seen on inspection of the sources of complexity in Tables 2-5 is the lack of explicit representation of interconnections between these sources. We propose that the interconnections between NPP sources of complexity can be represented and explored via a network representation. The Complexity Source Network (CSN) represents the basic sources of complexity (nodes) within the NPP control room and the interactions that the sources share with one another (connections). Figure 9 shows this network embedded in the categories of the HSC complexity chain. The identification of interactions between the sources is important in order to understand the overall complexity of the NPP control room environment, and sheds some light on the nature of coupling between individual sources. Visualizing the sources within the HSC complexity chain helps identify the connections between the complexity categories as well as isolating the sources in different complexity levels. Domain expert knowledge and operator interviews were used to identify the possible interconnections. The resultant list of interconnections is a large set of pair-wise connections, each of which is represented by a connection within the CSN.

The particular CSN in Figure 9 was generated from the list of complexity source connections using the GUESS (Eytan, 2007) visualization software package. There are several methods to analyze networks like the CSN, the simplest of which is identifying those nodes that have the greatest number of connections (or edges). The number of edges a particular node has is related to the relative importance of the complexity source in the control room. Thus, the more edges a node has, the higher chance the source has to impact safe plant operation. In this particular CSN, the node with the greatest number of connections is Cognitive Fatigue, with 22 connections to other nodes. Cognitive Fatigue has the greatest number of connections most likely because of its ability to have a detrimental effect on many activities that need to happen in the control room, especially in urgent or emergent situations (van der Linden et al., 2003). Cognitive fatigue is a prime example of the complex interactions that exist in a NPP control room in that cognitive fatigue can be viewed as the result of some complexity sources, as well as a source of complexity itself. Indeed, this concept of sink and source also applies to boredom and will be an area of future research.

The CSN can also be analyzed as a whole in terms of the number of nodes and number of edges. In this CSN, there are 66 individual nodes interconnected with 306 edges. The number of individual components and their connections has been described as a direct measure of complexity (Edmonds, 1995). The edge to node ratio is 4.64, indicating that on average each node is expected to be connected to roughly 4 or 5 other nodes in the network. This ratio also indicates that any given complexity source has the potential to impact four to five other sources in the control room, conceivably impacting performance in an un-isolated fashion.



Additionally, the CSN can be reorganized algorithmically. The advantage of this approach is that the CSN organization is based solely on the relations that the sources share with one another. This approach may be advantageous to identify naturally occurring groups of complexity sources that are very closely related. The circular algorithm, for example, generates a circular network, striving to make each edge as close to the same length as possible. Figure 10 shows the results of the CSN circular network. Two additional methods are termed force-directed algorithms: the Kamada-Kawai algorithm (Kamada and Kawai, 1989) and the Fruchterman-Reingold algorithm (Fruchterman and Reingold, 1991). Each of these algorithms strive to reduce the “energy” in the network by representing edges as springs. Figures 11 and 12 depict the results of the Kamada-Kawai and the Fruchterman-Reingold algorithms, respectively.

Figure 9: Complexity Source Network overlaid with the HSC Complexity Chain.

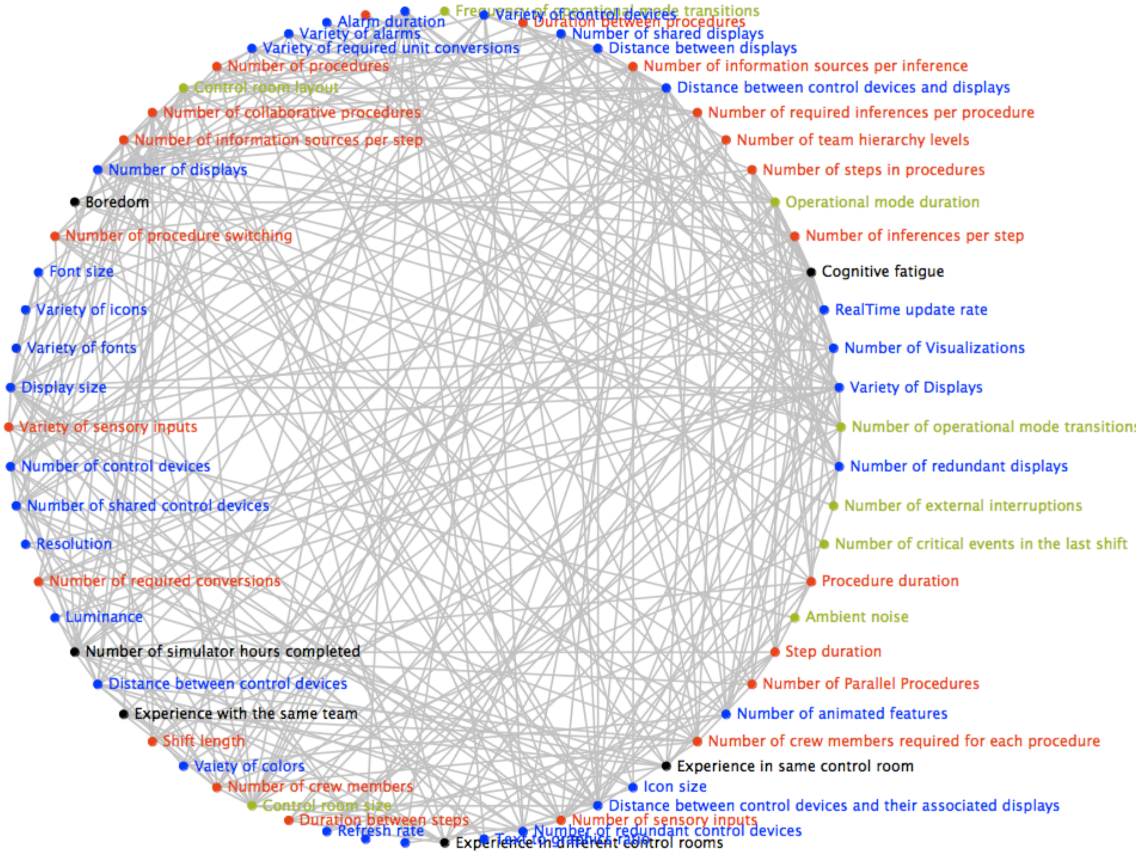


Figure 10. Circular algorithm result for the CSN.

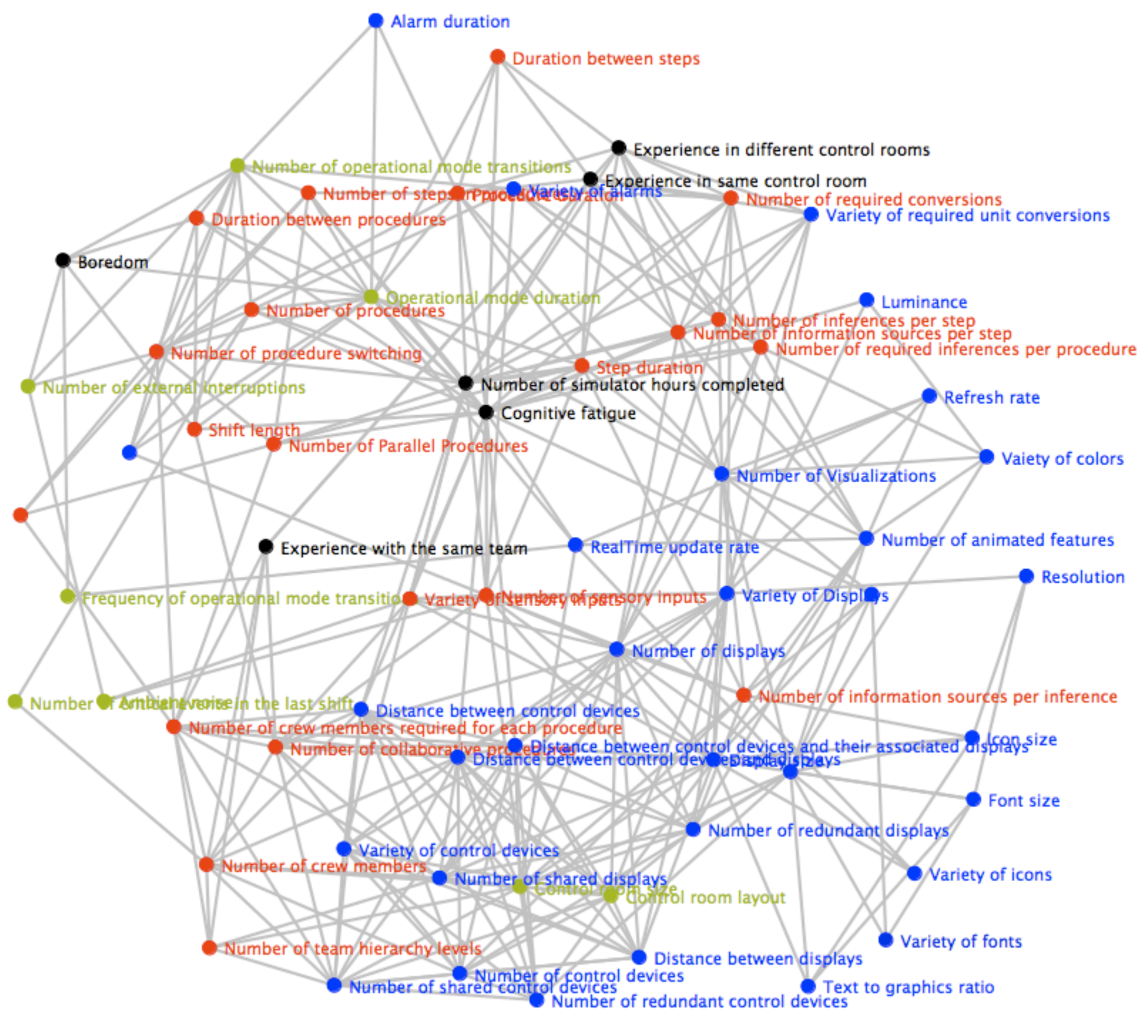


Figure 11. Kamada-Kawai algorithm result for the CSN.

Figure 12. Fruchterman-Reingold algorithm result for the CSN.

Identifying sources of complexity within safety-critical environments, such as nuclear power plant control rooms, is important for several reasons. Understanding the effect complexities can have on human behavior and decision-making is key to ensuring safe operation of a plant. Without proper management of these sources, negative effects from each source could potentially propagate to the whole system through complicated interconnections, as illustrated in the CSN. This understanding will also allow the creation of tools or mitigations to support safe plant operation and allow more informed adoption of advanced technologies.

Several sources of complexity and their interconnections were identified using various qualitative data gathering techniques. This analysis led to the development Complexity Source Network representation that can be used for additional analysis of system in terms of reducing the unnecessary coupling between the sources. A basic analysis conducted on the preliminary CSN for NPP control rooms suggests that operators' cognitive fatigue is a major contributor to cognitive complexity in the control room. If cognitive fatigue was completely removed from the CSN, the number of edges would be reduced to 284, the number of nodes reduced by one, and the resultant edge to node ratio would be 4.37. By removing this one node from the CSN, the ratio would decrease by nearly 6.8%, which would theoretically remove relatively that much complexity from the NPP control room. The idea of removing a node from the network can be extended to all nodes and edges in the network.

By systematically identifying sources of complexity that have high impact potential, specific tools and mitigation strategies can be developed to ensure safe human performance in both control rooms and other complex supervisory control systems

SUMMARY

Modernizing existing nuclear power plant control rooms and designing new, advanced control rooms are currently underway. Understanding complexity in the control room context is important for designing human-system interfaces that support safe and reliable operator behavior and decision-making. This report summarized several facets of the complexity literature and identified a generic complexity definition containing three common dimensions: number, variety, and interconnections (Xing and Manning, 2005). This generic definition was used, along with several other qualitative information-gathering techniques (operator interviews, operations observations and operational reviews), to inform the development of a list of complexity sources within nuclear power plant control rooms. The list of complexity sources was used to develop a large set of complexity connections, which is the basis of the Complexity Source Network (CSN).

The CSN is a novel visualization method for presenting and analyzing complexity sources and their associated relations within the control room. A network like the CSN can be analyzed simply by examining the number of nodes or edges, which allows for the identification of important sources of complexity within the control room. The CSN visualization is the important first step in identifying complexity sources that require special design attention or mitigation within the nuclear power plant control room environment.

To provide benefit to the nuclear power plant control room domain and the supervisory control research community in general, future work will concentrate on validating the complexity sources within the CSN. Additionally, future work will examine alternative methods to analyze and restructure the CSN to provide more insight to the complexities and their interactions within the control room. Ultimately, this research will lead to the development of a suite of tools that can be used to identify, classify, and analyze sources of complexity, which is the first step in targeting specific sources for mitigation design within the nuclear power plant control room.

ACKNOWLEDGEMENTS

This research was funded by the United States Nuclear Regulatory Commission Office of Nuclear Regulatory Research. The views and conclusions in this report are those of the authors and do not represent an official opinion, expressed or implied, by the US Nuclear Regulatory Commission. Special thanks are extended to Dr. Jing Xing and Dr. Amy D'Agostino for their insight and input. Thanks to Rachel Williams, undergraduate assistant, who gathered complexity information from the HERA database.

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APPENDIX A: OPERATOR QUESTIONNAIRE

Questionnaire for Managing Complexity in Nuclear Power Plant Control Rooms

Thanks for participating in this interview. Your input is extremely valuable and will be considered in the design of new generation control rooms.

Instructions: This questionnaire asks you to answer to a series of questions regarding the Nuclear Power Plant (NPP) control room you have worked in. Part I asks for some demographic information about your job. For Part II questions, please read the questions (in bold) carefully, then while thinking about the question, circle the number that best fits your opinion for each numbered argument. If you have any comments about the general question, please provide them in the space available. For Part III, please answer on the provided sheet. Please answer each question to the best of your ability.

*Please remember that the information you provide is confidential and is only being used for educational purposes. You don't need to provide any identifiable information about yourself.

**For the purposes of this questionnaire we define "display" as all the digital displays including computer monitors.

Part I

What is the name of the NPP you are operating in (or most recently operated in)?

What is the type of NPP you are operating in (or most recently operated in)?
(e.g. Research, Commercial, Military)

How long have you been licensed?

How many years have you worked in this particular control room?

How many years have you worked as an NPP operator in total?

If you are no longer working as an operator, how long has it been since you were an active operator?

How many control rooms have you been worked in? If more than one, please list the names and types of NPPs.

Part II

Please circle the number corresponding to your agreement to the particular statement.

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
1. Does the variety of display features assist you in acquiring information?					
1.1. The following visual features assist me in acquiring the information in the control room:					
1.1.1. Variety of **colors** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.2. Variety of **shapes** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.3. Variety of **font sizes** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.4. Variety of **icons** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.5. Variety of **graphics** in the displays assists me in acquiring information.	5	4	3	2	1
1.2. The following auditory features assists me in assessing the situation in the control room:					
1.2.1. Variety of **audio alarms** assist me in assessing the situation.	5	4	3	2	1
1.2.2. The **audio alarms** can be distracting.	5	4	3	2	1
1.3. The displays use too many different:					
1.3.1. Colors	5	4	3	2	1
1.3.2. Fonts	5	4	3	2	1
1.3.3. Shapes	5	4	3	2	1
1.3.4. Icons	5	4	3	2	1
1.3.5. Auditory alarms	5	4	3	2	1
1.3.6. Windows	5	4	3	2	1
1.4. I obtain information better if I ignore some details like:					
1.4.1. Colors	5	4	3	2	1
1.4.2. Fonts	5	4	3	2	1
1.4.3. Text formats	5	4	3	2	1
1.4.4. Graphics	5	4	3	2	1
1.4.5. Alarms	5	4	3	2	1
Note:					

2. How does the variety of control devices (e.g. buttons, knobs, etc.) assist you in control operations?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
2.1. The variety of control device **sizes** assists me in control operations.	5	4	3	2	1
2.2. The variety of control device **colors** assists me in control operations.	5	4	3	2	1
2.3. The variety of control device **shapes** assists me in control operations.	5	4	3	2	1
2.4. The variety of control device **text/descriptions** assists me in control operations.	5	4	3	2	1
2.5. The physical layout of the control devices assists me in locating them.	5	4	3	2	1
2.6. The physical layout of the control devices assists me in using them.	5	4	3	2	1
2.7. The control devices use too many different:					
2.7.1. hardware controls like dials/levers/buttons	5	4	3	2	1
2.7.2. soft, programmed buttons	5	4	3	2	1
2.7.3. sizes	5	4	3	2	1
2.7.4. colors	5	4	3	2	1
2.7.5. fonts	5	4	3	2	1
2.7.6. shapes	5	4	3	2	1
2.7.7. icons	5	4	3	2	1
2.8. I can see the controls better if I ignore some of the details such as:					
2.8.1. Colors	5	4	3	2	1
2.8.2. Layout	5	4	3	2	1
2.8.3. Text format	5	4	3	2	1
Note:					

3. How would you evaluate the overall complexity of the control room?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
3.1. The control room is too busy from a visual perspective.	5	4	3	2	1
3.2. Displays are easily distinguishable at first glance.	5	4	3	2	1
3.3. Control devices are easily distinguishable at first glance.	5	4	3	2	1
3.4. The displays are readable from my control station.	5	4	3	2	1
3.5. I have to stare at the displays for a while to read the information.	5	4	3	2	1
3.6. Adequate space between different displays exists.	5	4	3	2	1
3.7. Adequate space between different control devices exists.	5	4	3	2	1
3.8. I have difficulty remembering what different alarms mean.	5	4	3	2	1
3.9. I can effectively acquire information.	5	4	3	2	1
3.10. The control room layout is simple and easy to work in.	5	4	3	2	1
3.11. It is sometimes difficult to find all the information I need.	5	4	3	2	1
3.12. I do not like the control room layout because it is too complex.	5	4	3	2	1
3.13. I can effortlessly understand the information presented in the control room.	5	4	3	2	1
3.14. Working in this control room takes a significant amount of mental effort.	5	4	3	2	1
3.15. I feel overwhelmed by the amount of information presented.	5	4	3	2	1
3.16. More displays are needed in the control room.	5	4	3	2	1
Note:					

4. How would you evaluate the overall complexity of the displayed information in the control room?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
4.1. I can easily identify an alarm in a timely manner.	5	4	3	2	1
4.2. I have difficulty recognizing the situation when an alarm sounds.	5	4	3	2	1
Note:					

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
5. Some of the information presented in the control room is frequently updated. How do information changes on the displays affect the way you process information?					
5.1. Most information changes are predictable.	5	4	3	2	1
5.2. Most information changes are easy to track.	5	4	3	2	1
5.3. Keeping track of information changes distracts me from performing my primary tasks (makes me too busy).	5	4	3	2	1
5.4. The displayed information should change less frequently.	5	4	3	2	1
Note:					

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
6. How do the physical interactions within the control room affect you?					
6.1. The interaction with the control devices requires too many actions to perform tasks.	5	4	3	2	1
6.2. The amount of interaction required to perform tasks does not bother me.	5	4	3	2	1
6.3. The interactions required to accomplish my tasks can confuse me.	5	4	3	2	1
6.4. I feel overwhelmed by the amount of interaction required by the system.	5	4	3	2	1
6.5. I have to manage more than one action sequence to get a task done.	5	4	3	2	1
6.6. I can perform most tasks by following a single action sequence.	5	4	3	2	1
6.7. I might forget the actions needed to complete a task when I am busy.	5	4	3	2	1
Note:					

7. **How does going through procedure steps affect your performance?**	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
7.1. I have to access too many displays to perform a specific task.	5	4	3	2	1
7.2. I can effortlessly follow procedures to acquire information.	5	4	3	2	1
7.3. I can effortlessly follow procedures to perform tasks.	5	4	3	2	1
7.4. I have trouble performing tasks because there are so many steps in the procedure.	5	4	3	2	1
7.5. I have difficulty keeping track of constant action items in the procedure.	5	4	3	2	1
7.6. I use workarounds (post-it notes, etc.) to remember more than one procedure step at a time.	5	4	3	2	1
7.7. The environment around me (e.g. alarms) adds to my stress level.	5	4	3	2	1
Note:					

Part III

1. How long is your shift? What do you typically do during this time?

2. What percentage of your shift do you consider as low workload? Have you ever felt bored during your shift?

3. What percentage of your job involves monitoring digital displays? How many do you typically monitor? Is this more or less than what you need?

4. Can you imagine a situation where an operator could feel overloaded by the information available to him/her on the displays? Please explain.

5. Can you imagine a situation where an operator would want more information available to him/her on the displays? Please explain.

6. Can you name some of the mistakes that could happen in your work environment (e.g. near miss, major incident, minor incident, easily forgotten mistake)? What are the causes of these mistakes?

7. In an alarm situation, how would you rate (easy to difficult) transitioning from steady state monitoring to an emergency procedure? How long does it take to find the necessary information to execute a procedure?

8. How often do you encounter alarms? How long does it take to understand the situation?

9. What is the most important information you look at? Why is it the most important?

10. How complex is your job? What makes it complex or not?

11. What is the most complex display you look at/interact with? What makes it the most complex?

12. How would you change the following list of major responsibilities of a nuclear power plant operator? (Add, combine, subtract)

    Responsibilities:
    - Reactivity control
    - Maintain reactor core cooling
    - Maintain reactor coolant system integrity
    - Maintain containment integrity
    - Control of radioactive effluents
    - Start-up control
    - Steam generation
    - Electricity generation
    - Shutdown & Refueling control
    - Fuel Management

Do you have any other comments or suggestions?

APPENDIX B: HERA DATABASE ANALYSIS

Event	Indian Point 2 2/15/2000		Browns Ferry 1		Salem 1		North Anna 1		Crystal River 3		Calvert Cliffs 1	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)	1			1								3
Simultaneous tasks with high attention demands	5	1			10	1	3	1	2			
Extensive knowledge regarding the physical layout of the plant is required	1	1		1							1	
Coordination required between multiple people in multiple locations		1										
Demands to track and memorize information	1				2							
Ambiguous or misleading information present	1								3	1		
Information fails to point directly to the problem	1	2			4		1		3			
System dependencies are not well defined	1										5	
Scenario demands that the operator combine information from different parts of the process and information systems				3	2						3	6
Loss of plant functionality complicates recovery path				4								
Presence of multiple faults				1								
Problems in differentiating important from less important information					1		2				5	
Other						1						
Worker distracted/ interrupted					1		1					
High number of alarms							1	1				
Weak causal connections exist											1	
General ambiguity of the event									3			3
Dependencies well defined (pos)												
Few or no concurrent tasks (pos)												
Difficulties in obtaining feedback												
Complexity Sums	11	5	0	10	20	2	8	2	11	1	15	12

	Waterford 3		La Salle 2		Quad Cities 2		Davis-Besse		Point Beach 1		Indian Point 3	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)												
Simultaneous tasks with high attention demands	1	1	3	1								
Extensive knowledge regarding the physical layout of the plant is required												
Coordination required between multiple people in multiple locations							10					
Demands to track and memorize information												
Ambiguous or misleading information present			1				1					
Information fails to point directly to the problem			1				13					
System dependencies are not well defined		1										
Scenario demands that the operator combine information from different parts of the process and information systems			1									
Loss of plant functionality complicates recovery path												
Presence of multiple faults			1									
Problems in differentiating important from less important information							32		18			
Other												
Worker distracted/ interrupted												
High number of alarms												
Weak causal connections exist			1				5					
General ambiguity of the event												
Dependencies well defined (pos)		1								1		
Few or no concurrent tasks (pos)										1		
Difficulties in obtaining feedback	1						7					
Complexity Sums	2	3	8	1	0	0	68	0	18	2	0	0

	Indian Point 2 (8/14/2003)		Ginna		Fermi 2		FitzPatrick		Comanche Peak 2		Wolf Creek	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)												
Simultaneous tasks with high attention demands											4	
Extensive knowledge regarding the physical layout of the plant is required											1	
Coordination required between multiple people in multiple locations		1										
Demands to track and memorize information												
Ambiguous or misleading information present												
Information fails to point directly to the problem												
System dependencies are not well defined												
Scenario demands that the operator combine information from different parts of the process and information systems												
Loss of plant functionality complicates recovery path												
Presence of multiple faults						1						
Problems in differentiating important from less important information											2	
Other												
Worker distracted/ interrupted									1			
High number of alarms												
Weak causal connections exist											3	
General ambiguity of the event				1							4	1
Dependencies well defined (pos)												
Few or no concurrent tasks (pos)												
Difficulties in obtaining feedback												
Complexity Sums	0	1	0	1	0	1	0	0	1	0	14	1

	Diablo Canyon 1		Palo Verde 1 6/14/2004		Peach Bottom 2		Palo verde 1 7/30/2004		
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	Complexity Type Totals
Causal connections apparent (positive)									5
Simultaneous tasks with high attention demands			11	3	1				48
Extensive knowledge regarding the physical layout of the plant is required		2				1			8
Coordination required between multiple people in multiple locations		3	4						19
Demands to track and memorize information									3
Ambiguous or misleading information present							4		11
Information fails to point directly to the problem			4						29
System dependencies are not well defined			1				8	1	17
Scenario demands that the operator combine information from different parts of the process and information systems			2						17
Loss of plant functionality complicates recovery path	1	2							7
Presence of multiple faults		2	5						10
Problems in differentiating important from less important information			2						62
Other									1
Worker distracted/ interrupted									3
High number of alarms			1						3
Weak causal connections exist					1				11
General ambiguity of the event									12
Dependencies well defined (pos)									2
Few or no concurrent tasks (pos)									1
Difficulties in obtaining feedback									8
Complexity Sums	1	9	30	3	2	1	12	1	277