1999

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DOI: <https://doi.org/10.31979/etd.c5db-f3br>

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EVALUATION OF ALARM REDUCTION SCHEME USING SIMULATION
SOFTWARE

A Thesis

Presented to

The Faculty of the Program of Human Factors/Ergonomics

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Richard Gutiérrez

August 1999

UMI Number: 1396179

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ABSTRACT

EVALUATION OF ALARM REDUCTION SCHEME USING SIMULATION
SOFTWARE

By

Richard Gutiérrez

Published guidelines for alarm reduction schemes in nuclear power plant control rooms have hypothesized that operator task performance time would be reduced following the implementation of an alarm reduction scheme. By reducing the operator's task performance and decision-making time, the operator's mental workload and error performance potential is reduced. Using a personal computer (PC) based simulation program, an alarm reduction scheme proposed by regulatory guidelines was evaluated. Unique to this study is that the participants were also simulated. Six simulated two-person crews performed a postulated power plant scenario. The results of the simulation model indicated a significant reduction in the amount of time that the crew spent responding to alarm system audio and visual alerts and verification of associated plant parameters. A comparison of the results of the modeled conventional alarm system with those of the reduced alarm system indicated a reduction in operator physical workload. Though not directly measured by the simulation model, the reduction in task performance times indicate a potential for a reduction in the mental workload of the operator crew. The findings of this thesis support that operator reliability can be expected to improve if factors contributing to operator errors such as nuisance alarms are reduced or eliminated.

ACKNOWLEDGMENTS

I would like to thank my advisors Drs. Louis Freund and Kevin Corker and Mr. Jay Jelinek for their support and expertise during the preparation of this thesis. I would also like to thank my colleague at General Electric, Mr. Jerold Marks for his contribution of operations and alarms in the thesis review process. Drs. Louis Freund and Kevin Corker, thank you for sharing your knowledge and time during my three and a half years in the Human Factors Program. Dr. Freund has increased my knowledge and application of ergonomic principles. This knowledge has been effectively applied in operator anthropometry and full scale mock up evaluations for the design of a power plant control room. Dr. Corker's human-system interface courses have increased my knowledge of system and human models and their application in the evaluation of human-computer interaction interfaces.

And also my sincere gratitude to my wife Candyce and daughter Megan Ana, who gave me their support, but most important, my time away from them on evenings and weekends over the past three and a half years, so that I could complete this work.

TABLE OF CONTENTS

	<u>PAGE</u>
LIST OF TABLES	viii
LIST OF FIGURES	ix
INTRODUCTION AND BACKGROUND	1
Alarm System Shortcomings	3
Nuisance Alarms	6
Prior Work Related To Alarm Systems	8
Advanced Control Room Designs and Automation	12
Alarm Suppression and Priority Schemes	16
Human Error, Scanning and Reading of Annunciated Displays, and Human Performance Modeling	18
Performance Shaping Factors	23
Mode Awareness	24
Supervisory Models of Nuclear Power Plant Operator Performance	26
Analysis Methodologies	31
METHOD	35
Plant Scenarios and Plant Data	36
Micro Saint [®] and Network Modeling	38
Participants	39
Apparatus	39
Procedure	39

Software Model Development	42
Statistical Calculations of Software Model Data	48
RESULTS	50
DISCUSSION	53
Recommendations For Future Reviews	60
BIBLIOGRAPHY	64

LIST OF TABLES

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
1	Probabilities of Error for Annunciator Legend Lights	72
2	Taxonomy of Errors	73
3	Task Analysis for large Steamline	74
4	Data for Alarm System Task Network Model	78
5	Decision Node Descriptions	83
6	Statistical Results of Operator Network Model for Conventional Alarm System And Alarm System With Reduction Scheme Implemented	84
7	Raw Data for Micro Saint [®] Primary Operator Alarm Response Models	85
8	MINITAB [®] Descriptive Results for Primary Operator Task Performance (Without Secondary Operator) for Micro Saint [®] Simulation Models	86
9	T- Tests for Before-and-After Measurements of the Effect On Operator Task Performance By Implementation of Alarm Reduction	87

LIST OF FIGURES

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
1	Alarm System At A Conventional Nuclear Power Plant Control Room	88
2	Sketch of the Main Control Panels for An Advanced Boiling Water Reactor (ABWR)	89
3	Supervisory Control Model Structure	90
4	Decision-making Process Activities Based Upon States of Knowledge	91
5	Micro Saint [®] Model With Conventional Alarm System	92
6	Main Control Room Panel Arrangement of Reference Plant Used As Data Source	93
7	Model of Operator Response To Conventional and Alarm Reduction Schemes	94
8	Description for Subtask op2a	95
9	Description for Subtask op2b	96
10	Description for Subtask op2c	97
11	Variables for Alarm Reduction Model	98
12	Micro Saint [®] Model of Drywell Steam Line Break Model for High (-3SD), Average (SD), and Low (+3SD) Skill Level Tasks Without Alarm Reduction	99
13	Micro Saint [®] Model of Drywell Steam Line Break Model for High (-3SD), Average (SD), and Low (+3SD) Skill Level Tasks With Alarm Reduction	100
14	Description of Decision Dialog Box for Decision Node op6b	101

LIST OF FIGURES

15	Description of Decision Dialog Box for Decision Node op9a	102
16	Description of Decision Dialog Box for Decision Node OP15	103
17	Description of Decision Dialog Box for Decision Node OP26	104
18	Summary of Means For Alarm Reduction Tests	105
19	Box Plot Details For Alarm Reduction Tests, High Skill Crew Tests	106
20	Box Plot Details For Alarm Reduction Tests, Average Skill Crew Tests	107
21	Box Plot Details For Alarm Reduction Tests, Low Skill Crew Tests	108

INTRODUCTION AND BACKGROUND

Prior to the accident at Three Mile Island (TMI), the need to improve the human factors engineering (HFE) of alarm systems had been documented in studies performed by the Electric Power Research Institute (EPRI) (Seminara, Gonzalez, & Parsons, 1977). On March 28, 1979, at the TMI nuclear plant in Pottstown, Pennsylvania, over one hundred alarms overwhelmed the operators with flashing lights and blaring horns. With so many alarms (as many as two hundred at a time) annunciating in the early stages of the event, the operators had no way to diagnose the important anomalies taking place (Kemeny, 1979). Once the alarm system has the operator's attention, the operator must visually search the up to 2500 alarm tiles to detect the illuminated tile or tiles that indicate to the operator which system function, component, or parameter is really in an abnormal state. Having found the tile or tiles, the operators then diagnose, based upon training, procedures and experience, whether it is actually an alarm, or merely a change of state caused by the system's response to the real problem.

Published U.S. regulatory guidelines related to human factors guidelines for nuclear plant control room alarm systems have hypothesized that reducing the number of alarm messages presented to the operating crew during -off-normal conditions will support the crew's ability to detect, understand, and act upon all alarms that are important to the plant condition within the necessary time. The premise is that if the operator is freed up from responding to nuisance alarms, then there is more time available to attend to important alarms.

At first glance, the solution appears obvious, just reduce the number of alarms presented to the operators. Since there are no specific guidance available to the alarm system designer on the degree of alarm reduction required to support operator performance, the alarm system designer must evaluate the proposed alarm reduction scheme with plant operators to assess the effectiveness of the proposed alarm reduction process. The evaluation of operator task performance is necessary to allow the designer to quantify the benefits of the alarm reduction. The benefits, if any, must be presented to the plant management and regulatory agencies to support the proposed changes.

This thesis investigates the hypothesis that alarm reduction will reduce operator task performance time, thus allowing the operator more time to attend to important alarms being presented by the alarm system.

Using an operating crew consisting of two operators, it is hypothesized that the mean task performance time of the experienced operating crew, or higher skill level will be significantly less when compared to that of the task performance mean time of operating crews that are staffed by members with average and less than average skill levels. The task performance times of the three skill levels in responding to alarm-related tasks for conventional and reduction schemes will be evaluated.

Due to the limited availability of plant operators and the high cost of utilizing a full scope plant simulator, a simulation software package will be used to develop a simulation model of an existing alarm system configuration. The alarm system configuration is based upon an existing nuclear plant system and task analysis of operator responses. The baseline configuration of alarms will then be modified accordingly to

simulate an alarm reduction scheme. Using the alarm reduction simulation model, the operator task performance mean times will be modified.

Like an experiment using real operators, a distribution of personnel skill levels will be utilized. An assumption is made that the more experienced operator will respond quicker to the performance of alarm response tasks when compared to the response times for average or less experienced operators. To create the three experience levels, the operator task performance mean times will be modified as follows: The existing alarm system without alarm reduction will be performed using the Mean data from the conventional or baseline configuration. The alarm system with the reduction scheme will be performed using this same Mean data. Two other alarm reduction models will be run. One with +3 standard deviation (SD) to reflect the inexperienced operating crew or slower crew. A second model using -3SD to reflect the more experienced or faster operating crew. The task performance Mean times of the three operating crews will be compared. The simulation model will be modified further to isolate the response tasks for the primary operator from those of the secondary operator.

Alarm System Shortcomings:

1) In addition to the other HFE deficiencies, the EPRI studies focused on the inability of the plant annunciator (alarm) system to adequately provide the operating crew with information about important plant state changes. More importantly, the alarm systems at the operating nuclear plants did not clearly separate true alarms from system operation status. Because most plant alarm systems do not “know” what operating mode the plant is in, “nuisance” alarms are presented to the operating crew. As illustrated in

Figure 1, conventional alarm systems may alert the operator that a pump is starting, though it is part of the ‘expected’ normal operation of that system for the present mode of the plant. The EPRI studies concluded that there needed to be a systematic approach in how the “alarms” were defined for display to the operators.

2) A second shortcoming of the alarm systems was the limited capacity of the plant computer systems to process all the plant information needed by the alarm system. Pre-TMI era nuclear power plants relied on fast speed printers to capture all of the alarms that are being presented in the control room. The operators sorted through the many printer output pages to pick out the serious alarms from normal plant process alarms. After TMI, plant computers were upgraded, including the ability to store more plant parameter data and to utilize both printers and CRT displays to present alarms in a prioritized manner.

3) A third deficiency noted by the EPRI studies was the manner in which alarms are presented to the operators. The conventional control room alarm systems use audio cues that consist of horns, chimes, or a combination to alert the operator of a plant or system state change. The visual cue to the operating crew is provided by hundreds of rectangular tiles or windows. Figure 1 (Gutiérrez, 1996) illustrates these tiles. The tiles consist of engraved, translucent “tiles” that are illuminated by white, yellow, red, or green colored lamps, depending on the severity of alarm. In addition to the tiles, conventional plants also utilize cathode-ray tubes (CRTs) and fast line printers to present parameters that are in alarm. The CRT displays the alarmed parameter, displaying to the operator the parameter alarm limits, the present alarm value of the parameter, and the

time and date of the alarmed parameter. During a plant abnormal or emergency event, so many component state changes are displayed in chronological order, that the allocated alarm pages on the CRT display pages fill up and the operator must page through the many CRT display pages, because the more important alarms may be hidden off the screen on another page. The higher priority alarms are not automatically displayed at the top of the displayed alarm list or 'stack'. The information displayed on the CRTs is also presented through the use of high speed printers. These printers are also used by the operators to request plant computer data from nuclear industry specific programs such as fuel core monitoring programs.

4) Another important deficiency of conventional alarm systems, though not addressed in this thesis, is their inability to present alarms in some form of prioritized format. Based upon regulatory and plant emergency procedure guidelines, there is a predefined set of alarms that require immediate operator action, based upon their importance to plant safety. The alarm system alerts the operators of a potential problem, but it should also inform the operators of the priority and nature of the deviation. With all of the alarms that may be displayed during a major anomaly, the operators need assistance in focusing their attention on time-critical alarms. For both conventional and advanced nuclear plants, plant information systems should provide orienting cues that aid the operator in recognizing or recalling display locations and access methods. During off-normal events, such as when a water injection pump fails to start, larger demands are placed on the operator's short- and long-term memory. In these postulated transients, the operator will encounter from 100 to 400 visual and audio cues from the plant alarm

system. Postulated transients are those transients that the plant systems are designed to address and that the operating crew have been trained for their response. Recall from long-term memory is generally worse for information that is infrequently used (Wickens, 1992). During these transients, the operators are trying to recall from memory, those parameters that are relevant to the plant states and those alarms with their corresponding parameters that are nuisance alarms.

Nuisance Alarms

Figure 1 presents an example of the alarm system at a conventional nuclear plant control room during a plant start-up. Illuminated tiles in the figure are not alarms, but expected component and system changes based upon actions being taken by the seated operator in starting up the plant. The operators have memorized these parameter limits and verify them with the indication meters provided on the control panels. The figure also illustrates one of the most common operator complaints, that there are too many nuisance alarms during plant start-up, a time-critical and stressful phase of operation for the plant operator. During a plant upset such as losing off site power due to a tornado strike on the plant's switchyard, the problems associated with nuisance alarms become more critical. Under these time-critical conditions, the operator must visually search the 1500 to 2500 alarm tiles to detect the illuminated tile or tiles that indicate to the operator which system function, component, or parameter is really in an abnormal state. Having found the tile or tiles, the operators then diagnose, based upon training, plant operating procedures, alarm response procedures (ARPs), and experience, whether it is actually an alarm, or merely a change of state caused by the systems's response to the real problem.

The operator must remember the multiple alarms for a given tile or review in the ARP for that tile, to diagnose the actual cause of the alarm. The operators then sort through the information displayed on the meters and CRTs located on the control panels, the information presented on the high speed printers, and separate the alarms from the “nuisance” or non-alarms. Based on studies conducted at nuclear plant simulators, during real plant events, these nuisance alarms increase the mental workload of the crew in trying to sort out the “real” alarms from the nuisance alarms. Using EPRI guideline documents, nuclear plants reviewed and reduced the number of alarms (MPR Associates, 1985). Though conventional nuclear plants have upgraded their alarm systems and increased their reliability, most utilities have not undertaken the time-consuming task of reviewing all of the alarms in their plant computer database and filtering those that are not necessary.

Another form of nuisance alarms are those alarms that indicate change of component status. At many plants including the four reviewed, a pump start may be alarmed even though it is a part of expected operation. That system designer for those plants chose to provide feedback to the operator by means of an alarm. Roscoe and Weston (1986) believe that 15 to 20 percent of the annunciators fall into this category. This coincides with the findings of operators interviewed by Seminara et al., 1977, who indicated that as many as 15% to 50% of the alarms per shift were false or nuisance. Another aspect is the effect of the HEDs on the performance of the operator. As Roscoe and Weston (1986) point out, the operators typically receive as many as eighty-one (81)

alarms within a 120 second time period. In addition to obscuring the alarm signature or root cause, the number of alarms can be overwhelming to the operators.

Prior Work Related To Alarm System Modifications

Between 1980 and 1992, many studies and papers have been presented related to alarm systems, the changing role of the operator, and the affect of situation awareness on the performance of power plant operators. These studies and papers have pointed to the need to aid the operator in the decision- making process. Conventional alarm systems only make the operators aware of a problem. Because of the many alarms in the control room, the decision-making process, tasked the operation crew's knowledge and capability. The same studies and papers have identified various options available to the alarm system designer in the design, development and test of the proposed alarm system.

U.S. industry and government regulatory groups (MPR Associates, 1984; O'Hara, Brown, Higgins, & Stubler, 1994; O'Hara et al., 1996) have also provided guidelines for improving the control rooms, the alarm systems, and the human-computer interaction associated with new technologies being proposed. International groups have also performed studies related to improvement of alarm systems.

In an effort to aid the power industry, the Electric Power Research Institute (EPRI), a electrical utility funded organization, performed independent studies and established programs to assist the utilities with specific issues. One early report documented the human engineering discrepancies (HED) identified at five operating NPPs in the U.S. (Seminara et al., 1977). This report, published prior to TMI, identified the problems associated with NPP alarm systems. EPRI has also published other reports

that focus directly on the review and correction of HEDs associated the NPP alarm systems (MPR Associates, 1984, 1985). These reports reinforce the problems with conventional control room alarm systems and provide methods by which operating plants can improve their existing alarm systems.

The U.S. Nuclear Regulatory Commission (U.S. NRC) has also provided resources and funding for studies related to alarm system recommendations (Banks & Boone, 1981), studies related to display of alarms on CRTs (Danchak, 1982), plans for conducting experiments related to alarm prioritization (Roscoe & Weston, 1986) and reports related to modelling of supervisory control systems (Baron, Feehrer, Muralidharan, Pew & Horowitz, 1982). USNRC human factors engineering guidelines related to application of human factors in control room design and reviews have also been prepared for the use by the U.S. power industry (O'Hara et al., 1994, 1996). The HFE criteria presented in early and contemporary HFE guidelines from the U.S. NRC is based largely on established U.S military requirements for design and review of military facilities. Some additional information related to computer peripherals and software has been included in the most current U.S. NRC HFE guidelines (O'Hara et al., 1996). In response to regulatory requirements following TMI, U.S. utilities conducted reviews of their control rooms using checklists, questionnaires, operator interviews, and environmental (e.g. lighting, heating, etc.) measurements of the control room, using established HFE criteria for human capabilities and limitations. The reports provided guidance at different conceptual and design levels. For plants with existing alarms displayed on CRTs, guidelines are defined for effective use of CRTs (Danchak, 1982).

Roscoe & Weston (1986) provide a plan methodology by which an alarm system can be developed and evaluated. Their approach is discussed later in this thesis. The common thread of all of these studies is the same. The role of the operator must also be considered during the design of an alarm system.

As a part of the U.S. power plants surveys, HEDs related to alarm systems were also identified. The reports from four reviews submitted to the U.S. NRC public document room (PDR) were obtained and the checklists and summaries related to alarm system HEDs were reviewed. Though all four plants have conventional control consoles and alarm systems, at three of the plants, operators use CRTs, including one with a sit-down console, to view computer generated displays of plant system status. The operators are able to view, but not control the systems from the CRTs. These CRTs are also used by the operating crews to view process alarms.

At the reference plant selected for this thesis (U.S. NRC, 1985), the operators stand in front of eye-level CRTs to view computer-generated displays of plant systems. The CRTs are used during normal and abnormal operation. Though the plant makes extensive use of the CRTs, the operators' primary interface with the plant is still through the use of conventional meters, control switches, recorders, and a conventional tile window alarm system.

The four power plant survey reports point to a need for prioritized alarms, reduction of nuisance alarms, and a feature referred to as a 'first-out' alarm. First-out alarms are typically characterized as auditory and visual signals for time critical events that require immediate attention. These "first-out" features are an attempt to focus the

operator's attention on existing alarm systems that may have too many nuisance alarms.

HEDs related to the plant's alarm system were highlighted during the performance of the checklist and operator interviews. Since that time, many plants have implemented programs to highlight the 'first-out' alarms, though there is a belief by some operators and training staff that focusing on first out alarms may divert the operator from the true alarms. A parameter alarm may cause a Turbine or Reactor Trip, but that parameter, though the first in, may not necessarily be the real problem or most urgent component requiring operator attention. Nuisance alarms have been reduced at some of the four plants by reviewing the alarms and simply correcting the setpoints at which they will alarm, thus only addressing those alarms caused when the measured parameter 'bounces' up and down. One plant reported that as many as fifteen alarm tiles are continuously illuminated during normal plant operation. The plant staff addressed this HED by placing green tape on those tiles.

The OCED Halden Project is another organization that is also funded by utilities. Headquartered in Halden, Norway, it is supported by both European and U.S. utilities and government agencies. The Halden Project, a private organization, hosted workshops related to computerized alarm systems (OECD October 1992) and have continued their development of function and knowledge-based alarm systems (OECD April 1993; OECD May, 1996). More importantly, these studies have focused on implementation of computer-based alarm handling and display based upon models of human performance. While expanding the understanding of alarm handling and human performance, these studies have also contributed to the methodology being applied in the design of

contemporary alarm systems and design criteria (O'Hara et al., 1996). The Halden Project work in computerized alarm systems and models of human performance has contributed to the model for the alarm criteria prepared by the U.S. regulatory agencies (O'Hara et al., 1996). The OCED alarm methodology focuses on an alarm concept that defines a criteria that should be used by alarm system designers. Their work in NPP operator models supports their criteria that the alarm should alert, inform and guide the operator. Following the operator's actions, the alarm system should aid the operator by confirming that the correct operator action was taken.

Advanced Control Room Designs and Automation

In 1988, General Electric (GE), Hitachi, and Toshiba began a cooperative program to design a 1350 Mwe advanced boiling water reactor (ABWR) (Ross, 1993; Gutierrez & O'Neil, 1993; Gutierrez & O'Neil, 1994). The first application of that design is currently being demonstrated at the two Kashiwazaki-Kariwa 6 and 7 plants in Japan. These two plants have incorporated advanced human-system interfaces (HSI) and automatic functions throughout the plant. Functions that were previously monitored or initiated by the operator are now monitored and initiated by the plant's computer systems.

The key features of the ABWR control room design are a compact main control console (MCC), the central area for operator monitoring and control of plant functions, and an integrated wide display panel (WDP) that presents the operating crew with an overview of the plant status. The ABWR HSI addresses the deficiencies of pre-TMI designs through integrated design of the plant systems. In the plant's main control room, this includes the control room layout, console design, procedure development, and

training (O'Hara et al., 1996). Complete plant control is achieved from the main control console (MCC) for all phases of plant operation. This sit-down console design incorporates touch-screen flat displays and cathode-ray tubes (CRTs) technology. A limited set of conventional switches have been allocated for initiation of safety systems. Figure 2 presents a "sketch" of this concept. As depicted in the sketch, the WDP, a multi-section 12 foot high, large vertical panel, summarizes information about plant status, critical plant parameters, and more importantly, key plant and system-level alarms. From left-to-right, dedicated alarm panels, a fixed-position mimic, and four large visual display units (VDUs) at the right, provide the seated operators at the MCC with an overview of the plant's system status. Using information and controls displayed on the CRTs and flat panel displays (FPDs), the operators diagnose and respond to initial cues received from the WDP. Figure 2 also illustrates the concept of using a WDP to present critical plant alarms on the left side, a fixed-position mimic display in the center, and four large visual display units on the right. System-level alarms for each system are displayed above the fixed-position mimic.

An important feature of the ABWR is the application of automation technology to tasks that were previously performed by the operator. The tedious and stressful task for the operator of moving control rods during plant start-up is automated. This application of automation features for the plant operation has changed the role of the operator from monitoring and control to a stronger more focused supervisory role. Due to the increased levels of automation, there is a larger potential that the operator will have less participation in the direct operation of the plant. This reduces the physical workload but

increases the operator's mental work load. This new role may challenge the operator's ability to maintain awareness about the system and subsystem status. This becomes more important when monitoring systems with multiple modes that may change based upon overall plant modes. The operator's awareness of the system modal changes is tested during postulated events (Woods & Roth, 1988).

In 1996, GE was awarded a contract to design and construct two ABWRs in Taiwan. Using past experience at conventional nuclear plants, the design of the operating ABWRs in Japan, relevant human factors research related to alarms (OECD February, 1992, April 1993, May, 1996; O'Hara et al., 1996), and information processing has been incorporated into the design of the HSI for the Taiwan project. In addition to the incorporation of past experience, the advanced alarm system of Taiwanese project is based upon U.S. regulatory and utility requirements for computerized alarm systems (O'Hara et al., 1996). The alarm system presents information to the operating crew that guides their initial response to the auditory and visual information presented by the alarm system. When the crew performs a corrective action, which may include performance of a plant procedure or monitoring automation actions performed by the plant systems, the alarm system contributes to the operator's knowledge regarding the specific parameter or system state change. This advanced alarm system provides the operating crew with visual flashing windows, audio tones, and selected text messages that direct the operator to system-specific computer generated displays that aid the operator in determining the cause of the alarm.

With the introduction of computerized (automation) plant startup and shutdown, diagnostic capabilities, and computer generated graphic displays, the operator's cognitive load has increased as the operator is required to monitor these new automation processes assigned to the operator (Woods et al., 1988). The human-automation interaction relationship has been well documented in the context of commercial airline cockpits (Sarter & Woods, 1995), anesthesia management for surgery (Charante, Cook, Woods, Yue & Howie, 1993), and in the NPP process control (Woods, O'Brien & Hanes, 1987). The automation process at a nuclear plant poses similar demands for the operator as at other automated process plants. Automation has increased the task time allocated to purely monitoring a process, only intervening in the process if a problem arises. Systems that the operator might initiate are now initiated automatically. This increases the demand on the operator to be cognizant process mode changes. This same demand is also exists for the system designers who must consider these mode changes in the design of the operator interfaces. Placed in this new environment, the operator must now identify and diagnose problems using mental models that are different from those use at conventional power plants (Rasmussen, 1984; Woods., Roth & Hanes, 1986a, Woods et al., 1986b; Woods et al.,1988). Monitoring during normal operation and emergencies in dynamic environments have also been compared to other domains such as airplane cockpits (Roth, Mumaw, Vincente & Burns, 1997). Both the nuclear plant control room and airplane cockpit demand selective attention that is dependent on an assessment of the situation.

Alarm Suppression and Priority Schemes

In the ABWR design, only failures of equipment operation are alarmed. Expected pump start-ups or valves opening or closing are not alarmed. More importantly, the alarm system is aware of plant operating modes, ensuring that the alarm system will not provide nuisance alarms like those illustrated in Figure 1. The advanced alarm system presents the operator with plant system symptoms. Using this process, and working as a team, the operators identify symptoms, define the problem, and identify a possible event that may require further action by other plant staff. After the operator has taken the necessary action(s), the alarm system uses visual and auditory feedback to inform the operator if the corrective action taken was successful. Alarm filtering process has been implemented to limit the number of alarms presented to the operating crew. Based upon the plant's power ranges, the alarm system only displays those alarms that are consistent with the present plant power range.

Similar to automobile warnings displayed on the dash board, the alarm system implements a darkboard concept and alarms are not displayed to the operator unless in alarm. During normal plant operation, alarm tiles are not illuminated with fixed or variable text unless an abnormal plant system or function state change has occurred. The operator's ability to focus on time-critical alarms is enhanced through the development of a prioritization dimension to alert the operator of those alarms that require immediate operator action.

Detailed operator action in response to alarms is performed at the MCC using the modes of human-computer interaction (HCI) provided on the CRTs and flat panel

displays (FPDs). Implementation of plant system automation and computerized alarm systems further emphasizes the changes made to the model of the operator from an active participant to that of a supervisory monitoring role (Sheridan, 1987; Stanton, 1994). Development of the advanced alarm system must address this supervisory role and the cognitive tools required to monitor these automation processes (Woods & Roth, 1988). As described by Baron (1982), the supervisory role of the operator provides for monitoring, situation assessment, decision making, and operator action. Figure 3 illustrates this supervisory control model and the interrelationship between the operator and the system, including the important feedback process. The operator must now identify and diagnose problems using mental models that are different from those used at conventional power plants (Woods & Roth, 1988; Rasmussen, 1984). Operators at nuclear power plants (NPPs) must rely on up-to-date knowledge of situation parameters to manage the plant processes accurately. Based upon their knowledge operators must observe the state of numerous system parameters, state changes, and relational patterns between them, which all allow the operator to determine the present and future process changes based upon those patterns (Endsley, 1995). The operator uses rules, procedures, checklists in his decision-making process. These form some of the sources of the operator's static knowledge related to situation awareness (SA). To understand the situation, the operator pieces together bits of data on individual system variables to determine how good, different system components are functioning. Being aware of deviations from expected values is also a part of this SA process. The reduction of alarms supports the operator's SA process. By providing the operating crew with only

valid system states and eliminating nuisance alarms, the operating crew is able to focus on time critical tasks and monitor plant processes. The operator's awareness of plant states and changes affecting them is improved by this reduction of unnecessary information and tasks.

Human Error, Scanning and Reading of Annunciated Displays, and Human Performance Modeling

According to Swain and Guttman (1980), humans have acted not only as accident initiators and accident propagators, but also accident mitigators. Human error has been defined as being a deviation from expected human performance. The criterion for an error must be defined to distinguish between human behavior or the result of an interaction of the human-machine system as a whole. An error may be a single malfunction that leads to a complete failure of the task with no means of recovery. A mistake may be a single malfunction that is left unrecovered, would lead to a complete failure of the task. A slip would be a continuous malfunction that is not recovered that would result in the task being performed outside of the defined limits of the task.

Statistical computations of error reduction as a correlation of reduced alarms is not emphasized in this thesis. But it is beneficial to state some foundation for how errors may affect operator performance in their response to cues from alarm systems. In describing probabilities of error related to scanning and reading of annunciated displays, Swain and Guttman (1980) have presented a model of situations in the control room: 1) steady-state operating mode (i.e., the normal power generating condition in the plant), 2) maintenance or calibration operations involving control room personnel, 3) anticipated

transients, and 4) loss-of-coolant accidents (LOCAs). The basic measure of human performance is the human error probability (HEP). The HEP is the probability that when a given task is performed, an error will occur. The HEP is expressed as

$$\text{HEP} = \frac{\text{number of errors of a given type}}{\text{number of opportunities for the error}}$$

The probability that a task will be performed successfully is defined as 1-HEP. The error probability is the probability of unsuccessful performance per demand. There are many factors that may affect human performance. Some of these performance shaping factors (PSF) are external to the person in the system, and some are internal. Human reliability is affected by the entire work environment, especially the equipment design and the written or oral work procedures. The individual also contributes to his or her performance.

Psychological and physiological stresses may result from a work environment in which the demands placed on the operator by the system do not conform to the human's capabilities and limitations. As an example, if corrective action is not initiated within 1 minute after acknowledging the alarm, the probability that the action will be overlooked increases to 1.0 for some indeterminate period then declines (Swain and Guttman, 1980). This is an important concept because in most CRT based plants the information is now located on a display that may not be visible to the operator. The display may be obscured by some more recent display that the operator has requested. In addition to remembering the presence of an alarm, the operator must now remember where the alarm is located within the stacks. Table 1 identifies some probabilities of error for annunciated legend lights. In their studies, Swain and Guttman (1980) also identify errors related to

reading annunciator printer material, which for the ABWR , may be correlated to a computer generated list of alarms. A taxonomy of major types of possible errors are presented in Table 2 (Swain and Guttman, 1980, pp 10-2). From operator interviews, Swain and Guttman (1980) concluded that occasionally an operator forgot an annunciated indication after the sound and blinking of the light were canceled. This failure is infrequent when there are not competing signals. Swain and Guttman assigned a 10^{-4} (.00005 to .001) probability to this error. Swain and Guttman believe that for human responses, 10^{-4} is very small and signifies that 9,999 out of 10,000 times, the operator will initiate what he considers to be corrective action to a single annunciator within the allowed time. The error term of 10^{-4} applies to the act of responding, not to the accuracy of the action taken, which could consist of operating control switches, verifying displayed parameters, or communicating to other operators in the control room. Analysis work performed by Swain and Guttman (1980) assumes that the operators scan the lights at least once per hour. If corrective action is not initiated within 1 minute, after acknowledging the alarm, the probability that the corrective action will be overlooked increases to 1.0 for some indeterminate period then declines. The rationale is that the operator will take corrective action immediately after the alarm is acknowledged. If the operator does not, it is because an action of higher priority has demanded the operator's attention, thereby leaving the initial HEP at 1.0. The operator may not have taken action because of some other task or higher priority alarm. However, he may have forgotten the initial event while working on the second event, and the steady-on state of an acknowledged alarm is less compelling than one that is in an audio or blinking state.

Another error, according to Swain and Guttman, is that when the operator looks away from the blinking alarm tiles to locate the acknowledge pushbutton, the operator may return to look back at the incorrect steady-on lighted tile. This error is made likely by the numerous “normally on” alarm tiles, part of which do not require operator action. Rankin et al., (1985) have pointed out that the commercial airline industry has looked at voice alerts for time critical alarms. In their report for near-term improvements, they also suggest that for time critical alarms, pilots be provided with a 0.75 second tone that is automatically cancelled, followed by a voice command that must be cancelled manually. As the number of annunciators sounding increases, more personnel become involved, with a potential for communication errors between people. On some occasions, one operator may take actions that negate the actions previously taken by another operator (Seminara et al., 1977 and Kemeny, 1979). This problem has been remedied by new training and crew interaction techniques. As members of a crew, operators are being trained to make decisions and respond to plant process information as a team.

Anticipated transient events are perturbations in the steady-state operating condition of an NPP that may require rapid reactor shutdown. According to Swain and Guttman (1980), in 150 reactor years, no unanticipated transients have occurred, while there are about 10 anticipated transients per reactor year. The power industry considers anticipated transients as those transients which have been postulated to occur during the normal, abnormal, and emergency operations of the plant. This includes the probability of multiple events that have been considered in the design of the plant such as losing the ability to inject water into the reactor vessel while losing electrical power to the plant. As

would be expected, transients are very demanding of an operator's attention. The operator will focus on those annunciators directly related to the transient and will be less likely to attend to annunciated signals not directly related to the transient.

Information related to operator workload, errors, and automation was reviewed. Other sources provided theories, models and concepts related to human, and more specifically, human operator response in monitoring and control of complex systems such as alarm systems in NPPs (Morris & Rouse, 1993; Pew, Miller, & Feeher, 1982; Rouse, 1993; Roth et al., 1997; Senders & Moray, 1991). In addition to alarm systems, documents related to human performance modeling (HPM) (Lawless et al., 1995) has been reviewed. Human information processing and cognitive behavior need to be considered in the human performance model utilized in the design of control rooms (Rasmussen, 1986; Woods, Hollnagel, & Mancini, 1988). Engineering-based HPM such as illustrated by Figure 3 are quite different from conventional models that are more focused on traditional elements of psychology (Baron & Corker, 1989).

In addition to nuclear power plant control rooms, HPM have been used in other large complex systems such as aerospace and military projects. HPMs include in perception, human information processing, and cognitive behavior in their development. Predictive human-machine performance models are also based upon control theory models. Like control theory models, HPM require that human limitations be considered in the design of the other dynamic elements of the system. The performance issues of the control theory models are applicable to the operator model of the control room alarm system. Alarm system models are also associated with human-machine performance,

accuracy of control and information processing, system stability, and the ability to compensate for disturbances (Baron & Corker, 1989). Operators, in response to alarms, system parameter indications, and controls, functions as an information-processing or control-decision element in a closed loop system. An example of this interrelationship is illustrated in Figure 3. Closed-loop models, including HPM emerged from servo-mechanism paradigms. The alarm system HPM of the advanced reactor designs has followed a similar development process. It has emerged from an analog environment into a computerized and networked environment. Availability of computer processors that process, predict, display plant parameters must be considered in the HPM. Being aware of this interrelationship allows the alarm system designer to optimize alarm presentation to the operating crew.

Performance Shaping Factors

As part of the complex man-machine system, external and internal performance shaping factors (PSFs) may affect the operating crew's performance. The operator brings internal factors such as motivation, expectations, and job skills. External factors such as equipment design and plant operating procedures may affect operator task performance. Certain plant startup and shutdown procedures are also very demanding of the operator's attention, reducing the probability of the operator responding to a safety-related annunciator in time. Swain and Guttman also estimated that when the plant is in either a transient or plant startup or shutdown condition, the probability of the operator's failing to respond to an annunciated indicator not directly related to these conditions, is increased by an order of magnitude. This increase applies to both annunciated legend lights and

annunciated printouts. Some of the performance shaping factors (PSFs) that may contribute to human engineering deficiencies include: 1) the number of signals per unit time that the operator must process, 2) the number of false alarms, 3) the placement and design of annunciator systems and indicators, and 4) the stress levels (ranging from boredom to the emotions associated with a major accident). Though highly conjectural, Swain and Guttman (1980) concluded that due to the noise and confusion occurring during a simulated large LOCA, even experienced operators will commit errors of oversight and commission, and the estimated failure probability, expressed as $Pr [F]$ of .25 in transients where there are more than 40 annunciators, will hold.

During plant upsets and accidents, operator tasks may demand more mental resources than the operator has available. This cognitive overload may be further complicated by PSFs such as moods, stress and time pressure. During these behaviors, vital information may be overlooked or misunderstood. The operator may mis-assess the situation and take incorrect responses or fail to respond. Current conventional alarm systems are built from the 'bottom-up,' each alarm taken from a plant signal. This "one-signal-to-one-alarm" system creates several alarms for one fault, and contributes to the operator's cognitive overload.

Mode Awareness

Design of systems with more than one mode must consider that a human may be able to execute an action that may be appropriate for one mode, but the system may actually be in another mode. The role of the human supervisor is to select the mode best suited for the process goals. Once a system is in an automated mode the operator must

maintain vigilance and an awareness of that mode and its relationship to other processes taking place concurrently. Mode errors are a change of rules. Tasks performed in one mode, may be performed differently in a different mode. This change of the operator's mental model may lead to mode errors. Studies related to commercial airlines have addressed concerns related to the aircraft Flight Management System, where a mode transition can occur as a result of operator input, but also as a response to preprogrammed targets previously introduced by the crew (Sarter & Woods, 1995). NPP automation is similar to aircraft automation in that plant systems may be operating in the background under different plant and system modes. Like aircraft, changes to system and component performance may have been made to the NPP control models minutes or hours before, that may be transparent to the operating crew unless they are made aware of the plant and system modes. Studies regarding systems with more than one mode have shown that the user needs to be made aware of the present mode of operation. To support the operator's SA, the graphical user interface must ensure that the operator is kept informed of the status of multimodal systems. Using applicable results from published methodology (OECD February 1992; O'Hara et al., 1996), the computerized alarm system for the ABWR utilizes functional criteria to support the need for presenting the operators with alarm priority and deviation information that *alerts* the operating staff to the fact that a process or system deviation exists; *informs* the operating staff about the priority and nature of the deviation; *guides* the operating staff's initial response to the deviation; and *confirms*, in a timely manner, whether the operating staff's response corrected the deviation. Implementation of this functional criteria supports the operator's decision-

making process, to identify the status and carry out action planning tasks. (Rasmussen, 1984, 1986).

Supervisory Models of Nuclear Power Plant Operator Performance

Several industry experts (Sheridan, 1987; Rasmussen, 1984, 1986; Reason, 1990; Stanton, 1994; Woods, 1994) have also provided concepts of alarm systems and their affect on operator behavior in a supervisory role. According to these published reports, the cognitive model of the operator is different if an automated process is being monitored than when the operator is both monitoring and controlling the process. Studies have also documented the analogous environments of the control room and cockpit. Both the nuclear plant control room and airplane cockpit demand selective attention that is dependent on an assessment of the situation. (Roth et al., 1997). The human-automation interaction relationship has been well documented in the context of commercial airline cockpits (Sarter & Woods, 1995), anesthesia management for surgery (Charante, M., Cook, R.I., Woods, D.D., Yue, L., & Howie, M.B. (1993) and in the NPP process control (Woods, O'Brien & Hanes, 1987).

As the use of automation in the power industry has increased, the role of the plant operator has changed. With the implementation of these automatic and semi-automatic systems, the participation of the operator's monitoring tasks in the control system loop have been expanded. The operator's participation in direct control of the plant processes has changed to that of a supervisory role. In this new role that focuses on automatic system vigilance, the role of the human supervisor is to select the mode best suited for the process goals. Mode errors are caused by a change of rules and tasks performed in one or

more modes of a system, that may be performed differently in each mode. This change of the operator's mental model may lead to mode errors. Studies related to commercial airlines have addressed concerns related to the aircraft industry's implementation of automatic systems and the potential for modal errors (Sarter & Woods, 1995).

Operator performance models, including modeling of human-system interaction and human information processing were also reviewed. These sources included theories, modeled and concepts related to operator responses in the monitoring and control of complex systems (Lawless, Laughery & Persensky, 1995). These resources provided the initial use by the power industry of software programs to model operator tasks. The role of the operator, in a conventional or supervisory role is reinforced by numerous studies. (Baron et al., 1982; Morris & Rouse, 1993; Senders & Moray, 1991; Sarter & Woods, 1995)

The design, development, implementation, and testing of an alarm system is a major undertaking. In addition to the 'mechanics' of the alarm system, there is also the presentation aspects of how the alarms are presented to the operating crew. Design of the alarm system needs to support the operator's ability to rapidly discern the priority of the alarm; the alarm state (new, acknowledged, or cleared due to corrective actions taken), and the need to verify the alarm, based upon other control room information. Methods used to present of new and old alarms should consider the operator's mental work load. In the operator's new supervisory role, the operator will be expecting the advanced control room design to provide the necessary information. This information must be in a format that is readily accessible and usable. The design needs to support the operator's

decision-making process by reducing the multiple alarms that are found in conventional control rooms.

To provide appropriate auditory and visual cues to the operator, a model of the closed-loop supervisory role of the operator must be established. Various models have been proposed. With regards to decision-making and human performance, Rasmussen's (1984, 1986), model is closer to the decision-making tasks of the NPP operator. Figure 4 illustrates this relationship between the elements of behavior, depicted as data processing activities with states of knowledge as their outputs. Paths identify elements which according to Rasmussen, may be skipped when the state of knowledge existing at the conclusion of an element is, or at least may appear to the operator to be sufficient to justify omission of intervening steps. Based upon the operator's cognitive process, knowledge-based, rule-based, and skill-based behavior all contributed to this decision making process. Baron et al. (1982) have proposed a simplified model of the supervisory controller of a NPP (See Figure 3). These models, Figures 3 and 4, collectively reinforce that the most critical and perhaps most difficult process to model is that of operator performance of situation assessment and decision making tasks. The monitoring and control tasks of the new automated systems must consider the cognitive capabilities of the operating crew. In this new modern computerized control rooms, the operators' supervisory role and responsibilities have been increased. (Woods et al.,1988). Operators must be able to monitor and redirect the computerized plant's automated systems The information process of this new role must support the operator's problem-solving process and the operator's ability to identify the plant's state, define a task to change the system

condition, then formulate a procedural plan of action (Rasmussen, 1984). In addition to errors committed by the operator in response to displayed alarms (See Table 2), Sarter and Woods (1995) and others, have also identified the potential for commitment of mode errors. Both of these are important to the reduction and prioritization of alarms for new advanced designs. Initial reports related to alarms indicated a need to prioritize alarms based upon plant modes and reduce the number of alarms presented to the operating crew. More importantly, is the need to reduce the presence of nuisance alarms and thus reduce the potential for operator errors that may occur in the decision-making process.

The consensus of all researched literature related to alarm systems indicates that the alarm system should ensure that alarms which require immediate operator action or indicate a threat to plant critical safety functions are presented in a manner that supports the operator's decision-making process (i.e. observation, data collection, identification of system state, etc.) while at the same time, reducing the decision points encountered in conventional alarm conditions (O'Hara et al., 1996). Some of the alarm reduction methods that have been suggested, include:

- a) time filtering and/or time delay to alarm inputs to allow filtering of noise signals;
- b) plant system status indication which do not meet the functional definition of an alarm condition should not be alarmed to the operators;
- c) component status or parameter values should only be alarmed in their appropriate mode;

- d) implementation of a dark board concept so that no alarms are present during normal operations; and
- e) first-out processing to identify the initiating or 'signature alarms' of a possible event. First-out processing has been utilized at conventional plants in an effort to consolidate important alarms based upon an event-based concept of plant operation. All nuclear plants in the U.S. have migrated to symptom-based procedures as opposed to event-based.

As supported by previously cited literature (Seminara et al., 1977; Swain & Guttman, 1980; Roscoe & Weston, 1986) during plant transients, operator work load increases significantly as a result of the large number of alarms.

The alarm reduction schemes proposed by the researched literature, both industry and regulatory in nature, are not supported with analytical data. The regulatory guidelines rely on studies performed at U.S. and foreign national research laboratories. The quantitative data from those studies, is not provided in the published reports. It is this data that quite frequently the alarm system designer or human factors engineer, must have available to substantiate to the engineering team or management staff, justification for the implementation of a specific alarm system design.

Using a published power plant scenario, task analysis and simulation software, this thesis reviews those alarms that are present during a postulated plant transient, and evaluates the operator performance relative to workload and potential affect on mental workload. In the performance of the detailed control room design review (DCRDR) by U.S. and selected foreign utilities, a task analysis of normal and transient scenarios was

performed. The intent of those task analyses was to identify operator performance using the existing control room displays and controls. One of those published DCRDR reports (U.S. NRC, 1985) was retrieved from the PDR. The subject plant uses CRTs, conventional meters and a conventional alarm system to display plant and system status to the operating crew. Conventional switches are also used to control plant system components. Using the information from one of those transient scenario task analyses in the report, the task performance time of the operators was evaluated in response to the alarms presented to the operators. Based upon the alarm reduction guidelines, operator work performance time should be reduced when the alarm system has implemented a alarm reduction scheme based upon modes of operation and system state changes (Roscoe & Weston, 1986; OCED February, 1992; O'Hara et al., 1996). More importantly, operator mental workload should be reduced, thus improving the operator's decision making process. These improvements transfer into reduced operator errors because the operator is able to attend to fewer visual and audio cues. Though alarm reduction is well documented in industry and government reports (Roscoe & Weston, 1986; OCED February, 1992; O'Hara et al., 1996), what is lacking is sufficient data or methods to allow the alarm system designer to make tradeoffs between the benefits of specific human-system performance in the design of the system.

Analysis Methodologies

In addition to control room surveys, some work has also been performed using simulators. An annunciator experiment by Roscoe and Weston (1986) presents a plan for the experimental evaluation of alarm reduction techniques using a full scale nuclear

power plant simulator. To highlight the need for alarm reduction and prioritization,

Roscoe and Weston noted an example from an actual plant alarm system. The example indicated that a steam leak inside of containment has 17 signature alarms, but that within the initial 120 seconds, an additional sixty-four (64) alarms are displayed to the operators, masking the real 17 alarms. Signature alarms are those alarms that can adequately define the problem or root cause. Roscoe and Weston proposed implementing a 120 second time delay on the sixty-four (64) to allow the operators to analyze and respond to the 'real' alarms. In addition, the report provided the methodology, including statistical models, to be used in performing an evaluation of six annunciator system configurations and using six different crews of operators.

The industry practice is to develop a part-task or full scope simulator, allowing the design team to verify and validate their proposed design. The disadvantage of this type of evaluation is two-fold. First, the use of human subjects, software, and hardware are expensive to prototype at a system level. Secondly, in the early stages of system design, system data may not be mature enough to contribute to the necessary fidelity that a prototype warrants or is needed by the models of full scope simulator. An alternative evaluation process is the use of limited scope computer software modeling. With the increased capabilities of computers and the development of easier to use modeling tools, there has been an increase in the use of computer-based tools to predict human task performance. This use of modeling, early in the design phase, provides the human factors engineer with a means of extending the knowledge base of human factors through a limited level of experimentation. The focus of this limited modeling is not on the

individual elements of human behavior but, rather on models that can be used to describe human performance in systems. Using a reductionist approach, the larger tasks for human-system performance are reduced down to smaller elements of behavior. This has been described as a top-down approach to modeling human-system performance (Laughery & Corker, 1977; Baron & Corker, 1989). The back bone and basis of the human-system model is the task analysis. Using the top-down approach, functions are decomposed into a series of sub-functions, which are then decomposed into tasks. These tasks then serve to form a task network. Task network models of human performance in complex systems are extensions of the task analysis. Figure 5 illustrates the task network model based upon data collected from an operating plant (U.S. NRC, 1985) of operator tasks in response to a nuclear power plant scenario. Task network models can also become sub-models of the plant hardware and software to create closed-loop representations of the human-machine system. Task network models can be used to address questions regarding time-to-perform and error rates associated with tasks. One such modeling tool is Micro Saint[®] (1992), developed by Micro Analysis & Design Simulation Software, Inc. This modeling program is a personal computer (PC) based software program that has been available since 1992.

Micro Saint[®] was developed to model and evaluate human operator behavior in closed-loop systems. Using task network modeling, this software can be used to build models that include changing variables, probabilistic logic, sorted queues, and conditional task execution. Questions regarding time-to-perform a set of tasks as a function of system design, task allocation, and individual capabilities can be addressed. Workload

demands on the human as a function of system design, and task allocation and automation may also be addressed. It also has the capability to model expected error rates for a crew of operators as a function of system design, task allocation and individual capabilities. The software has been used to model production lines in manufacturing processes, scheduling and response requirements in transportation systems, and human operator performance and interaction under changing conditions. Micro Saint[®] has also been successfully used by the nuclear industry determine its feasibility and validity in predicting operator performance in a nuclear power plant control room (Lawless et al., 1995).

According to referenced literature (Swain & Guttman, 1980; Roscoe & Weston, 1986, OECD February, 1992 and O'Hara et al., 1996), it is hypothesized that reduction of alarms in a nuclear control room will reduce operator workload and potential for errors during in response to a postulated plant transient. By eliminating the redundant alarms and those alarms that merely indicate a system or component change, it is hypothesized that the operator's task performance time in response to alarm related tasks will be reduced. Using the alarm reduction scheme proposed by U.S. regulatory guidelines (O'Hara et al., 1996), this thesis will provide task performance data necessary to support implementation of an alarm reduction scheme. The evaluation of the proposed alarm schemes provides the alarm and human factors engineers, with early operator task performance time data. This early data allows the design team to determine whether the proposed alarm design warrants being pursued further.

METHOD

The alarm reduction experiment plan proposed by Roscoe and Weston (1986) suggests using a full-scale simulator and six crews of different levels of experienced licensed nuclear plant operators. Due to the limited availability of plant operators and the high cost of utilizing a full scope plant simulator, a simulation software package will be used to develop a simulation model an exiting alarm system configuration. The alarm system configuration is based upon an existing nuclear plant system and task analysis of operator responses (U.S. NRC, 1985). The baseline configuration of alarms will then be modified accordingly to simulate an alarm reduction scheme. Using the alarm reduction simulation model, the operator task performance mean times will be modified.

Like an experiment using real operators, a distribution of personnel skill levels will be utilized. An assumption is made that the more skilled and experienced operator will respond quicker to the performance of alarm response tasks when compared to the response times for average or less experienced operators. To create the three experience levels, the operator task performance standard deviations (See Table 4) will be modified accordingly. The Mean time data from the baseline alarm configuration will serve as the basis for all six task performance models. The models will differ in the standard deviation (SD) that is applied to each model. The baseline and alarm reduction models will utilize the SD. An SD of +3 SD will be applied to the low skilled operating crew model. An SD of -3 SD will be applied to the high skilled level operating crew. A model with a -3SD will create a faster operator performance time and reflects the more experienced operating crew. The three operating crews (independent variable) will

perform the scenario (dependent variable) without alarm reduction and with alarm reduction. The results of the crew task performance times will be compared.

A simulation model, using Micro Saint[®] was developed to evaluate operator performance in response to the implementation of an alarm reduction scheme. Because Micro Saint[®] software network utilizes tasks and subtasks, the task analysis (See Table 3) from the control room design review report (U.S. NRC, 1985), was conveniently adapted for implementation into the software program.

Plant Scenarios and Plant Data

A postulated plant anomaly from the same control room survey report (U.S. NRC, 198) was used. The plant's control room survey report had been submitted to the U.S. NRC PDR (U.S. NRC, 1985) in response to regulatory requirements following the accident at TMI. Available to the general public, the contents of the report were reviewed and the applicable plant scenario, a Large Steamline Break in the Drywell was selected. The detailed contents of operator activities related to alarm silencing, acknowledgment, and parameter verification contributed to the selection of this scenario. The scenario task analysis in Table 3, identifies the expected operator actions in response to multiple alarms. The scenario utilizes two operators to respond to the audio and visual cues presented to the two operators by the plant system state changes described by the scenario's task analysis. Figure 6 illustrates the control room panels and primary operator interfaces defined in the task analysis (Table 3) and in the resultant simulation model. Table 3 illustrates the operator tasks and task elements that are necessary by the operating

crew in response to the plant system changes as a result of the scenario. The task analysis was also used to build the simulation model.

Prior to building the simulation models, the operator task performance actions and response times of the task analysis were verified. Verification was performed by a review of the scenario task analysis with experienced engineers and plant operations staff. The reviewers offered task performance action response times. This was critical for those tasks in which the published scenario did not provide a detailed operator response time. Plant operations staff were specially helpful in verifying that operator performance sequences were accurate.

The software model provides, with some limitations, results that are close to those that might have been provided by the more costly method of full-scope simulation.

This thesis does not evaluate the mental process of the operator in response to mode or event based alarms, but instead evaluates operator task performance time in response to alarm reduction and quantifying its effectiveness in reducing operator burden. This thesis work provides some early information about the effectiveness of the alarm system reduction methods proposed by the researched literature (O'Hara et al., 1996).

This work is not intended to replace the verification of alarm system designs using a part-task or full scale simulators. It does provide the alarm system developer with some early data regarding the effects of alarm response tasks and their effect on overall operator task performance time.

Micro Saint[®] and Network Modeling

To utilize Micro Saint[®], human performance of tasks in systems must be defined into a task sequencing structure. The elements of this task sequencing structure are further reduced into task elements. This is a top-down approach to modeling human-system performance. Micro Saint[®] utilizes the task analysis and task elements from Table 3 as a part of its *task network modeling*. This sequence of tasks is defined by constructing a task network as illustrated in Figure 5. Figure 5 constructed from the data in Table 3, illustrates the Micro Saint[®] task network model for the operator performance in task analysis. Similar to a task analysis, the model documents in a time log, the actions taken by the operators over time. But unlike a task analysis using plant staff and a prototype or simulator, the model can be run many times with different results based upon the variability designed into the model (e.g. task queues, probability of success). The job queue function also allows the program developer to define sorting functions such as first-in, first-out (FIFO) and last-in, last-out (LIFO). User defined performance shaping factors (PSFs) such as time to perform and probability of failures, can both be linked to individual tasks. The task network modeling of Micro Saint[®] extends the task analysis into predictive models based around a network representation of the human's activity. The data collected from the executed model may be reviewed within the model's own statistics analysis and is provided in Table 5. The model developer inputs estimates of the probability that a task will be performed successfully or unsuccessfully. The consequences of failing to complete the task also can be modeled. Unlike the proposed plans that simulators and operators be used to verify alarm system design (Roscoe &

Weston, 1986) this simulation software models the operator performance in response to plant cues and reduces the reliance on operator and simulator availability.

Participants

The participants in the software models consist of three crews of simulated plant operators. Each crew consists of a primary and secondary operator, both having the same skill level and corresponding experience levels. The baseline crew utilizes the same SD as the average crew. Each operator crew has an assigned skill level of below average (+3 SD), average (SD), and above average (-3 SD). Each of the the crews participated in the conventional (without alarm reduction) and alarm reduction models. Other than skill levels, the participants have not been assigned any other physical characteristics.

Apparatus

The simulation was performed using Micro Saint[®] (1992), Release 1.3, 1992 for Windows. The software model was prepared and run using a COMPAQ 133 MHzPC laptop using a Microsoft Windows 95[®] operating system. The data from the simulation software was evaluated using MINITAB[®] (1996), Release 11.2 for Windows. This is a pc-based statistical package.

Procedure

A baseline alarm configuration was prepared (See Table 3) using an existing plant system and task analysis (U.S. NRC, 1985). The task analysis provides task elements that identify alarm audio and visual responses, verification of plant parameters, and control actions taken at control consoles by the operating crew in response to a specific postulated event. Figure 6 illustrates the configuration of the reference control room.

Table 3 illustrates the operator tasks, supporting information, controls, and alarms used by the operators in response to the plant state changes. Though these actions by the operators are not identical to the responses that the operator may perform in using the ABWR interface, the operator actions associated with monitoring and activating control devices, including response to alarms, is similar. This approach is consistent with the referenced annunciator test plan (Roscoe & Weston, 1986). Using the Micro Saint[®] software, a simulation program of the tasks analysis as defined in Table 4 was developed. The simulation utilizes data that is typically not available until later in the design. This simulation technique, is similar to rapid prototyping in that it allows for the evaluation results to contribute to the design. The two alarm system configurations selected for simulation are; 1) No alarm reduction (existing condition) and 2) Elimination of irrelevant alarms based upon plant mode, transient, or system state changes.

Prior to constructing the Micro Saint[®] model, a simplified model was prepared to illustrate the operator's response to alarms. Figure 7 illustrates this model and the actions taken by an operator in response to a conventional alarm system without alarm reduction (a) and at the bottom of the Figure 7, in grey pattern fill, a system with alarm reduction (b). In the conventional alarm system, the operator must respond to multiple alarms. In doing so, the operator must also verify the parameters associated with those multiple alarms. Even though the operator may know that the redundant alarms are just that, he must verify to ensure that a "real" alarm does not exist. Responding to alarms and verifying associated parameters causes the operator to rely on his short-term and long-term memory. The operator must remember which alarms are truly "alarms", and which

are merely state changes (Swain & Guttman, 1980). Figure 7a also illustrates that a conventional alarm system presents more alarms, more parameters to verify, and more potential for errors. In responding to the various flashing alarm lights (windows), the operator goes through a mental process to eliminate the “non-alarms” from the real alarms. In this process, the operator performs these tasks over a period of time. Figure 7b illustrates the reduced alarm system and the potential for fewer audio and visual alarm cues. In this reduced alarm scheme, based upon plant operating mode and system state changes, the operator performs fewer activities by attending to fewer alarms. In addition to reducing the operator’s physical movements between the control panels, it more importantly, reduces the operator’s mental work load as recommended by government regulatory documents (O’Hara, et al, 1996). Though this thesis is evaluating task performance times of tasks, reducing the tasks also reduces operator work load. Workload is the relationship between resource supply and resources demanded. If the task requires more resources than the operator has available, then the task will break down. Tasks can require mental or attention resources. With fewer resources, available for other tasks, performance will deteriorate. The task performer must schedule the presence of multiple tasks, whether mental or attention. Workload is inversely related to the level of task performance (Wickens, 1992). By reducing the number of tasks, including those that are attention demanding, the workload of the operator can be reduced. Having identified the task performance or time load, multidimensional rating scales may be employed to assess mental effort or stress loads following task performance. The alarm reduction scheme being evaluated reduces the number of alarm cues and supporting tasks that must be

attended. This reduction in task performance indirectly reduces work load. The alarm reduction scheme is based upon regulatory guidelines that have proposed the implementation of event and mode-based alarms in reducing operator burden.

It is important to note that the alarm response model presented in Figure 7 was also reviewed with experienced operating plant engineers and plant operations staff, including personnel with operator licenses and operator training experience. This review was important to independently verify the accuracy of the model of operator response to alarms before and after alarm reduction, prior to actually building the software models.

Software Model Development

Using the scenario (Large Steam Line Break in the Drywell) and the operator response models described in Figures 7a and 7b, a simulation software model was developed. Figure 5 illustrates the Micro Saint[®] task network model (hereinafter referred to as “the model”) that was developed for the Steam Line Break scenario. The model in Figure 5 identifies the top level tasks (Network Elements). Table 4 defines the operator model task-time performance requirements for the model. Operator alarm response tasks, displayed plant system information, and alarm response controls are presented in the table.

Micro Saint[®] allows the model developer to define Network Elements (See op2 in Figure 5) and also define subtasks using “subnetwork elements” (See op2a, op2b, and op2c in Table 4). Figure 8 illustrates the subtask diagram for task op2a. Figure 9 illustrates subtask op2b and Figure 10 illustrates subtask op2c. These figures illustrate the subtask networking methodology that was developed and its relationship to the task

analysis. The variables of this simulation software are defined in Figure 11. With the exception of the Time variable, variables such as the standard deviation (SD), -3 SD, and +3 SD, are defined by the model developer for each task.

Using the tasks identified in Table 3, Table 4 was prepared to document the contents of each Task Description (See Figure 8). Table 4 proved to be very helpful in checking the contents of each Task Description in the software model. Table 4 identifies the tasks performed by the operator in responding to plant alarms, both audio and visual, directing the operator's attention to a system and/or component state change. Each action taken by the two-person operating crew is identified in Table 4 as a Network Element in bold font. The term 'Network Element' is being used to be consistent with the software program terminology. Within each of the Network Elements, there are subtasks that must be performed to accomplish the top level Network Element. Micro Saint[®] allows for each of these elements to be identified (See Op2). Each subtasks is also identified in Table 4, directly following the bold font Network Elements. The mean time to perform each action is based upon a comparison of the task analysis report with other reports of similar scenarios and comments from subject matter experts with control room operating experience. The tasks and subtasks for the scenario, task performance times (Mean, SD, -3 SD, and +3 SD) and operating crews are identified in Table 4.

A total of six software programs were developed. One program modeled the existing or baseline alarm scheme using the scenario and supporting task analysis (See Tables 3 and 4) from the literature (U.S. NRC, 1985). The baseline alarm configuration tasks consist of all of the tasks in the task analysis. All of the operator performance task

times in the model utilize the same Mean. Selected tasks based upon their specific functions, have SDs assigned to them. The experience levels of the operating crews were created by assigning three different SD values to the task performance times (See Task op2a). The assumption being that the performance times of the operating crews would vary based upon their skill levels. In addition to the average skilled crew, the same tasks were performed by the highly skilled crew (-3 SD) and the least experienced crew (+3 SD). Using the conventional model, three models were developed, one for each of the three SD or skill levels. The other three models consisted of the same model, with the same skill levels, except that redundant and nuisance alarms have been eliminated. Tasks and subtasks that are to be eliminated by the alarm reduction process are identified by bold italic font (See OP4 in Table 4).

In this thesis, it is assumed that skill level is commensurate with experience and that they are one and the same. The operating crew with average skills was assigned an SD. The least skilled operating crew was assigned an SD of +3. The operating crew with a high skill level was created by assigning an SD of -3 to the Mean value for the task performances. The tasks that were eliminated by the alarm reduction process do not have values for -3 SD and + SD assigned to them (See Task OP4) in the model; so they should have an equal impact when eliminated. The tasks in Table 4 have SD values assigned because they were used to calculate the $\text{SD} = (\Sigma \text{SD}/n-1)$ for all six models. OP20 is a Network Element associated with the primary operator. The '2' in front of the OP identifies the task as being assigned to the secondary operator. 2OP1 is a Network

Element associated with the secondary operator. The Mean times were kept constant between the models and were not changed.

The alarm reduction criteria, as recommended by the regulatory guidelines (O'Hara et al., 1996) consisted of the elimination of redundant alarms (i.e., two or more alarms for the same state change or parameter) and the elimination of alarms associated with state changes. Some redundant alarms are duplications caused by the initial system design and its inability to process multiple signals into one alarm, thus providing the operator with duplicate alarms for the same parameter. An example of a state change may be that the operator changed the position of the mode switch as a course of expected plant operation (See Table 4, Task op6b). An intentional operator action should not cause an alarm. Some other form of feedback should be used instead of an alarm. This also includes expected changes such as a Turbine Trip alarm when the operator has tripped the Turbine. The alarm models were reviewed further and non-alarm-related operator tasks were eliminated from the three skill level models without alarm reduction. These are tasks that are not directly in response to alarms. Figure 12 identifies the tasks that remain. This model was used to provide the task performance time for the three skill levels of operator performance tasks before implementation of the alarm reduction criteria.. Application of the alarm reduction criteria resulted in a subset of those tasks. These alarm reduction tasks are illustrated in Figure 13. This model provided the alarm reduction task performance times for the three skill levels. Using the alarm reduction criteria, tasks OP4, OP5, OP6, OP7, OP8, OP10 through OP19, and OP22 through OP24 were eliminated. In the process of this alarm reduction of 24 operator tasks and subtasks,

3 of the 5 decision nodes were also eliminated. The elimination of the nodes was caused by the removal of these operator decision points that were created by redundant alarms. Removal of the redundant alarm means that the operator only has one decision path to follow. Figure 13 illustrates the Micro Saint[®] network model with the alarm reduction incorporated and the remaining 33 operator tasks. Following a review of the scenario tasks, it was concluded that the second operator of the crew did not perform any tasks in response to the audio and visual cues from the alarm system. The second operator has been eliminated from the task performance models and does not contribute to the operator task performance times for tasks without or with alarm reduction.

Figures 8 through 10 also illustrate the Task description dialog that contains all of the information that defines a typical task. The dialog box defines mean time, standard deviation, and applicable release conditions. Mean time defines average task performance time for this task. This can be in the form of a number, equation, or algorithm. Standard deviation is the standard deviation of task performance time.

Release condition is the condition that will hold up task execution until the condition is met. These conditions are utilized for all four models. An example is a condition stating that a task won't start before an operator is available may be represented by a release condition such as:

operator = 1;

Which means that there must be an operator available for the task to commence. If both operators in this model were busy, the value of the variable "operator" would equal zero until a task is completed at which time an operator becomes available. The task would

remain suspended until the condition was true before beginning execution, which would occur as a result of the operator completion of the task currently being performed, based upon the time assigned. Beginning effect defines how the system will change as a result of the commencement of this task. For example, if this task has used an operator that is needed by other tasks, the condition would be set to show that the operator is unavailable while the task is being performed, and indicated as such:

operator: = 0;

Beginning effects ties the start of one task with another tasks. This is the link between the tasks. As indicated in Figure 5, selected tasks such as OP1 and OP26, are followed by a diamond shaped icon. Like real-life tasks, at some point in the performance of task, the human operator must make a decision when confronted with multiple tasks. Which task should be performed first? In the task network model, this indicates that there are more than one task that may commence at the completion of the previous task. A decision must be made by the human to select which of the potential actions should be taken. The model designer defines the decision logic in the decision dialog box. The probability weights assigned are based upon probable action that operators will take in accordance with the model in Figure 7 and task analysis data. To control variability, the probability values will not be changed in any of the six models. Instead, the SD assigned to the task performance times will be used to provide the variability between the three conventional and three alarm reduction models. Figure 14 illustrates the Description of Decision dialog for the highlighted decision node (OP6b). The decision nodes and their assigned weights are defined in Table 5 for both models. Some decision nodes may not be visible

at the system model (See Figure 9) level because they are specified in sub-network elements within Network Elements. The tasks eliminated from the model also include sub-network tasks. In many cases there are from 2 to 5 of these subtasks. These subtasks contribute to the total operator task performance time for the scenario. Decision nodes are also associated with sub-networking tasks OP9a (See Figure 15), OP15 (See Figure 16), and OP26 (See Figure 17). There are three types of decisions to the simulation model. These three decision types may be used or ignored by the program developer. Probabilistic decisions allow the human to begin with one of several tasks based upon a random draw weighted by the probabilistic branch value inserted into the dialogue box. This decision type was used to model human error. The tactical decision allows the human within the model to begin one of several tasks based on the branch with the highest “value”. This is used to model the human’s rule-based decisions. The multiple decision is used to begin several tasks at the completion of this task, such as when one human issues a command that begins other crew member activities.

The three models without and with alarm reduction were each run fifty (50) times, an arbitrary number, but large enough to ensure randomness provided by the software’s Monte Carlo attributes. The number of runs ensures that there is sufficient opportunity for the decision (probability) nodes in the model to be performed.

Statistical Calculations of Software Model Data

Due to the large SD encountered in the Micro Saint[®] statistics (See Table 6), the task performance mean time raw data from the six Micro Saint[®] models were placed into a Microsoft Excel worksheet (See Table 7). The data was then imported into MINITAB[®],

a pc-based statistical software program. The MINITAB[®] program was used to prepare descriptive statistics and graphs. Table 8 presents the descriptive statistics, including Means (M) and SD for each of these operator skill levels. Using box plot graphs, the descriptive statistics are summarized in Figure 18. The high (HI), average (AVG), and low (LOW) skill levels are presented without(1) and with(2) alarm reduction. As discussed previously, the secondary operator has been eliminated from the models and is not reflected in the descriptive statistics or the graphs. The box plots present the maximum and minimum observations; the 75th, 50th, and 25th percentile; and the M. Details of the summary skill level graphs are presented in Figures 19, 20, and 21. As mentioned previously, all of the tasks that are not in direct response to alarms, have been eliminated from the models and calculations. Using the data from Table 7, a *t*-test (Keppel, Sautley, Jr. & Tokunaga) was performed for the differences of the means for before-and-after task performances. Table 9 presents the results of those *t*-tests.

RESULTS

As noted in Table 4 and Figures 12 and 13, the alarm reduction scheme has reduced the number of primary operator tasks by 17 from initial 27 tasks. This reduction of tasks reduces the amount of time (independent variable) that the primary operator will allocate to alarm response. These tasks represent both physical tasks and mental processes that were performed by both of the operators as they moved between the panels. Table 4 identifies the italicized alarm related tasks that were eliminated through review of redundant and nuisance alarms. These nuisance alarms merely notified the operator of plant system or component state changes that were either expected or initiated with the operator's knowledge. Table 4 specifically identifies the control manipulation and parameter verification actions that the operators must perform, based upon the alarm system cues. The dependent variables consist of number of operator crew size and time to perform each task. Though each crew consisted of two operators, the alarm response tasks were performed by the primary operator. The results presented are for the primary operator. No attempt has been made to reassign alarm response tasks to the secondary operator. There was no attempt to perform any type of multiple resource evaluation. Instead, the task performance times of the six crew models are evaluated. As previously presented in the Methods section, in all six models, the related alarm response tasks were performed by the primary operator. Since random levels of skills were not built into the software model, a bounding technique was used in which operator skill level (IV) was manipulated by assigning an SD, +3 SD, or -3 SD to affect the operator crew's performance. Due to the nature of the participants and tests, the software data collection

does not lend itself to conventional inferential statistics. Instead, a comparative analysis of the task performance times for the average operator crew (SD), skilled operator crew (-3 SD), and less skilled ($+3$ SD) operator crew was performed. The box plots in Figure 18, prepared from data provided by the Micro Saint[®] software model and MINITAB[®], illustrate the results (Means) of the conventional alarm response model and the reduced alarm system model for all three skill levels. As previously mentioned, the task performance times include only primary operator actions. The baseline configuration model utilized the SD during task performance. This same SD was assigned to the average skilled crew. The summary means for the high (-3 SD), average (SD), and low ($+3$ SD) skill levels are presented in Figure 18. Table 6 presents the initial Micro Saint[®] simulation software data for the six models. Table 7 presents the MINITAB[®] data used to prepare the box plots for the six models. As presented in Table 7, the high skilled operating crew (-3 SD) performed the scenario in a mean time of 51.5 seconds (SD = 11.7). With implementation of alarm reduction, the crew performed the same scenario in a mean time of 50.9 seconds (SD = 5.66). As presented in table 9, the task performance differences resulted in a M of 0.6 and a SD of 10.5. The *t*-test value of 0.01 is consistent with the results presented in Figure 18 for H1 and H2. The alarm reduction did not produce a significant effect in operator task performance. The average skilled crew (SD) performed the baseline scenario in a mean time of 367.4 seconds (SD = 19.2). With alarm reduction, the scenario was performed in a mean time of 195.5 seconds (SD = 22.7). The task performance improvement of 171.5 seconds is a 47% improvement in task performance. The results of the *t*-test (See Table 9) indicate that the implementation of

alarm reduction has produced a significant effect ($t = 41.8$). The statistical results of the t -test are consistent with the graphs presented in Figure 18. AVG1 illustrates the average skilled crew without alarm reduction and AVG2 illustrates the task performance with alarm reduction. The less skilled operating crew (+3 SD) performed the scenario in a mean time of 574.6 seconds (SD = 52.5). In the alarm reduction model, the operating crew (+3 SD) performed the tasks in a mean time of 205.5 seconds (SD = 22.7). With alarm reduction, operator performance times were reduced by 369.1 seconds (SD = 38.1) or a reduction of 64% (See Table 8). For the low skilled crew, the results of the t -test (See table 9) indicate a highly significant effect ($t = 68.6$). This highly significant effect is illustrated in Figure 18. LOW1 illustrates the low skilled crew without alarm reduction and LOW2 illustrates the task performance with alarm reduction. As indicated in Table 4, the primary operator performs all of the tasks in response to alarm system cues.

As illustrated in Table 4, in addition to the elimination of the 17 operator tasks, 3 of the 5 decision nodes were also eliminated. The five decision nodes are summarized in Table 5. Two of the those nodes, OP1 and OP6b, are associated with alarm response tasks. Based upon the raw data of the model presented in Table 4, these two nodes utilized 54 seconds of the operator's time. In performing the simulation models, it is not possible to isolate and evaluate the effect of these nodes when they are run 50 times. As noted by Swain and Guttman (1980), these decision nodes do provide opportunities for errors of omission. By reducing the number of these nodes, the potential for operator errors of omission due to redundant or parallel tasks related to operator tasks in response to alarm system audio and visual cues, is reduced.

DISCUSSION

Industry and regulatory guidelines have proposed various schemes for reducing the number of alarm presented to the operator. A deficiency of these guidelines is that they have not provided the alarm system designer with quantifiable data. Using an evaluation method (Baron et al., 1982) this simulation has utilized a task-based simulation program, an existing plant scenario, a proposed alarm reduction scheme, and a bounding technique to identify the benefits of the proposed alarm scheme when performed by three different skill levels. The following conclusions regarding this work are:

- 1) As expected, the improvement of the highly skilled crew was not significant ($t = 0.01$). Referred to as a “ceiling effect” (K. Corker), a high skilled crew would have less room for improvement. The MINITAB[®] summary results presented in Table 8 indicate that the high skilled crew performance time of 50.90 seconds with alarm reduction, was 86% faster than the baseline or average crew’s task performance time of 367.4 seconds without alarm reduction.

The increased performance was hypothesized, though due to the simulation method used, its not certain that the high skilled crew would improve their task performance times by 86% if evaluated on a real full scope simulator using real operators. Using the same alarm reduction criteria, other scenarios and an operator population sample size would need to be evaluated.

- 2) The average skilled crew also performed as hypothesized. Through the use of alarm reduction, the task performance time was reduced by 171.9 seconds.

This improvement of 47% is significant and could be used by the engineering staff to pursue further investigation into the benefits of the alarm reduction criteria implemented in this thesis. As supported by the calculated t test ($t = 41.8$), the differences are significant.

This thesis has used one scenario and limited scope simulation software.

Additional scenarios should be identified and modeled. If those also result in significant results, the next step would be to apply this criteria using a full scope simulator and real plant operating crews.

- 3) The performance improvement of the low skilled crew was highly significant ($t = 68.6$). Though the low skilled crew's performance time of 205.5 seconds was still slower than the average crew, the performance improvement of 64% over the initial task performance time of 574.6 seconds is significant. Though a benchmark for task performance improvement does not exist, this type of improvement may be expected in the real operator population, where operator aids used in the control room tend to benefit the less experienced crews. As stated previously, the industry and regulatory guidelines concerning alarm reduction and implementation rationale do not provide the system developers with statistical data to support suggested alarm reduction techniques. It is left up to the system developers to develop their own benchmarks. This analysis presents preliminary data and has provided a method for the collection of data for operator alarm response tasks. Methods such as these should be considered by the regulatory agencies when providing guidelines to the power industry. The regulatory agencies should provide statistical and simulation

references to other software programs to aid the alarm designer in implementing new alarm reduction programs.

- 4) Alarm reduction benefited the lower skilled crew. Due to the reduced number of alarms, the inference and problem solving associated with a problem action response is improved. The alarm system's simplicity may also improve the lower skilled crew's system knowledge. The simplified alarm system may also improve the operator's rule-based behavior such as pattern recognition. Reducing the number of alarm response tasks and the physical number of alarms that the operator must memorize and learn, it is highly probable that task performance by real operators would also see these benefits.
- 5) Though the simulation models did not directly address modal errors, the task analysis and models identified the presence of decision nodes that were eliminated by the reduction process. These are potential areas where the operator's decision or mental workload can be reduced. The software simulation results indicate that alarm reduction has the potential to reduce the operator's task performance time. This reduction of task performance time allows for an allocation of resources, whether physical or mental, to other tasks. The decision nodes represent points where the crew must decide on multiple courses of action. These are potential points for errors and mental resource demands. By reducing the resource demands, specially during time critical tasks, the crew's mental and stress loads are reduced. In effect, the crew's workload is reduced.

- 6) One aspect of this thesis and the hypothesis was that the performance of the models would generate data that could be used early in the design project. It has been pointed out that the regulatory guidelines concerning alarm systems do not provide the alarm system designers with supporting rationale or data as to the benefit of one approach over another. Strong recommendations and evaluation criteria are provided without the benefit of any type of performance values regarding improvement to the operator crews. The benefits of the simulation models is enlarged as their capability to predict the outcome of tasks is only limited by the changes made to the task performance values placed in the applicable dialog boxes. By having the ability to manipulate the decision nodes, means, SD, etc., the simulation model becomes a design and evaluation tool. The models allowed for the manipulation of the tasks allocated to the primary and second operator, including the elimination of the second operator from the simulation data. This evaluation has also shown that simulation software offers the alarm system designer a quick and inexpensive tool with which to evaluate the proposed alarm system, or other task-based operator activities. Given sufficient time, the variability of the probability data provided may be changed to produce “what if” scenarios, changing not only the probabilistic data but also the operator task response times. Early in the design process, complete project specific data may not be available thus prohibiting the use of a part-task or full scope simulation. The use of this simulation software allows the designer to use applicable plant scenarios and data from existing projects that can be extrapolated and used as input data

sources. In addition to affecting the design of the alarm system, the use of this modeling process may also affect the design of other operator interfaces in the control room. As illustrated in Figure 7, the evaluation process clearly reduces the number of parameters that an operator must verify in a conventional alarm system. The alarm reduction model illustrated in Figure 7b indicates that there is a potential for reducing the operator tasks performed as a part of the parameter verification process. The power industry would benefit from the performance of baseline evaluations for selected guidelines, thereby providing examples for alarm system designers. More importantly, these baseline evaluation can provide the designers with examples of benchmark data on operator performance for selected plant scenarios.

- 7) The validity of the results is greatly determined by the availability of valid data that closely models the systems being modeled and evaluated. Because the software program used in this thesis is based upon task networks, the availability or preparation of a task analysis to define the order of function performance is a prerequisite to designing the software model. The Micro Saint[®] software program has previously been used in the nuclear industry (Lawless et al., 1995) to evaluate operating procedures which are also task-based. The response times used for the modeled tasks are based upon reviews of other task analysis provided in reports for conventional operating plants. As discussed in the Methods section, the task analysis and operator performance times were reviewed with subject matter experts from engineering, plant operations, and training groups. The reduction of alarms was not arbitrary but

is based upon documented criteria (O'Hara et al., 1996). Prior to implementation of this alarm reduction process, the alarm models and results should be reviewed with the actual plant alarm systems that are to be affected.

- 8) As discussed in 7) of this discussion, it would be beneficial to the alarm designer to have references of more than one software program that could provide valid simulation data. Presently, with limited research, it appears that Micro Saint[®] is the only provider of a simulation program, though others may exist.
- 9) The implementation of alarm reduction schemes may also benefit operator training and operation procedure preparation. The reduced number of alarms results in fewer alarms that the operator has to remember. As noted previously, this is a benefit to the less experienced operator. An outcome of TMI is that the manner in which operator crews are staffed and trained was changed. Prior to TMI, operators were trained individually and the crews were staffed arbitrarily without regard to experience. Each operator was tested individually. Following TMI, operators are now trained in their assigned teams. The crew mix is also reviewed to ensure that there are also experienced operators on the crew. The implementation of an alarm reduction scheme will aid the less experienced members thus providing the experienced operators with more time to analyze problems in a real or training setting. As there are fewer alarms, the alarm procedures, used for operator response, will be fewer in number.

10) Finally, before undertaking a simulation project, the alarm system designers should ensure that the software being used to develop the simulation models is supported by readily available technical staff and documentation. Using a current version that is supported by some form of vendor technical support is highly recommended. One of the shortcomings of this thesis is that it was not possible to determine the methods used to derive the SD in the Micro Saint[®] data. The documentation of this early version of Micro Saint[®] did not explain the methods used to calculate the descriptive statistics. Like most software programs, technical support is available on a limited basis following its purchase. The support for the program used in these models had lapsed. Another problem was that the data collected was not easily imported into other software programs such as Microsoft Excel or MINITAB[®]. Instead, the simulation had to be manually placed into Excel, then imported into MINITAB[®]. As mentioned previously, the system designers might also want to do a quick search of the availability of other comparable software for a comparison of benefits. Finally, to verify the significance of the average skilled group, a *t* test was performed. It should be expected that some hand calculations may be necessary to verify statistical data that may conflict with what is being presented in a graph. In the case of the average group, Figures 18 and 20 indicate a significance in improvement that was supported by the statistical calculations presented in Table 9. In the course of preparing this thesis, it was determined that statistical packages may not always utilize published statistical formulas when computing the results, and that the results

should be verified using another form of calculation method. Microsoft Excel was used to perform the *t*-tests and verify the significance of the data presented in Figures 18 through 20.

This thesis has presented alarm system models, new advanced control room designs, human error and performance criteria, alarm reduction methodologies, and a task network-based simulation tool. Using this software tool, the benefits of alarm reduction have been presented. The results of this thesis have provided substantive quantitative data to believe that the results of a full scope simulation would result in positive findings as to the benefits of alarm reduction proposed by contemporary regulatory guidelines. A software package such as Micro Saint[®] can provide the necessary engineering data to support the expenditure of resources toward the development of a proposed alarm scheme. Though the outcome of some proposed design solutions may appear to be obvious to the design team, it may be necessary to utilize an analytical process to support the continued expenditure of resources and funds for a proposed alarm reduction scheme, or any other design solution.

Recommendations for Future Reviews

Only one postulated scenario with six simulated operator crews has been evaluated in this thesis. With this small sample it is not possible to generalize that these levels of task performance benefits will be realized for other postulated scenarios. Other scenarios should be reviewed to determine if similar results are achieved.

Another area that needs further review is the use of momentary verbal cues to the operating crew. In prior studies of proposed alarm schemes, interviews with operators from U.S. operating plants, concluded that operators want to know when a major

component such as the Main Turbine or safety related system pumps changed state (e.g. turbine tripped, or pump started or stopped, etc.). Use of a momentary verbal alarm such as “the turbine has tripped” offers the operator the information without requiring the conventional silencing or acknowledging actions. These types of reviews of modifications to an existing system can be carried forward and considered for more advanced designs such as the ABWR, using design and evaluation criteria from NUREG-0700 (O’Hara, et al., 1996). Use of momentary verbal communication has been used in military system to notify the crew that immediate corrective action must be taken. In the case of the alarm system, it can also be used for those highly critical components of the plant systems. The benefits of momentary verbal cues to the operating cue warrant further review during the ABWR simulator evaluations.

In a conventional power plant, the operator may not only respond to alarm system cues, but must also take parallel control actions. The effects of multiple-resources was not evaluated in this thesis. A more sophisticated simulation such as found in a full scope simulator, is needed. Crew mental workload was also not evaluated. Though alarm reduction may free up the operators, the operator may still have other resource demands that may affect the crew’s workload. It would be necessary to conduct an interview of the crew to really understand if the alarm reduction has reduced mental workload. The elimination of the physical tasks and decision nodes in their totality can be used to support that the operator’s decision making process is improved and thus increase the operator’s ability to focus on real alarms and the process parameters associated with those alarms.

By identifying and modeling the tasks performed by both operators, it is also evident that redundant information located at different panels can contribute to both physical and mental workload. The task analysis and simulation model indicate that the second operator verifies redundant indication on other panels. It was not the intent of this thesis to question the physical arrangement of the panels and why indication is located on panels that are separated by 10 to 15 feet. However, a redesign of the panels to reduce the area that is traversed by the two operators might free up the second operator to focus on decision-making tasks. Under the existing panel arrangement the secondary operator is verifying redundant parameters on another panel rather than assisting the primary operator. Tables 3 and 4 both identify the redundant tasks performed by the operators. During time critical tasks, the secondary operator could be better used performing other tasks. This reallocation might improve monitoring and control tasks, while at the same time, reducing the stress levels of the crew. The second operator was removed from the software model to see if there was any effect. As expected, because the second operator does not respond to alarm related tasks, there was not effect on task performance.

In most advanced systems, the user's mental work load has been increased by the monitoring and control demands of the computer-generated interfaces and the new supervisory role of the operator. Previously, the operator had a full view of the controls and displays available for the performance of his tasks. With the new advanced systems the operator's physical movement across the control room panels and control room is reduced but he must now rely on his memory to quickly locate the needed interfaces that may be located on one of the many visual display units. The reduction of operator mental and physical tasks will contribute to the pool of time (resources) that the operator or crew

can allocate for tasks that may be associated with this new supervisory role. Evaluations must be performed using the proposed system interfaces. Further evaluations need to include operator interaction using displays, controls, and alarms that are displayed on CRTs.

For most advanced systems, including the ABWR, the operator will navigate through displays of plant systems. The alarm reduction scheme used plant and system modes as a criteria for eliminating an alarm. The models did not evaluate the operator's SA with regards to plant modes. Systems and components that are in alarm must also be quickly and easily conveyed to the operator and the operator must be cognizant of which mode the plant and specific system is in.

BIBLIOGRAPHY

Banks, W.W. & Boone, M.P. (1981). Nuclear control room annunciators: Problems and recommendations, NUREG/CR-2147. Washington, DC: U.S. Nuclear Regulatory Commission.

Baron, S. (1984). A control theoretic approach to modeling human supervisory control of dynamic systems. In Rouse, W.B. (Ed.). Advances in man-machine systems research (Vol.1). (pp. 1-47). Greenwich, CT: JAI Press, Inc.

Baron, S. & Corker, K. (1989). Engineering-based approaches to human performance modeling. In McMillan, G.R. et al (Ed.) Applications of human performance models to system design. (pp. 203-217). New York: Plenum Publishing Corporation.

Baron, S., Feehrer, D.L., Muralidharan, R., Pew, R., & Horowitz, P. (1982). An approach to modeling supervisory control of a nuclear power plant. NUREG/CR-2988. Washington, DC: U.S. Nuclear Regulatory Commission.

Charante, M., Cook, R.I., Woods, D.D., Yue, L., & Howie, M.B. (1993). Intravenous controllers in the heart room. In Stassen, H.G. (Ed.). Analysis, design and evaluation of man-machine systems (pp.320-341). New York: Pergamon Press.

Chignell, M.H. & Peterson, J.G. (1988). Strategic issues in knowledge engineering. Human Factors 30(4), 381-394.

Danchak, M.M. (1982). Alarms within advanced display systems: Alternatives and performance measures. NUREG/CR-2776, EG and G Idaho, Inc., Idaho Falls.

Electric Power Research Institute (EPRI) (1991). Advance light water reactor utility requirements document., vol. III, ch. 10, Man-machine interface requirements. Palo Alto, CA: Author.

Endsley, M.R. (1995). Toward a theory of situation awareness in dynamic systems. Human Factors. 37(1), 32-64.

Gutierrez, R. (1996). Evaluation of control room operator hand tools, manual material handling tasks, and physiology. Unpublished manuscript, San Jose State University.

Gutierrez, R. & O'Neil, T.J. (1993). Human-system interfaces for the ABWR control room. In Proceedings of the American Nuclear Society (Winter Session), San Francisco, CA.

Gutierrez, R. & O'Neil, T.J (1994, June/July). The operator meets the first 'advanced' reactor. Atom. 36-38.

Hollywell, P.D. & Marshall, E.C. (1994). An experiment to support the design of VDU-based alarm lists for power plant operators. In Stanton, N. (Ed.). Human factors in Alarm Design. (pp31-44). London: Taylor & Francis.

Kemeny, John G. (1979, October). The president's commission on the accident at Three Mile Island, The need for change: The legacy of TMI. Washington, DC: U.S. Government Printing Office.

Keppel, G., Saufley, Jr., W.H. & Tokunaga, H. (1992). Introduction to design and analysis-A student's handbook. New York: W.H. Freeman and Company.

Laughery, Jr., K.R. & Corker, K. (1977). Computer modeling and simulation of human/system performance. In Salvendy, G. (Ed.). Handbook of human factors and ergonomics. (pp. 1375-1408), New York: J. Wiley & Sons.

Lawless, M.T., Laughery, K.R. & Persensky, J.J. (1995). Using Micro Saint to predict performance in a nuclear power plant control room. Washington, DC: U.S. Nuclear Regulatory Commission.

Madni, A.M. (1988). The role of human factors in expert systems design and acceptance. Human Factors, 30 (4), 395-414.

Micro Saint[®] 1.3 [Computer software]. (1992). Boulder, CO: Micro Analysis & design Simulation Software, Inc.

Morris, N.M. & Rouse, W.B. (1993). Human operator response to error-likely situations in complex engineering systems. In Rouse, W.B. (Ed.). Human/technology interaction in complex systems: (Vol. 6, pp. 59-103). Greenwich, CT: JAI Press, Inc.

MPR Associates (1984). A procedure for reviewing and improving power plant alarm systems, Volume 1 and 2. (NP-3448). Palo Alto, CA: Electric Power Research Institute.

MPR Associates (1985). Power plant alarm systems: A survey and recommended approach for evaluating improvements. EPRI NP-4361. Palo Alto, CA: Electric Power Research Institute.

OECD Halden Reactor Project. (1992, February). An integrated alarm system. A concept study. Halden, Norway: Bye, A., Kårstad, T., Nilsen, S., Bramsnes, K.A., Førdestrømmen, N., Valseth, A., Pehrsen, M., & Follesø, K.

OECD Halden Reactor Project. (1992, October). The Halden Reactor Project Workshop Meeting on Computerised Alarm Systems. Halden Norway: Bye, A., Kårstad, T., Nielsen, S., Barmsnes, K.A., Førdestrømmen, Valseth, A., Pehrsen, M., & Follesø, K.

OCED Halden Reactor Project (1993, February). GOMS Analysis as an evaluation tool in process control: An evaluation of the ISACS-1 prototype and the COPMA system. Halden, Norway: Endestad, T. and Meyer, P.

OCED Halden Reactor Project (1993, April). CASH: Computerised Alarm System for HAMMLAB-An Outline of Required Functions. Halden, Norway: Miazza, P., Torralba, B., Kårstad, T., Moum, B., & Follesø, K.

OCED Halden Reactor Project (1996, May). CASH: The new alarm system in HAMMLAB. Halden, Norway: Moum, B.R., Decurnex, C., Førdestrømmen, Karlsen, T.V.

O'Hara, J., Brown, W., Baker, C., Welch, D., Granda, T., & Vingelis, P. (1996) Advanced Human-system interface design review guidelines, Volume 1: Process procedures and guidelines for human factors engineering reviews. NUREG-0700, revision 1., Upton, NY: Brookhaven National Laboratory.

O'Hara, J.M., Brown, W.S., Higgins, J.C., & Stubler, W.F. (1994). Human factors engineering guidance for the review of advanced alarm systems. NUREG/CR-6105. Upton, NY: Brookhaven National Laboratory.

Pew, R.W., Miller, D.C., & Feeher, C.E. (1982). Evaluation of proposed control room improvements through analysis of critical operator decisions. . EPRI NP-4361. Palo Alto, CA: Electric Power Research Institute.

Preece, J. (1994). Human-Computer Interaction. Wokingham, England: Addison-Wesley.

Proctor, R.W. & Van Zandt, T. (1994). Human factors - In simple and complex systems. Boston: Allyn and Bacon.

Rankin, W.L., Rideout, T.B., Triggs, T.J., & Ames, K.R. (1985). Computerized annunciator systems. NUREG/CR-3987. Washington, DC: U.S. Nuclear Regulatory Commission.

Rasmussen, J. (1984). Strategies for state identification and diagnosis in supervisory control tasks, and design of computer-based support systems. In Rouse, W.B. (Ed.). Advances in man-machine systems research (Vol.1). (pp. 139-193). Greenwich, CT: JAI Press, Inc.

Rasmussen, J. (1986). Information processing and human-machine interaction - An approach to cognitive engineering. New York: North-Holland Series System Science and Engineering.

Reason, J. T. (1990). Human error. Cambridge: Cambridge University Press.

Roscoe, B.J & Weston, L.M. (1986). Human factors in annunciator/alarm systems: Annunciator experiment plan I. NUREG/CR-4463, SAND85-2545. Washington, DC: U.S. Nuclear Regulatory Commission.

Ross, M.A. (1993). Advanced control rooms: balancing automation and operator-responsibility. Nuclear Engineering International, March, 37-39.

Roth, E.M, Mumaw, R.J, Vincente, K.J., & Burns, C.M. (1997). Operator monitoring during normal operations: Vigilance or problem-solving.?, Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting, pp 158 - 162.

Rouse, W.B. (1988). Adaptive aiding for human/computer control. Human Factors, 30(4), 431-443.

Rouse, W.B. (Ed.). (1993). Human/technology interaction in complex systems. (Vol. 6). Greenwich, CT: JAI Press, Inc.

Sarter, N.B. (1997). Team play with a powerful and independent agent: Operational experiences and automation surprises on the airbus A-320. Human Factors, 39(4), 553-569.

Sarter, N.B. & Woods, D.D. (1995). How in the world did we ever get into that mode? Mode error and awareness in supervisory control. Human Factors, 37(1), 5-19.

Seminara, J.L., Gonzalez, W.R., & Parsons, S.O. (1977). Human factors review of nuclear power plant control room design. (NP-309). Palo Alto, CA: Electric Power Research Institute.

Senders, J. W. & Moray, N. P. (1991). Human error: Cause, prediction, and reduction. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Sheridan, T.B. (1987). "Supervisory Control", in G. Salvendy (ed.) Handbook of Human Factors (pp. 1243-1268). New York: J. Wiley and Sons.

Sorkin, R.D., Kantowitz, B.H., & Kantowitz, S.C. (1988). Likelihood alarm displays. Human Factors, 30 (4), 445-459.

Stanton, N. (Ed.) (1994), Human factors in alarm design. London: Francis & Taylor.

Swain, A.D. & Guttman, A.D. (1980). Handbook of human reliability analysis with emphasis on nuclear power plant applications (Draft Report). NUREG/DR-1288. Washington, DC: U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission. (1985). Susquehanna Steam Electric Station Detailed Control Room Design review Supplement Summary Report. Public Document Room (PDR ADOCR 05000387). Washington D.C: Author.

Vicente, K.J. (1992, July-September). Multilevel interfaces for power plant control rooms I: An integrative review. Nuclear Safety, 33, (3), 381-397.

Wickens, C.D. (1984). Engineering psychology and human performance. Columbus, OH: Charles E. Merrill.

Wickens, C.D. (1992). Engineering psychology and human performance. New York: Harper-Collins.

Woods, D.D. (1994). Cognitive demands and activities in dynamic fault management: abductive reasoning and disturbance management. In Stanton, N. (Ed.). Human factors in Alarm design. (pp.63-91). London: Taylor & Francis.

Woods, D.D., Hollnagel, E., & Mancini, G. (1988). Cognitive engineering in complex worlds. London: Academic Press.

Woods, D.D., O'Brien, J.F., & Hanes, L.F. (1987). Human factors challenges in process control: The case of nuclear power plants. In Salvendy, G. (Ed.). Handbook of human factors (pp. 1724-1770). New York: John Wiley & Sons.

Woods, D.D. & Roth, E.M. (1988). Cognitive engineering: Human problem solving with tools. Human Factors, 30(4), 415-430.

Woods, D.D., Roth, E.M., & Hanes, L.F. (1986a). Models of Cognitive Behavior in nuclear power plant personnel. (NUREG/CR-4532), Vols 1 & 2. Washington DC: U.S. Nuclear Regulatory Commission.

Woods, D.D., Roth, E.M., & Hanes, L.F. (1986b). Models of Cognitive behavior in nuclear power plant personnel: A feasibility study. Vol.1 Summary of results. NUREG/CR-4532, Washington, DC: U.S. Nuclear Regulatory Commission.

Table 1 Probabilities of Error for Annunciated Legend Lights

The term one annunciator includes a functional grouping of annunciators consisting of more than one annunciator with complete dependence among them

Task	HEP
Respond to an annunciated legend light (one of one)	.0001 (.00005 to .001)
Reading the message (this figure includes the probability of reading the wrong legend light)	.001 (.0005 to .005)
Resume attention to a legend light within 1 minute after an interruption (sound and blinking cancelled before interruption)	.001 (.0001 to .01)
Respond to a legend light if more than 1 minute elapses after an interruption (sound and blinking cancelled before interruption)	.95 (.9 to .99)

Table 2 Taxonomy of Errors

Annunciated legend lights	
Omission errors	Failure to initiate some kind of corrective action within a few minutes (this may include an incorrect decision to take action)
Errors in scanning of unannunciated conditions of annunciated lights	During any subsequent scan, failure to recover the initial error of failing to respond to the steady-on legend light
Reading errors	Either the wrong light is read or an error is made in reading the correct light
Judgment errors	The indication is read correctly but the operator makes the wrong decision as to the required action
Annunciated printout equipment	
Omission errors	Same as omission errors
Errors in scanning	Same as errors in scanning of unannunciated conditions of annunciated lights
Reading errors	The message is incorrectly read
Judgment errors	Same as the indication is read correctly but the operator makes the wrong decision as to the required action

Table 3

Task analysis for Large Steamline Break Inside of Drywell Scenario

TASK NO.	OPERATOR	SUBTASK	ELEMENT	SYSTEM	INFORMATION AND CONTROL REQUIREMENTS	CONTROL ROOM INSTRUMENTATION	CONTROLS MANIPULATED
1		EVALUATE CONDITION Monitor Panel	OBSERVE ANNUN (OB ANNUN)	RX CONTROL	AUDIO CUE AND ANNUN BLINKING		
2,3			OB ANNUN		• RX AUTO SCRAM	ANNUN AR3 • RX AUTO SCRAM	
			OB ANNUN		• PRIMARY CONT	• PRIMARY CONT	
			OB ANNUN		• HI PRESS TRIP	• HI PRESS TRIP	
			OB ANNUN		• RX VESSEL LO LVL TRIP	• RX VESSEL LO LVL TRIP	
4,5			OB ANNUN			ANNUN AR4 • RX AUTO SCRAM	
			OB ANNUN			• PRIMARY CONT	
			OB ANNUN			• HI PRESS TRIP	
			OB ANNUN			• RX VESSEL LO LVL TRIP	
6		VERIFY /INFO RCE AUTO ACTIONS	MODE SWITCH TO SHUTDOWN	RX CONTROL	• SWITCH POSITION TO SHUTDOWN		RX MODE SWITCH
						ANNUNCIATOR RX MANUAL SCRAM	
7		SILENCE ANNUN					
8		ACK ANNUN					
9		VERIFY /INFO RCE AUTO ACTIONS	VERIFY ALL RODS FULLY INSERTED	RX CONTROL	RODS FULL-IN INDICATION	• FULL CORE DISPLAY AND/OR	
10			VERIFY ALL RODS FULLY INSERTED	RX CONTROL	RODS FULL-IN INDICATION	• RSCS DISPLAY or DISPLAY #5	
						• IF NOT FULL IN BRANCH TO TRIP RECIR PUMPS	

TASK NO.	OPERATOR	SUBTASK	ELEMENT	SYSTEM	INFORMATION AND CONTROL REQUIREMENTS	CONTROL ROOM INSTRUMENTATION	CONTROLS MANIPULATED
11		INSERT SRM/IRM DETECTORS		RX CONTROL			<ul style="list-style-type: none"> • SRM A-D SELECT PB'S • IRM A-H SELECT PB'S • POWER ON PB • DRIVE IN PB
12		VERIFY /ENFORCE AUTO ACTIONS			<ul style="list-style-type: none"> • ALL PB'S BACKLIT • "OUT" LIGHTS GO OUT • "DRIVING IN" LIGHT COMES ON 	STATUS SRM/IRM DETECTOR DRIVE	
13	PCO	VERIFY /ENFORCE AUTO ACTIONS	TRIP MAIN TURBINE	TURBINE CONTROL	<ul style="list-style-type: none"> • TRIPPED LIGHT ILLUMINATES • MAIN TURBINE TRIP ANNUN 	MAIN TURBINE PB TO TRIP	TURBINE TRIP PB
14	PCO	SILENCE ANNUN		RX CONTROL	<ul style="list-style-type: none"> • MAIN TURBINE TRIP ANNUN SILENCE 		<ul style="list-style-type: none"> • ANNUN SILENCE PB
15	PCO	ACK ANNUN		RX CONTROL	<ul style="list-style-type: none"> • MAIN TURBINE TRIP ANNUN SOLID 		<ul style="list-style-type: none"> • ANNUN ACK PB
16	PCO	EVALUATE CONDITIONS	CHANGE CRT DISPLAYS (DCS)	RX CONTROL	CRT'S CHANGE FORMAT	PB BACKLIGHTS	MASTER DISPLAY SELECT MATRIX-"EMERG. SHUTDOWN" PB
17a	PCO	EVALUATE CONDITIONS	MONITOR	RX CONTROL	BARGRAPHS RESPOND <ul style="list-style-type: none"> • DW PRESS >1.69 (TS) 	<ul style="list-style-type: none"> • CRT'S ON UOB • CRT'S ON UMC 	<ul style="list-style-type: none"> • IRM RANGE SWITCHES • CONFIRMS ENTRY CONDITIONS FOR EO
17b	PCO	EVALUATE CONDITIONS	MONITOR RX POWER	RX CONTROL	BARGRAPHS RESPOND <ul style="list-style-type: none"> • RX POWER 0% APRM (SME) 0-125% +/- 5% 	<ul style="list-style-type: none"> • CRT'S ON UOB • CRT'S ON UMC 	

TASK NO.	OPERATOR	SUBTASK	ELEMENT	SYSTEM	INFORMATION AND CONTROL REQUIREMENTS	CONTROL ROOM INSTRUMENTATION	CONTROLS MANIPULATED
17c	PCO	EVALUATE CONDITIONS	MONITOR VESSEL LEVEL	RX CONTROL	BARGRAPHS RESPOND <ul style="list-style-type: none"> RX LVL <13" TS (-150 TO +80" +/- 5 IN) 	<ul style="list-style-type: none"> CRT'S ON UOB CRT'S ON UMC 	
17d	PCO	EVALUATE CONDITIONS	MONITOR RX PRESSURE	RX CONTROL	BARGRAPHS RESPOND <ul style="list-style-type: none"> MSL ISOLATION DUE TO RPV PRESS (861 PSIG (TS) 0-1500 PSIG +/- 50 PSIG) 	<ul style="list-style-type: none"> CRT'S ON UOB CRT'S ON UMC 	
18a	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> CRT'S 	RX CONTROL	LEVEL CAN'T BE DETERMINED <ul style="list-style-type: none"> RX PRESS LOW <100 PSIG (SME) 0-1500 PSIG +/- 50 PSIG 	DCS/CRT'S #1 & 3 ON IC651 (UOB)	
18b	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> CRT'S 	RX CONTROL	<ul style="list-style-type: none"> DW PRESS HIGH >20 PSIG (SME) 0 +/- 0.1 PSIG (0-75 PSIG) 	DCS/CRT'S #1 & 3 ON IC651 (UOB)	
18c	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> CRT'S 	RX CONTROL	<ul style="list-style-type: none"> DW TEMP HIGH >212 °F(SME) 0 +/- 5 °F (0-350 °F) 	DCS/CRT'S #1 & 3 ON IC651 (UOB)	
19a	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> SIP ECCS BOARD INDICATIONS 	SIP, ECCS	LEVEL CAN'T BE DETERMINED <ul style="list-style-type: none"> DW PRESS HIGH >20 PSIG (SME) 0 +/- 0.1 PSIG (0-75 PSIG) 	METERS ON SIP (IC652) <ul style="list-style-type: none"> IC32 R608 IC32 R605 IC32 606A IC32 606B IC32 606C IC32 604 	
19b	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> SIP ECCS BOARD INDICATIONS 	SIP; ECCS	<ul style="list-style-type: none"> DW TEMP HIGH >212 DEGREE (SME) 0 +/- 5 °F (0-350 °F) 		
19c	PCO	DETERMINE PLANT CONDITIONS	OBSERVE <ul style="list-style-type: none"> SIP ECCS BOARD INDICATIONS 	SIP, ECCS	<ul style="list-style-type: none"> RX PRESS LOW <100 PSIG (SME) 0-1500 PSIG +/- 50 PSIG 		

TASK NO.	OPERATOR	SUBTASK	ELEMENT	SYSTEM	INFORMATION AND CONTROL REQUIREMENTS	CONTROL ROOM INSTRUMENTATION	CONTROLS MANIPULATED
Sl a	SCO			SIP, ECCS	<ul style="list-style-type: none"> DW PRESS HIGH >20 PSIG (SME) 0 +/- 0.1 PSIG (0-75 PSIG) 	METERS ON RCCB (IC601) <ul style="list-style-type: none"> IC601 B11R615 IC601 B21R623A&B IC601 PR 15702 IC601 LR15776A&B IC601 PR15710A&B IC601 TR1579A&B 	

Table 4

Data for Alarm System Task Network Model

Task Number	Task Name	Mean Time (sec.)	High (-3) SD (sec.)	Average SD (sec.)	Low (+3) SD (sec.)
Op1	Monitor Panels (From desk)	120	0	0	0
	Decision Node op1 (See Table 5)				
Op2	Audio Alarm	--	--	--	--
op2a	Go to the board	30	22.5	2.5	37.5
op2b	Depress silence PB	2	0	0	0
op2c	Alarm silent	NA	NA	NA	NA
Op3	Alarms Blink	--	--	--	--
op3a	Move across board	15	0	5	30
op3b	Rx auto scram	5	2	1	8
op3c	Primary Containment	5	2	1	8
op3d	High pressure trip	5	2	1	8
op3e	Rx level lo level trip	5	2	1	8
op3f	Depress acknowledge PB	2	0	0	0
op3g	Alarms stop flashing	--	--	--	--
OP4	Audio Alarm				
<i>op4a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>0</i>
<i>op4b</i>	<i>Depress silence pb</i>	<i>2</i>	<i>0</i>	<i>0</i>	<i>0</i>
<i>op4c</i>	<i>Alarm silent</i>	<i>--</i>	<i>--</i>	<i>--</i>	<i>--</i>
OP5	Alarms Blink				
<i>op5a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>30</i>
<i>op5b</i>	<i>Rx auto scram</i>	<i>5</i>	<i>2</i>	<i>1</i>	<i>8</i>
<i>op5c</i>	<i>Primary Containment</i>	<i>5</i>	<i>2</i>	<i>1</i>	<i>8</i>
<i>op5d</i>	<i>High pressure trip</i>	<i>5</i>	<i>2</i>	<i>1</i>	<i>8</i>
<i>op5e</i>	<i>Reactor vessel low level trip</i>	<i>5</i>	<i>2</i>	<i>1</i>	<i>8</i>
<i>op5f</i>	<i>Depress acknowledge PB</i>	<i>2</i>	<i>0</i>	<i>0</i>	<i>0</i>
<i>op5g</i>	<i>Alarms stop flashing</i>	<i>--</i>	<i>--</i>	<i>--</i>	<i>--</i>
OP6	Switch Mode Switch to Shutdown	--		--	
op6a	Move across board	15	0	5	30
1P6b	Move Mode Switch to Shutdown	5	2	1	8
	Decision Node op6b (See Table 5)				
OP7	Audio Alarm	--	--	--	--
<i>op7a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>30</i>
<i>op7b</i>	<i>Depress silence PB</i>	<i>2</i>	<i>0</i>	<i>0</i>	<i>0</i>
<i>op7c</i>	<i>Alarm audio silent</i>	<i>--</i>	<i>--</i>	<i>--</i>	<i>--</i>
OP8	Alarm Blinks	--	--	--	--
<i>op8a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>30</i>

Task Number	Task Name	Mean Time (sec.)	High (-3) SD (sec)	Average SD (sec.)	Low (+3) SD (sec.)
<i>op8b</i>	<i>Depress acknowledge PB</i>	2	0	0	0
<i>op8c</i>	<i>Alarm stops flashing</i>	--	--	--	--
OP9	Verify Control Rods Full-in	--	--	--	--
op9a	Move across board	15	0	5	30
	Decision Node op9a (See Table 5)				
op9b	Verify full core	15	3.75	3.75	26.25
op9c	Verify on CRT #5	60	15	15	105
OP10	Insert SRM/IRM	--	--	--	--
op10a	Select SRM A-D	10	2.5	2.5	17.5
op10b	Select IRM PB	10	2.5	2.5	17.5
op10c	Select Power On	10	2.5	2.5	17.5
op10d	Select Drive In	10	2.5	2.5	17.5
OP11	Verify Drive In Lights	30	7.5	7.5	52.50
OP12	Trip Main Turbine	--	--	--	--
op12a	Move across board	15	0	5	30
op12b	Depress Turbine PB	2	.5	.5	3.5
op12c	Turbine Trips	--		--	
OP13	Audio Alarm	--		--	
<i>op13a</i>	<i>Move across board</i>	10	2.5	2.5	17.5
<i>op13b</i>	<i>Depress Silence PB</i>	2	.5	.5	3.5
<i>op13c</i>	<i>Alarm audio silent</i>	--	--	--	--
OP14	Alarm Blinks	--	--	--	--
<i>op14a</i>	<i>Move across board</i>	10	2.5	2.5	17.5
<i>op14b</i>	<i>Depress acknowledge PB</i>	2	0	--	0
<i>op14c</i>	<i>Alarm stops</i>	--		--	
OP15	Change CRT Format	--		--	
	Decision Node op15 (See table 5)				
op15a	Change CRT	90	67.5	22.5	157.5
op15b	Select master Display	40	28	4	52
op15c	Select Emerge Shutdown PB	2	0	0	0
OP16	Monitor Rx Power, Level, & Press	--	--	--	--
op16a	Go to Unit Monitoring Console (UMC)	40	28	4	52
op16b	Use CRTs on UMC	90	63	9	117
op16c	Check Drywell Pressure	10	.01	3.33	19.99
op16d	Check Rx level	10	.01	3.33	19.99
op16e	Check Rx power	10	.01	3.33	19.99
OP17	Monitor Rx Power & Level				
op17a	Go back to UOB	40	28	4	52
op17b	Use CRTs on UOB	90	63	9	117

Task Number	Task Name	Mean Time (sec.)	High (-3) SD (sec.)	Average SD (sec.)	Low (+3) SD (sec.)
op17c	Check drywell pressure	10	.01	3.33	19.99
op17d	Check Rx level	10	.01	3.33	19.99
op17e	Check Rx pressure	10	.01	3.33	19.99
op17f	Check Rx power	10	.01	3.33	19.99
OP18	Meters on Standby Information Panel (SIP)	--	--	--	--
op18a	Go to SIP	50	35	5	65
op18b	Check drywell press	10	.01	3.33	19.99
op18c	Check drywell temperature	10	.01	3.33	19.99
op18d	Check Rx pressure	10	.01	3.33	19.99
OP19	Observe ECCS Board	--	--	--	--
op19a	Go to Reactor Core Cooling Board (RCCB)	60	45	15	105
op19b	Verify RCIC out of service	10	.01	3.33	19.99
op19c	Verify both CS systems injecting	10	.01	3.33	19.99
op19d	Verify both LPCI injecting	10	.01	3.33	19.99
op19e	Verify all MSIVs closed	10	.01	3.33	19.99
op19f	Verify all valve positions closed	10	.01	3.33	19.99
op19g	Verify HPCI out of service	10	.01	3.33	19.99
OP20	Alarms Audio	--	--	--	--
op20a	Move across board	15	0	5	30
op20b	Depress silence PB	2	0	0	0
op20c	Alarm audio silent	--	--	--	--
OP21	Alarms Blink	--	--	--	--
op21a	Move across board	15	0	5	30
op21b	RCIC Out of service	10	.01	3.33	19.99
<i>op21c</i>	<i>Both CS injecting</i>	<i>10</i>	<i>.01</i>	<i>3.33</i>	<i>19.99</i>
<i>op21d</i>	<i>Both LPCI loops injecting</i>	<i>10</i>	<i>.01</i>	<i>3.33</i>	<i>19.99</i>
<i>op21e</i>	<i>All MSIVs closed</i>	<i>10</i>	<i>.01</i>	<i>3.33</i>	<i>19.99</i>
op21f	HPCI out of service	10	.01	3.33	19.99
op21g	Depress acknowledge PB	2	0	0	0
op21h	Alarm stop blinking	--	--	--	--
OP22	Monitor RHR/LPCI	30	7.5	7.5	52.5
OP23	Alarm blinks	--	--	--	--
<i>op23a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>0</i>
<i>op23b</i>	<i>Depress acknowledge PB</i>	<i>2</i>	<i>0</i>	<i>0</i>	<i>0</i>
<i>op23c</i>	<i>Alarm stop flashing</i>	--	--	--	--
OP24	Audio Alarm	--	--	--	--
<i>op24a</i>	<i>Move across board</i>	<i>15</i>	<i>0</i>	<i>5</i>	<i>30</i>

Task Number	Task Name	Mean Time (sec.)	High (-3) SD (sec)	Average SD (sec.)	Low (+3) SD (sec.)
<i>op24b</i>	<i>Depress silence PB</i>	<i>2</i>	<i>0</i>	<i>0</i>	<i>0</i>
<i>op24c</i>	<i>Alarm audio silent</i>	<i>--</i>		<i>--</i>	
OP25	Verify MSIV Closed	20	5	5	35
OP26	HPCI out of service	20	5	5	35
	Decision Node op26 (See Table 5)				
OP27	Verify Auxiliary Bus Fast Transfer	--		--	
op27a	Go to electric board	45	0	15	90
op27b	Verify offsite power busses	20	5	5	35
op27c	Verify Diesel Generator	20	5	5	35
2OP1	SCO OB RCCB	--		--	
2op1a	SCO to RCCB	45	30	5	60
2op1b	Monitor drywell pressure	20	5	5	35
2op1c	Monitor drywell temperature	20	5	5	35
2op1d	Monitor Rx pressure	20	5	5	35
2OP2	Report to Shift Supervisor	--		--	
2op2a	SCO verify Rx level	10	.01	3.33	19.99
2op2b	SCO move across ECCS panel	15	0	5	30
2op2c	Monitor level indication	20	5	5	35
2op2d	Monitor level recorder	20	5	5	35
2OP3	Verify Rx level Not Determined	--	--	--	--
2op3a	SCO move across boards	15	0	5	30
2op3b	Verify Rx level	10	.01	3.33	19.99
2op3c	Verify Drywell temp	10	.01	3.33	19.99
2op3d	Proceed to lvl restoration	120	30	30	210
2OP4	Verify Suppression Pool Temp	10	.01	3.33	19.99
2OP5	Initiate Suppression Pool Cooling	--		--	
2op5a	SCO move across ECCS board	15	0	5	30
2op5b	Initiate suppression pool cooling	45	11.25	11.25	78.75
2op5c	Verify RHR Sys in Standby	10	.01	3.33	19.99
2op5d	Verify RHR SW Available	10	.01	3.33	19.99
2op5e	Verify RHR pump running	10	.01	3.33	19.99
2op5f	Verify suppression pool temp	10	.01	3.33	19.99
2opg	Verify RHR pump flow	10	.01	3.33	19.99
2oph	Verify RHRSW flow available	10	.01	3.33	19.99
2OP6	Verify DW Temp per SS	--		--	
2op6a	SCO to ECCS panel	15	0	5	30
2op6b	Verify DW temp	10	.01	3.33	19.99
2OP7	End of DW Temp Response	120	90	10	150
2OP8	Verify Containment (CONT) Press per SS	--	--	--	--

Task Number	Task Name	Mean Time (sec.)	High (-3) <u>SD</u> (sec)	Average <u>SD</u> (sec.)	Low (+3) <u>SD</u> (sec.)
2op8a	SCO move across ECCS panel	15	0	5	30
2op8b	Verify CONT press on TR	30	7.5	7.5	52.5
2OP9	End of CONT Response	60	15	15	105
2OP10	Verify SP Temp per SS	--	--	--	--
2op10a	SCO move across ECCS panel	15	0	5	30
2op10b	Verify SP level	10	.01	3.33	19.99

Table 5

Decision Node Descriptions

Task No.	Task Name	Next Task No.	Next Task	Routing Condition	Decision Type
OP1	Monitor panels from desk	OP2	Audio Alarm	1;	Probabilistic
		OP3	Alarms Blink		
		OP4	Audio Alarm	1;	Probabilistic
		OP5	Alarms Blink		
OP6b	Switch Mode Switch to Shutdown position	OP7	Audio Alarm	.2;	Probabilistic
		OP8	Alarm Blink		
		OP9	Verify Control Rods Full-In	.8;	Probabilistic
OP9a	Verify Control Rods Full-In	OP9c	Verify on CRT #5	.5;	Multiple
		OP9b	Verify on Full Core Display	.5;	Multiple
OP15	Change CRT Format	OP17	Monitor Rx Power and Level at UOB	1;	Probabilistic
		OP16	Monitor Rx Power, Level, and Pressure at UMC	1;	Probabilistic
OP26	HPCI Out of Service	OP27	Verify Auxiliary Bus Fast Transfer	1;	Multiple
		2OP1	SCO monitors at OB	1;	Multiple

Table 6

Statistical Results of Primary Operator Task Performance (Without Secondary Operator)
for Micro Saint Simulation Models

High Skills / Experience (-3SD) Crew (High)

	Min.	Max.	Mean	SD
Without alarm reduction	0.00	1468.1	751.6	540.7
With alarm reduction	0.00	791.2	411.0	297.6

Baseline Alarm Configuration and Average (SD) Crew (Average)

	Min.	Max.	Mean	SD
Without alarm reduction	0.00	1216.0	720.5	512.7
With alarm reduction	0.00	1135.8	684.8	487.3

Low Skills / Experience (+3 SD) Crew (Low)

	Min.	Max.	Mean	SD
Without alarm reduction	0.00	2567.8	1250.4	909.7
With alarm reduction	0.00	1782.3	1087.8	774.4

Table 7

Raw Data From Micro Saint[®] Primary Operator Alarm Response Models

	T1	T2	T3	T4	T5	T6		T1	T2	T3	T4	T5	T6
1.	57.3	45.3	360.4	173.0	534.0	183.0	26.	68.5	56.5	370.7	218.0	626.3	228.0
2.	68.5	56.5	346.5	218.0	582.0	228.0	27.	36.8	45.3	366.9	173.0	609.0	183.0
3.	57.3	45.3	346.8	173.0	465.5	183.0	28.	48.0	56.5	343.5	218.0	653.7	228.0
4.	68.5	56.5	344.3	218.0	606.5	228.0	29.	57.3	45.3	383.1	173.0	536.8	183.0
5.	36.8	45.3	398.3	173.0	561.0	183.0	30.	68.5	56.5	400.2	218.0	640.8	228.0
6.	48.0	56.5	402.5	218.0	642.0	228.0	31.	57.3	45.3	367.3	173.0	523.1	183.0
7.	57.3	45.3	343.1	173.0	611.2	183.0	32.	68.5	56.5	371.0	218.0	585.1	228.0
8.	68.5	56.5	360.0	218.0	699.1	228.0	33.	36.8	45.3	368.6	173.0	533.7	183.0
9.	36.8	45.3	348.9	173.0	516.0	183.0	34.	48.0	56.5	348.5	218.0	583.6	228.0
10.	48.0	56.5	348.6	218.0	608.0	228.0	35.	36.8	45.3	387.2	173.0	541.7	183.0
11.	57.3	45.3	365.1	173.0	474.7	183.0	36.	48.0	56.5	379.5	218.0	591.5	228.0
12.	68.5	56.5	355.8	218.0	562.0	228.0	37.	57.3	45.3	356.7	173.0	512.6	183.0
13.	36.8	45.3	361.8	173.0	518.0	183.0	38.	68.5	56.5	367.1	218.0	620.8	228.0
14.	48.0	56.5	377.3	218.0	553.0	228.0	39.	57.3	45.3	345.8	173.0	518.0	183.0
15.	36.8	45.3	351.8	173.0	538.4	183.0	40.	68.5	56.5	398.7	218.0	607.0	228.0
16.	48.0	56.5	371.3	218.0	612.4	228.0	41.	57.3	45.3	397.2	173.0	525.0	183.0
17.	36.8	45.3	364.5	173.0	558.6	183.0	42.	68.5	56.5	368.5	218.0	605.5	228.0
18.	48.0	56.5	355.3	218.0	588.4	228.0	43.	36.8	45.3	380.5	173.0	581.0	183.0
19.	36.8	45.3	345.3	173.0	579.7	183.0	44.	48.0	56.5	346.2	218.0	639.8	228.0
20.	48.0	56.5	363.0	218.0	634.4	228.0	45.	36.8	45.3	350.0	173.0	532.0	183.0
21.	57.3	45.3	343.0	173.0	503.9	183.0	46.	48.0	56.5	349.1	218.0	635.0	228.0
22.	38.8	56.5	406.6	218.0	589.2	228.0	47.	36.8	45.3	363.0	173.0	538.5	183.0
23.	48.0	45.3	368.4	173.0	486.0	183.0	48.	48.0	56.5	358.6	218.0	665.4	228.0
24.	68.5	56.5	403.2	218.0	608.0	228.0	49.	36.8	45.3	384.9	173.0	534.0	183.0
25.	57.3	45.3	403.7	173.0	541.1	183.0	50.	48.0	56.5	361.0	218.0	618.5	228.0

Table 8

MINITAB® Descriptive Results for Primary Operator Task Performance (Without Secondary Operator) for Micro Saint® Simulation Models

High Skills (-3 SD)

Test 1 - Without alarm Reduction; Test 2 With alarm reduction

Descriptive Statistics

Variable	N	Mean	Median	Tr Mean	StDev	SE Mean
test1	50	51.46	48.00	51.30	11.69	1.65
test2	50	50.900	50.900	50.900	5.657	0.800

Variable	Min	Max	Q1	Q3
test1	36.80	68.50	36.80	57.30
test2	45.300	56.500	45.300	56.500

Average Skills (SD)

Test 3 - Without alarm Reduction; Test 4 With alarm reduction

Descriptive Statistics

Variable	N	Mean	Median	Tr Mean	StDev	SE Mean
test3	50	367.39	364.80	366.50	19.16	2.71
test4	50	195.50	195.50	195.50	22.73	3.21

Variable	Min	Max	Q1	Q3
test3	343.00	406.60	349.05	380.42
test4	173.00	218.00	173.00	218.00

Low Skills (+3 SD)

Test 5 - Without alarm Reduction; Test 6 With alarm reduction

Descriptive Statistics

Variable	N	Mean	Median	Tr Mean	StDev	SE Mean
test5	50	574.63	581.50	574.71	52.48	7.42
test6	50	205.50	205.50	205.50	22.73	3.21

Variable	Min	Max	Q1	Q3
test5	465.50	699.10	533.92	611.50
test6	183.00	228.00	183.00	228.00

Table 9

T-test for Before-and-After Measurements of the Effects On Operator Task Performance
By Implementation of Alarm Reduction

Test Groups	Mean	SD	<i>t</i> Value
High Skills Before (T1)	51.5		
High Skills After (T2)	1.0		
High Skills Difference	0.6	10.5	0.01
Average Skills Before (T3)	367.0		
Average Skills After (T4)	195.5		
Average Skills Difference	171.5	29.0	41.8
Low Skills Before (T5)	574.6		
Low Skills After (T6)	205.5		
Low Skills Difference	369.1	38.1	68.6

Figure 1. Alarm system at a conventional nuclear power plant control room.

Figure 2. Sketch of the main control room panels for an advanced boiling water reactor (ABWR).

Figure 3. Supervisory control model structure

Figure 4. Decision-making process activities based upon states of knowledge

Baron, S. (1982)

Figure 5. Micro Saint model with conventional alarm system.

Figure 6. Main control room panel arrangement of reference plant used as data source

Figure 7. Model of operator response to conventional (7a) and alarm reduction (7b) schemes

Figure 8. Description for subtask op2a

Task Description	
Looking at Task	op2a
Task Number	op2a
Name	Go to board
☐ Show Expressions ☐ Notes	
Task Timing Information	
Mean Time:	Time Distribution: Normal
30;	Standard Deviation: 2.5;
Release Condition and Task Execution Effects	
Release Condition:	Beginning Effect:
1;	operators:=operators-1;
Launch Effect:	Ending Effect:
	operators:=operators+1;
<input type="button" value="Accept"/> <input type="button" value="Cancel"/>	

Figure 9. Description for subtask op2b

Task Description	
Looking at Task	op2b
Task Number	op2b
Name	Depress silence PB
☐ Show Expressions ☐ Notes	
Task Timing Information	
Mean Time:	Time Distribution: Normal
2;	Standard Deviation:
Release Condition and Task Execution Effects	
Release Condition:	Beginning Effect:
1;	operators:=operators-1;
Launch Effect:	Ending Effect:
	operators:=operators+1;
<input type="button" value="Accept"/> <input type="button" value="Cancel"/>	

Figure 10. Description for subtask op2c

Task Description

Looking at Task

Task Number Show
☒ Expressions
☐ Notes

Name

Task Timing Information

Mean Time: Time Distribution
 Standard Deviation:

Release Condition and Task Execution Effects

Release Condition: Beginning Effect:
 Launch Effect: Ending Effect:

Figure 11. Variables for alarm reduction model

Figure 12. Micro Saint[®] model of drywell steam line break model for High (-3 SD), Average (SD), and Low (+3 SD) Skill Level Tasks Without Alarm Reduction

Figure 13. Micro Saint[®] model of drywell steam line break model for High (-3 SD), Average (SD), and Low (+3 SD) Skill Level Tasks With Alarm Reduction

Figure 14. Description of decision dialog box for decision node op6b

Figure 15. Description of decision dialog box for decision node op9a

Network op9 Verify Rods Full in

Description of Decision

Looking at Decision **op9a**

Task Name **Move across** Decision Type **Multiple**

Next Task: Routing Condition: **More**

op9c	.5;	
Verify on		
op9b	.5;	
Verify on		

Accept **Cancel** **More**

Figure 16. Description of decision dialog box for decision node OP15

Network op15 Chg crt format

Description of Decision

Looking at Decision **op15c**

Task Name **Select Emerg** Decision Type **Multiple**

Next Task: Routing Condition: **More...**

op17	1;	
Mon rx		
op16	1;	
Mon rx		

Accept **Cancel** **More...**

Figure 17. Description of decision dialog box for decision node OP26

Figure 18. Summary of Means for Alarm Reduction Tests

Figure 19. Box plot details for alarm reduction tests, high skill crew tests

Figure 20. Box plot details for alarm reduction tests, average skill crew tests

Figure 21. Box plot details for alarm reduction tests, low skill crew tests